Welding procedure research of zirconium tube-to-tubesheet

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Abstract The welding characteristics of zirconium tube-to-tubesheet, the joint structure and quality influencing factors are analyzed in the paper. The automatic pulsed GTAW procedure are formulated and examined by welding sample test. The tube-to-tubesheet procedure is qualified by joint surface inspection, joint sections observation, height measurement of the weld metal and metallographic examination. It has the great significance of the successful welding procedure qualification to guide the actual manufacture of R60702 zirconium heat exchanger.

1. Induction
A pressure vessels order for acetic acid production unit was received by a company in Shanghai, including reaction distillation tower, extractor tower reboiler and finished tower reboiler. R60702 zirconium tube and R60702+SA516 Gr.70 zirconium composite materials are widely used in design of these heat exchangers tube side. R60702 zirconium tube is ASME SB523 material (equivalent to Zr-3 according to NB/T 47011-2010 in China); R60702 zirconium plate in the composite materials is ASME SB551 material (equivalent to Zr-3 according to NB/T 47011-2010 in China). The company intends to study the welding properties, choose welding method and conduct welding procedure qualification before product manufacturing process.

Zirconium has strong corrosion resistance in most organic acids, mineral acids, strong bases and some molten salts. Compared with other structural materials, zirconium has the unique characteristics: The process medium does not stick to the surface of zirconium materials with good surface brightness and surface hardness; Efficient heat transfer and durability of zirconium heat exchanger has non-corrosion, non-adhesion and high film coefficient; The corrosion allowance and adhesion allowance are not considered in the design; It can withstand a very high fluid velocities; It does not require regular cleaning during use\textsuperscript{[1]}. Therefore, zirconium is the preferred material for heat exchanger applications today. The weld connection between tubes and tubesheet is the very important bearing joint in heat exchanger. The quality of the joint directly affects the normal use of heat exchanger, and even seriously affects the normal operation of the production system. Therefore, the weld joints of tube-to-tubesheet are the key check point of users and manufacturers.
2. Welding technology of zirconium tube-to-tubesheet

2.1. Welding properties of R60702 zirconium

There is obvious difference in weldability between R60702 zirconium and stainless steel. Compared with steel, R60702 zirconium has the characteristics of high melting point, low thermal conductivity, small density and good surface tension. High melting point and low thermal conductivity are disadvantageous to the formation of molten pools, but small density and good surface tension are beneficial to the realization of all-position welding.

As an active metal, R60702 zirconium material is easily polluted by atmosphere and pollutants. When welding, if the high temperature area of the weld joint is not well protected or cleaned, it is susceptible to pollution by air, oil, dust and water, which seriously reduce the joint corrosion resistance and even lead to cracks or become broken powder. The thickness of heat exchange tube is thin, the welding heat input is relatively small, and the welding pores may be generated by incomplete cleaning before welding or poor protection when welding\(^2\). Zirconium materials are single-phase structure before welding. When the welding stay time is too long in the high temperature zone, the bulky β-structure is formed. Then the structure is changed to be the martensitic α-phase after rapid cooling, which makes the joint toughness decreased.

2.2. Structural characteristics of tube tube-to-tubesheet weld joints

R60702 zirconium tubes and tubesheet of the heat exchanger are often connected by end face welding (strength welding) and expansion. End face welding belongs to partial penetration welding, which has a certain depth of groove. Thus, the joint welding is affected by the outer diameter of tube, the thickness of tube, the thickness of the tubesheet, the groove size, the groove depth, the groove angle and the extension length of tube head. The larger the outer diameter of tube or the thickness of tube, the more convenience to welding; Thin pipe wall, deep groove, small groove angle and long extension length of pipe head are not conducive to root penetration, and may lead to welding penetration damage of tube and reduction of effective pipe diameter. When the thicknesses of tubes and tubesheet are very different, the welding heat input must be small because tube is thin, but the welding heat input also needs to be large because the tubesheet thickness is large and the heat dissipation is quick\(^3\). So the proper welding heat input is an important procedure to ensure good fusion of the joint. The large diameter of welding wire or improper operation will result in the welding quality problems.

2.3. Technology requirements for tube-to-tubesheet weld joints

As the key point of R60702 zirconium heat exchanger, the weld joint of tube-to-tubesheet should have good mechanical properties and corrosion resistance performance. The welding quality should be guaranteed that: 1. the root of the weld joint is fully welded and fused; 2. the weld joint should has no oxidation, pollution, pores, tungsten inclusions, cracks and other defects; 3. the weld joint should have a certain bearing section.

According to the characteristic analysis of the tube-to-tubesheet joint of zirconium heat exchanger, the tube head should be not only compliance with the material standard to ensure material chemical composition and properties, but also strictly cleaned up before welding and protected the welding process. Because the end face joint of the tube-to- tubesheet should have a certain welding depth to obtain the strength and tightness of the joint, and the actual welding procedure should be all-position welding, the method of automatic pulse Gas Tungsten Arc Welding (GTAW) is adopted. The automatic pulse GTAW has the following advantages: it is advantageous to control the welding heat input; it can obtain instantaneous large current; it will help to increase the depth of fusion; the unit heat input is low; it can effectively prevent the welding penetration damage and control the weld joint formation\(^4\).
3. Welding procedure and test preparation

3.1. Welding equipment selection
The automatic pulsed DC GTAW machine is chosen as welding equipment. This welding machine has the characteristics of three-point plane support, core bar centering, water-cooled welding torch with big porcelain nozzle and protective device of drag cover. The welding machine can realize the following functions: automatic tracking by arc pressure feedback, flow control of inert gas, welding current control, rotation control of welding torch, wire feed control, yaw control of welding torch, arc length control and partition setting, etc.

3.2. Test materials
The tubesheet for welding test is made of ASTM 898-2016 explosive composite plate ASME SB551 R60702+ SA516 Gr.70 with the specification of 170mm×130mm×(2+30)mm. The tube for welding test is made of ASME SB523 R60702 with the specification of OD19.05×2mm. The chemical composition and mechanical properties of R60702 plate of the tubesheet, the tubes and welding wires are shown in Table 1.

| Test materials      | Chemical composition | Mechanical properties |
|---------------------|----------------------|-----------------------|
|                     | Zr+Hf   | Hf     | Fe+Cr | H   | N    | C     | O    | Tensile strength R_p0.2 (MPa) | Yield strength R_m (MPa) | Elongation δ (%) |
| R60702 plate        | 99.4    | 1.7    | 0.15  | 0.02 | 0.006 | 0.004 | 0.14 | 467                          | 291                         | 34                 |
| R60702 tubes        | 99.2    | 2.2    | 0.19  | 0.02 | 0.008 | 0.016 | 0.14 | 443                          | 278                         | 35                 |
| welding wires       | 99.5    | 0.7    | 0.09  | <0.0003 | 0.004 | 0.01  | 0.10 |                             |                             |                   |

The welding shielding gas is chosen argon gas with purity of at least 99.995%, low water content, dew point not higher than -50°C, which satisfies the standard of GB/T 4842-2017. The welding wires are chosen ERZr2 wires coiling with the diameter of 1.2mm produced according to ASME SFA-5.24. The main chemical composition of ErZR2 wires are the same as R60702 base materials, but the inclusion elements are lower than the base materials.

3.3. Welding structure and preparation
The form of the test sample and the structural size of the welding joint are shown in Figure 1. According to the design document, the product tube-to-tubesheet adopts flush welding structure to facilitate the flow of medium.
Before welding, the surface of the test tubesheet and the end of the tubes should be cleaned within 50mm. The oxides, oil, dust and other dirt on the welding area of zirconium tubesheet and tubes should be removed by mechanical grinding\cite{5}. The welding area should be cleaned by acetone and be dry in a clean environment.

3.4. Welding procedure

Large heat input and rapid welding is adopted in this tube-to-tubesheet welding. This procedure is selected in accordance with the characteristics of pulse welding. Specific welding parameters are shown in Table 2. The most important procedure in the welding process is protection of high temperature zone. In order to realize this procedure, a large porcelain mouth is used, and a drag cover with inert gas protection for the weld metal with the temperature higher than 250℃ is adopted. The drag cover has a lot of copper wire meshes to enhance the function of gas screen. The argon gas is supplied in advance and delayed shutdown to ensure that the high temperature zone is always under the protection of inert gas during welding. The argon gas flow of welding torch is 8~10L/min, and the drag cover is 12~15L/min.

Welding operation shall be carried out in a clean and dust-free site. Three welding layers are used: the first layer is self-melted, the other layers are welded by adding welding wires. The welding layer temperature should be controlled, which should be generally controlled below 100℃. During welding the second layer and face layer, the welding wires should be continuously fed and the welding wire should always be under the protection of argon gas.

| Weld layers | Filler metal | Current (A) | Voltage range (V) | Impulse frequency (Hz) | Impulse width ratio | Travel speed (cm/min) |
|-------------|-------------|-------------|-------------------|------------------------|---------------------|---------------------|
|             | Type & Diameter (mm) | Type & Polarity | Basic current | Peak current |                     |                     |
| 1           | No filler wire | DCEN | 30~60 | 120~150 | 8~10 | 3~5 | 1:1 | 14~16 |
| 2~3         | ERZr-2 | 0.8 | DCEN | 30~60 | 120~150 | 9~11 | 3~5 | 1:1 | 15~17 |

4. Test results

4.1. Joint surface inspection

The welding test sample of R60702 zirconium tube-to-tubesheet is welded by an experienced welder using the welding procedure in Table 2. After welding, the surface of the weld joint was inspected by eyes and a 10 times magnifying glass. The surface of the weld joint was silvery white and partially light golden yellow, as shown in Figure 2. The weld surface is taken dye penetrant inspection according to NB/T 47013-2015. The results show that the surface has no defects such as cracks and pores, which satisfies level I of NB/T 47013.5-2015.
4.2. joint sections observation and size measurement
The joint of welding test sample is cut open, in which the four cut surfaces of each tube joint should include the starting arc point and the extinguished arc point. The macroscopic observation of the joints open sections is conducted by 10 times magnifying glass. The weld joint root is fully penetrated, and there are no cracks, no fusions, no pores and other defects. The effective height of the weld joint is measured with the weld joint root as the center of the circle. The height outcomes are shown in Table 3.

Table 3. Weld foot height of examined sections in the sample joint (mm)

| Inspection surface No. | 1-1 | 1-2 | 1-3 | 1-4 | 2-1 | 2-2 | 2-3 | 2-4 |
|------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| weld root height       | 2.57| 2.48| 2.53| 2.94| 3.18| 2.84| 3.07| 3.12|
| Design requirement     | ≥1b (b=2mm) |    |    |    |    |    |    |    |
| Result                 | Acceptable |    |    |    |    |    |    |    |

4.3. Metallographic examination
The microstructures of the weld joint sections are normal by metallographic examination, as shown in Figure 3. The microstructures and the grains of the weld seam and the heat-affected zone (HAZ) are grew up obviously, and no microcracks and other defects are found in each area of the weld joint.

![Metallographic structures](image)

Figure 3. Metallographic structures of each area of the weld joint

5. Conclusions
The welding procedure qualification test shows that: the important measures to prevent contamination to weld joints of active zirconium metal are strictly controlling the impurity elements of materials, cleaning up before welding and protecting the welding process with inert gas; the technological measures of pre-melting current, self-melting root and increased pulse peak current can effectively improve the quality of all-position R60702 tube-to-tubesheet joint with high melting point and large thermal conductivity difference and realize good welding penetration at arc starting point and the root;
automatic pulsed GTAW can fully play the advantages of high instantaneous peak current, low heat input and controllability of welding pool, which can improve the weld joint formation and welding microstructure in all-position welding.

In the real welding process of pressure vessels of the acetic acid production unit, the above welding procedure is adopted to weld R60702 zirconium heat exchangers with the same specification. The welding was conducted zonally and the inter-layer temperature was controlled strictly. The surface color of the tube-to-tubesheet is normal, and the test outcome by PT is qualified. The hydraulic pressure test at 2.2MPa and air tightness test at 0.4MPa are carried out on the pipe side of the pressure vessels, and the helium leak test is carried out. All these tests are qualified, which indicates that the joint has the designed bearing capacity and good compactness.

According to the welding characteristics and structure of R60702 zirconium tube-to-tubesheet, automatic pulsed GTAW is feasible to satisfy the code and standard of the heat exchanger. The welding procedure qualification test and production manufacture show that the welding procedure by automatic pulsed GTAW has good joint quality and bearing capacity. It has the great significance of the successful welding procedure qualification to guide the actual manufacture of R60702 zirconium heat exchanger.

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