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Research on Ultrasonic Flaw Detection of Steel Weld in Spatial Grid Structure

Tao Du[1], Jiandong Sun[1], Shengguang Fu[2], Changquan Zhang[3], Qing Gao[4]
[1]Shandong Academy of Building Research Institute of Structure Jinan; 250031
[2]Feicheng Construction Engineering Quality Supervision Station Tai'an; 271000
[3]Shandong Provincial Department of housing and urban rural development Jinan; 250000
[4]Shandong Hi-speed Company Limited Jinan; 250000

dt7777@126.com

Abstract. The welding quality of spatial grid member is an important link in quality control of steel structure. The paper analyzed the reasons that the welding seam of small-bore pipe with thin wall grid structure is difficult to be detected by ultrasonic wave from the theoretical and practical aspects. A series of feasible detection methods was also proposed by improving probe and operation approaches in this paper, and the detection methods were verified by project cases. Over the years, the spatial grid structure is widely used the engineering by virtue of its several outstanding characteristics such as reasonable structure type, standard member, excellent space integrity and quick installation.

The wide application of spatial grid structure brings higher requirements on nondestructive test of grid structure. The implementation of new Code for Construction Quality Acceptance of Steel Structure Work GB50205-2001 strengthens the site inspection of steel structure, especially the site inspection of ultrasonic flaw detection in steel weld. The detection for spatial grid member structured by small-bore and thin-walled pipes is difficult due to the irregular influence of sound pressure in near-field region of sound field, sound beam diffusion generated by small bore pipe and reduction of sensitivity. Therefore, it is quite significant to select correct detecting conditions. The spatial grid structure of welding ball and bolt ball is statically determinate structure with high-order axial force which is connected by member bars and joints. It is welded by shrouding or conehead of member bars and of member bar and bolt-node sphere. It is obvious that to ensure the quality of these welding positions is critical to the quality of overall grid structure. However, the complexity of weld structure and limitation of ultrasonic detection method cause many difficulties in detection. No satisfactory results will be obtained by the conventional detection technology, so some special approaches must be used.

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1. Analysis of Welding Process

Spatial grid structure is generally made from low-carbon steel Q235 or low alloy steel 16Mn, and the member bar is small-bore steel pipe with thin wall in size of Φ48×3.5mm- Φ15×98mm. When the shrouding or conehead of member bars and of member bar and bolt-node sphere, if the wall thickness of a member bar is less than or equal to 6mm, it can be welded through even if not setting a groove; When the wall thickness of a member bar is larger than 6mm, an approx. 300mm grove is required to be set. The common defects in welding seam include incomplete penetration or fusion of root, slag inclusion and air hole, but cracks seldom appear. Manual arc welding generally uses Φ2.5mm or Φ3.2mm welding rod, otherwise the root is not easy to be welded through. If downgrade welding is adopted during the gas shielded welding, the deposited metal is easy to flow down, resulting in incomplete fusion. If the welding spot is too high to realize smooth transition, incomplete penetration and slag inclusion will appear on two sides of the welding spot, and the root at arc striking position and arc suppression position will have incomplete penetration and slag inclusion.

2. Analysis on the Reasons for Ultrasonic Wave Which Is not Easy to Detect

2.1. Influence of near-field region

Based on the fundamental principle of ultrasonic detection, the thin-walled weld must be detected by special probe. Its main reason is that the large probe chip used in general weld detection causes a length of near-field region, which is larger than the distance from the detected thin-walled weld to sound source. The severe inference in near-field region and uneven sound pressure distribution plate make it impossible to quantify defects and give accurate and reliable judgment on defect echo. Additionally, the front distance of probe is above 12mm. The main sound beam with a perpendicular incidence of the probe cannot reach the weld even if the large retracted angle (e.g. 700) is adopted. The scanning on the whole beam can realized only by the second-trace echo and third-trace echo. But nearly three times of manufacturing error of wall thickness will appear in the third-trace echo reflection, and the sound velocity of multi-trace wave detection is too wide against the plate thickness, which will significantly affect the detection and positioning of defects. In the detection of thin-walled weld, the following requirements should be met to finish the detection by the first-trace echo and the second-trace echo:①

small-sized chip;② large refracted angle (large K value);③ Short front distance L.

2.2. Interference of head wave

If the defect echo of thin-walled workpiece is too close to head wave, the shape of head wave will have a significant influence on defect echo, and the head wave width and non-detection zone will be directly affected.

Head wave width: It refers to the time of duration emitting pulse, and is indicated by the ultrasonic propagation distance which is equivalent to the horizontal distance between scale "0" to trailing edge of head wave and the intersection of vertical scale 20% line under a certain upper sensitivity. The wider the head wave is, the poorer capacity for detecting defects on sub-surface will be. For example, the actually measured head wave width of commonly used CTS-22 ultrasonic detector (manufactured by Shantou Ultrasonic Instrument Plant) and 2.5PKz angle probe is 5mm.When the butt-welded seam of 3mm thickness steel plate is detected, the scanning ratio is adjusted deeply as 1:1 as a result, the defect echo cannot be determined by the primary wave (horizontal distance ≤3mm) and secondary wave (horizontal distance ≤6mm), but by the tertiary wave. The sound pressure and sound intensity of ultrasonic wave have been increased considerably after tertiary wave attenuation, so the defect echo is totally impossible to be identified.

Non-detection area is an area near the detection surface, where no defects can be detected, and indicated by the minimum distance from the detection surface to the surface where defects can be detected. If the non-detection area is small, the defects near the detection surface can be detected; on the contrary, only the defects away from the detection surface can be detected. The non-detection area is not only related to probe performance, also inseparably interconnected with head wave width. For example, the measured non-detection area for CTS-22 detector and 2.5PK2 angle probe on CSK-IA test block is within 0～5mm.

It can be inferred that this non-detection area is also near to the defect echo of the secondary wave from the butt weld of 3mm plate, and its defects only can be determined by the tertiary wave as well.

2.3. Influence of curvature

Spatial grid member is small-bore and thin-walled steel pipe with a diameter of Φ48～Φ159mm and large surface curvature, which cause the contacting area between probe and workpiece reduces from surface contact to line contact and even point contact. The poor coupling condition will result in severe loss of acoustic energy, which will significantly reduce wave signal. In addition, the curvature has a large influence on positioning and length measurement of defects. It is obvious that the defect length measured from excircle will exceed its actual length, so its indicating length should be calculated by a formula, which is extremely inconvenient on site.

Other influencing factors

Weld detection of thin-walled workpiece is also influenced by signal-to-noise ratio, surplus sensitivity, resolving ability and other factors. These factors are composite performance indexes of detector and probe, and the composite performance of general detector and probe does not meet the demand of weld detection of thin-walled workpiece.

The above influence factors make it extremely difficult to weld detection of thin-walled workpiece by general instrument and detection methods. In practice, we have made repeated tests and researches on the particularity of grid structure joint weld and other factors influencing ultrasonic detection, and prepared a set of simple and practical technique with better effect.

3. Test method

The detection method is described by an example of steel pipe (diameter 50mm, wall thickness 4mm) butt weld in welded spherical joints.

3.1. Detector

Union Pxut-3300 six channels full digital ultrasonic detector is selected. It is equipped with a 0.8Kg battery, and the light weight, high luminance and long continuous working hours are suitable for site detection. In particular, its performance indexes represent the highest level of current ultrasonic detection of steel structure.

Its main performance:

① Horizontal linearity. Its horizontal linearity is tested to be less than and equal to 1%, see test method in Ultrasonic Detection P89.

② vertical linearity. Its vertical linearity is measured as $\Delta d \leq 4\%$;

③ Dynamic range. Its dynamic range is measured as D≥30dB;

④ Attenuator precision. The attenuator precision has an impact on reliability of defect detection and the accuracy of defect quantitative. Its attenuation range is 0-120dB, which can be stepped by 0.1dB.

3.2. Probe

Selection of probe parameters:

①Probe frequency: The attenuation coefficient of the primary wave can be ignored because its sonic path distance is too short for the thin-walled member bars. To improve the directivity of ultrasonic beam, reduce noise wave and improve the resolution, it is better to use higher detection frequency. We use a probe with a detection frequency of 5MHz.

② Probe K value; Considering the particularity of grid structure joint weld and the distribution rule of defects, the detection can only be carried out from one side of member bar, and the primary wave should be used as far as possible. To make the primary wave step over the root of weld, sonic path distance and span should be long enough, which mean K value should be large enough. We use the probe with a K value of 2.5.

③Frontal L:The front distance L of probe should be short enough. We use the probe with a front distance of L=6mm.

④ Composite performance of detector and probe: signal-to-noise ratio N=50dB, surplus sensitivity S=50dB, head wave width W0<2mm.

⑤ Probe curvature:

The probe surface is flat when it is manufactured, so it may have point contact or line contact when contacting with a hook surface, which will cause a loss of effective acoustic energy. The calculation formula of ultrasonic sound pressure:

$$\rho = \rho_0 \frac{A}{\lambda S}$$

ρ ---sound pressure incident on a certain reflector

ρ_0 --- radiated sound pressure

A----effective chip area
S-----beam path distance
λ -----Wavelength

Known that the incoming sound pressure of ultrasonic wave against reflector is in direct proportion to the effective chip area. If the coupling area decreases, the incoming sound pressure will reduce accordingly, which will result in a reduction of reflection wave height and detection sensitivity. It certainly will affect the defect quantitative and leak detection. The research on butt-welded seam of steel pipe with different curvature showed that the defect reflection echo is relatively stable when the curvature radius is larger than 20mm, and similar echo amplitude can be received at the same position in repeated detections. But the reflection echo is not stable when the curvature radium is less than 20mm, and reflection echo may not be received at the same position in repeated detections. The research results indicated that the defects is possible to be undetected when the curvature radius of a workpiece is less than 20mm.When the probe surface is polished to a similar status of workpiece curvature, the defect reflection echo will recover to stable. For the purpose of conservation, it is suggested that when the curvature radius of a workpiece is less than 40mm during the practical operation, the possibility of leak detection can be considerably decreased if the probe surface is polished to as similar status with workpiece curvature. We made curvature finishing to the probe by polishing the polymethyl methacrylate of the probe with steel file and fine abrasive paper to match the detection surface to the curvature radius of test block. The curvature radius of the finished probe is 27mm, which is approximate to the curvature radius 25mm of pipes to be tested. The polished probe is shown as follows(see figure 1):

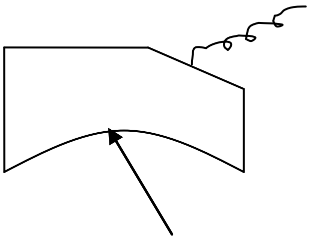

Figure 1. Polished probe.

3.3. Test block

CSK-1C test block specially for profile steel grid structure is adopted. Every three test blocks are divided into one group, and the curvature radius of the three test block are 27mm, 40mm and 60mm respectively, which can meet the requirements in JG/T3034.1-1996 that the curvature radius of detection surface should be 0.9-1.5 times of test block.

3.4. Couplant

Engine oil is selected.

3.5. Detection surface

Considering the particularity of grid structure joint weld, the detection can only be carried out from one side of member bar. The primary wave should be used as far as possible to detect the root defects; the secondary wave is mainly used to detect the defects at the upper part; sometimes, the tertiary wave is used to detect the defects at one side of shrouding or conehead. Single-face and bilateral inspection can be adopted for butt weld between steel pipes; for single-face and single-side inspection can be used for the butt weld of pipe sphere limited by operating conditions. The demand of primary wave and secondary wave detection can be met only if the width of detection surface is determined to be 30mm.

3.6. Selection of detection direction

The direction specified in JG/T3034.1-1996 can be used, i.e. the moving mode of a probe should be in a shape of "W" with swing in angle of 100-150°.To determine the position and shape of defects, observe dynamic waveform of defects and distinguish echo signal, various scanning methods such as forward and backward scanning, left-to-right scanning, turning scanning and circle scanning should be added.

3.7. Adjustment of scanning speed (scanning rate)

The horizontal distance adjustment method is adopted and the scanning rate is determined as 3:1, the results proved that defect echo can effectively avoid the interference from noise wave of head wave, and the waveform is clear, which is beneficial to identifying the defects.

3.8. Positioning and quantitative of defects

During the practical operation, the sensitivity can be detected according to JG/T3034.1-1996.Adjust the detector to the assessment curve to detect the sensitivity, and then increase to 10dB to measure it roughly. Fix the probe after finding defect echo, and draw a line along the direction of main sound beam of the probe. Mark the position where the line crosses through the weld, which is the position of weld defect. Adjust the detection sensitivity to the specified sensitivity and quantify the defects according to attenuator reading at this time.

4. Application example

The top floor of complex office building of a certain mechanical manufacturing enterprise in High-tech Development Zone of Jinan is a spatial grid structure covering 1000m2. It is connected by welded spherical joints and 6 kinds of member bars are used. Ten joints and 30 pipe-sphere butt welds and pipe-pipe butt welds are detected by ultrasonic wave, the flaw detector, probe and the couplant is engine oil. The surface coupling loss compensation is 4dB, and Φ3 horizontal holes are taken as standard defects, as well as a distance-amplitude curve is made.

There are 25 defects in total, and the defects are planed with a gouge immediately. It is proved that the actual defects is roughly consistent with the defects inferred by ultrasonic detection, and the coincidence rate reach above 90%.See Table 1:

Table 1. Comparison of detected and actual defects on test piece.

No.	Pipe specification	Nature of defects	Defect length	Wave height
1	Φ48×3.25mm	Slag inclusion	5	RL+2dB
2	Φ48×3.25mm	Incomplete penetration	5	RL+2dB
3	Φ48×3.25mm	Incomplete penetration	7	RL+8dB
4	Φ48×3.25mm	Incomplete penetration	9	RL+6
5	Φ60×3mm	Incomplete penetration	10	RL+6
6	Φ60×3mm	Slag inclusion	5	RL+6
7	Φ60×3mm	Crack	8	RL+6
8	Φ60×3mm	Slag inclusion	5	RL+4
9	Φ60×3mm	Incomplete penetration	8	RL+6
10	Φ75.5×3mm	Incomplete penetration	6	RL+8
11	Φ75.5×3mm	Incomplete penetration	7	RL+6
12	Φ75.5×3mm	Incomplete penetration	5	RL
13	Φ75.5×3mm	Incomplete penetration	5	RL+4
14	Φ75.5×3mm	Incomplete penetration	10	RL+6
15	Φ75.5×3mm	Incomplete penetration	8	RL+6
16	Φ88.5×3.25mm	Incomplete penetration	6	RL+6
17	Φ88.5×3.25mm	Incomplete penetration	7	RL+6
18	Φ88.5×3.25mm	Incomplete penetration	5	RL+6
19	Φ114×3.5mm	Incomplete penetration	5	RL+2
20	Φ114×3.5mm	Incomplete penetration	5	RL+2
21	Φ114×3.5mm	Incomplete penetration	5	RL+2
22	Φ114×3.5mm	Incomplete penetration	5	RL+2
23	Φ114×3.5mm	Incomplete penetration	5	RL+2
24	Φ140×3.5mm	Incomplete penetration	7	RL+2
25	Φ140×3.5mm	Incomplete penetration	7	RL+6

Table 2. Defect types.

Defect class	Incomplete penetration	Crack	Slag inclusion or air hole
Quantity	21	1	3

Table 3. Reflection wave height of each defect type

Defect class	Incomplete penetration	Crack	Slag inclusion or air hole
Reflection wave height	RL+0～+8	RL+6	RL+2～+6

The following can be deferred from Table 2 and Table 3:
(1) Incomplete penetration accounts for 84% in the 25 defects, which can be considered that the incomplete penetration is more frequent than other defects and has strong reflection under the normal welding condition. For all incomplete penetrations exceeding 5mm, the defect echoes are at or above the defect line. Too narrow clearance at groove root is the main reason for incomplete penetration.
(2) Cracks and slag infusion of air holes seldom appear under the normal welding condition, and the reflection wave heights of cracks and slag infusion of air holes in this detection are above the defect line.
(3) By a comparative analysis, the wave height of defect echo is not completely direct proportional to the indicating length of defects.
(4) The coincidence rate between detection results and actual results reaches above 90%, which indicates that instrument, probe, test block and detection methods used in this study are feasible and the detection results can meet the requirements of quality control.

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