Welding procedure research of white copper heat exchanger

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Abstract: In order to satisfy the corrosion resistance requirement, the original pipe material of a heat exchanger is replaced by BFe30-1-1 white copper. Based on analysis of the welding characteristics, joint structure and factors affecting the welding quality of BFe30-1-1 tube-to-tubesheet, the welding procedure is made. The morphology inspection, test of pull-off strength, metallographic structure examination and hardness test of the tube-to-tubesheet joints which is welded according to the welding procedure, can satisfy the standard and design requirements. The success of the test provides a good reference for the welding quality control of white copper heat exchangers.

1 Introduction

A heat exchanger in an offshore platform was manufactured by a company in 2017. The medium on the tube side of the heat exchanger was seawater, so the tubes material of the heat exchanger was designed and manufactured as BFe30-1-1. The material of other parts on the tube side were low alloy steel SA516Gr70 lined with stainless steel S31603. When the internal inspection was carried out in 2020, the tubesheet and cylinder were found seriously corroded and the service life was greatly shortened by calculation. The corroded tubesheet and cylinder will be replaced as requested by the user. Through

the material analysis and redesign of the heat exchanger, all parts of the tube side contacted the medium were designed as BFe30-1-1.

The heat exchanger was a six-trip heat exchanger, which was manufactured according to TSG 21-2016 ‘Safety Technical Supervision Regulation for Stationary Pressure Vessels’, GB/T 151-2014 ‘Heat Exchangers’ and JB/T 4755-2006 ‘Copper Pressure Vessels’. The longitudinal weld joints and circumferential weld joints of the tube side were taken 100% radiographic inspection, which qualified Grade II or above in accordance with NB/T 47015-2015. The main design parameters of the heat exchanger are shown in Tab.1.

Table1. Design parameters of the heat exchanger

Channel	Design pressure (MPa)	Design temp. (°C)	Medium	Working pressure (MPa)	Working temp. (°C)
shell side	0.6	95	crude oil	0.35	80
sube side	0.5	95	seawater	0.25	45

The tube-to-tubesheet weld joints are always the weakest position of the heat exchanger. Therefore, the quality control of tube-to-tubesheet weld joints is particularly critical^[1]. There are many factors affecting the quality of tube-to-tubesheet weld joints, so it is necessary to take full consideration of structural design, welding procedure formulation and welding process control to ensure reliable welding quality.

2 Material selection

Because the tube-to-tubesheet joints of the heat exchanger are the most seriously corroded area, the tubes material are the same as the original BFe30-1-1 white copper, but the material of the tubesheet is changed to SA516Gr70 +

BFe30-1-1 composite material. The cladding is BFe30-1-1 white copper plate with a thickness of 3mm. BFe30-1-1 is a copper-nickel alloy with good mechanical properties and high corrosion resistance in seawater^[2]. The chemical composition of BFe30-1-1 white copper materials used are shown in Tab.2. The mechanical properties of BFe30-1-1 white copper materials used are shown in Tab.3.

In design, BFe30-1-1 white copper plate is only used as corrosion resistant layer and does not participate in strength calculation. Its state of supply is annealing. The BFe30-1-1 white copper tubes and tubesheet are designed to be expanded and strength welded. In order to ensure the expansion quality, semi-hard supply of the tubes is adopted.

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Table2. Chemical composition of the BFe30-1-1 white copper materials (%)

Materials	Cu	Ni+Co	Fe	Mn	Zn	Pb	Si	S	P	C	Sn	Sum of impurities
BFe30-1-1 plate	remainder	30.3	0.8	1.0	0.25	0.02	0.11	0.008	0.005	0.04	0.22	0.6
BFe30-1-1 tubes	remainder	29.6	0.6	1.1	0.26	0.01	0.10	0.007	0.004	0.04	0.21	0.5

Table3. Mechanical properties of the BFe30-1-1 white copper materials

Materials	Specification	Tensile Strength Rm (MPa)	Elongation δ (%)	Heat treatment condition
BFe30-1-1 plate	3.0mm	387	25	annealing
BFe30-1-1 tubes	OD25×2.0 mm	532	16	annealing

3 Welding process analysis and test scheme

3.1 Weldability analysis

Copper and copper alloys are widely used in industrial fields for their excellent electrical conductivity, thermal conductivity and corrosion resistance. When nickel element is added to copper, copper gradually turns white from purple and the mechanical strength of the material is improved. This copper-nickel alloy is called white copper. BFe30-1-1 is an iron-white copper material, in which a little iron is added to copper-nickel alloy. This material has good mechanical properties, excellent corrosion resistance and good antifouling performance. Moreover, it does not produce stress corrosion crack and has good cutting performance^[3]. This material is of great demand in the marine environment, which is widely used in the condensing pipes, ship hulls and fire pipes of ships and coastal power stations.

The melting point of BFe30-1-1 white copper is about 1200°C, which is lower than the melting point of steel. That is conducive to the welding of the white copper tubes and composite tubesheet. BFe30-1-1 white copper has a single α phase structure, and its thermal conductivity is close to carbon steel. BFe30-1-1 white copper belongs to Cu-4 category, which is sensitive to phosphorus and sulfur impurities and prone to form thermal cracks and porosity defects. During welding, BFe30-1-1 white copper and its impurities can generate eutectics with low melting point, such as Cu+Pb, Cu+Bi, Cu+Cu₂S, etc. These eutectics are distributed between grains or at grain boundaries during crystallization, which makes them have obvious thermal brittleness. In order to avoid hot cracks and thermal brittleness in joints, the content of impurities in BFe30-1-1 tubes, tubesheet and welding materials should be strictly restricted.

3.2 Selection of welding method

The welding method with high thermal efficiency and energy concentration should be selected for the welding of BFe30-1-1 white copper. The commonly used welding methods in BFe30-1-1 production are gas welding, electrode arc welding, gas tungsten arc welding (GTAW) and plasma welding. According to the characteristics of the heat exchanger and the existing welding equipment in the company, GTAW is adopted for the tube-to-tubesheet welding.

GTAW has the following advantages: good visibility of the arc and molten pool; easy to operate; easy to control the joint shape and molten pool; no slag; not required post-weld cleaning; beautiful weld forming; concentrated heat source; increased depth of penetration; reduced porosity; small heat-affected zone; small deformation; not affecting the expansion procedure, etc. Argon gas has a good protective effect in the welding process and can effectively isolate the surrounding air. Moreover, argon gas does not react with metal and does not dissolve in metal, which makes the metallurgical reaction in the welding process simple and easy to control. GTAW can be used for all-directional welding and is also an ideal method to realize single-sided welding but double-sided forming^[4].

3.3 Welding structure design

In the heat exchanger, the commonly welding structure of the tube-to-tubesheet are the extension connection, the contraction connection, and the flat end welding^[5]. Flat end weld joints have the advantages of good visibility, convenient welding operation, small flow resistance of medium, not easy to accumulate dirt between the tube bridges, and so on. Because there are many impurities and dirt in the seawater medium of the tube side, flat end weld joints are used in the structure design of tube-to-tubesheet. Higher tensile strength can be obtained by using this groove type, and the service life of the heat exchanger can be effectively extended.

Fig 1. Sketch map of the aligned welding sample

The back of tubesheet is difficult to protect by inert gas during welding. Therefore, the tube holes should be machined in strict accordance with the procedure documents, and the machining size error should satisfy the procedure requirements. In addition, the air between the tubes and the tube holes can be effectively removed by expansion before welding, so as to effectively reduce the oxidation degree of the root weld joint. The tooling and spot welding was performed on the tubes and tubesheet in the same position, as shown in Fig.2.

Fig 2. Structure of tooling and spot welding

3.4 Welding process parameters

The welding of BFe30-1-1 white copper tube-to-tubesheet requires high cleanliness of the workpiece. Before

welding, the inner and outer wall of the tubes, the inner wall of the tube holes and the surface of the tubesheet must be thoroughly cleaned. The oxide film of welding grooves and 25mm width on both sides should be removed. The oil, water and other pollutants should be removed with acetone. The welding work shall be carried out in a clean and pollution-free area^[6]. During welding, argon gas with purity greater than or equal to 99.99% and dew point no higher than -50℃ shall be used for protection. Argon gas should be passed through 10 seconds in advance before welding, and argon protection shall not be turned off until 15 seconds after welding. The welding procedure parameters are shown in Tab.4.

When welding, measures should be taken to strictly protect the weld joints and reduce the entry of hydrogen and oxygen in the air. The maximum solubility of the hydrogen in liquid BFe30-1-1 white copper at the melting point is several times higher than that of carbon steel, so the supersaturation degree of hydrogen in the weld joint crystallization is much larger than that of steel. It will form diffusible pores in the BFe30-1-1 weld joints. In addition, Cu₂O in the molten pool and the water vapor or CO₂ generated by its reaction with hydrogen or CO are easy to form pores. Therefore, the measure of adopting the welding wire containing deoxidizer can be adopted.

Table4. Welding parameters of BFe30-1-1 tube-to-tubesheet

Weld layers	Welding method	Polarity of power	Current (A)	Voltage (V)	Speed (mm/min)	Shielding gas		Inter-pass temp. (℃)
						Type	Flow rate (L/min)	
1	Autogenous GTAW	DCEN	125~145	13~15	60~70	≥99.99% Ar	16~20	≤100
2~4	GTAW with filler wire	DCEN	130~150	13~15	60~80	≥99.99% Ar	16~20	

4 Test of the welding procedure sample

4.1 Morphology inspection after welding

The BFe30-1-1 tube-to-tubesheet sample was welded according to the above procedure, as shown in Fig.3. The weld joint was silver white with a small part of golden.

The joint surface was well formed. The weld seam width was uniform, and the joint transition was good. There were no surface defects, such as cracks, pores, shrinkage holes, not full fusion, continuous undercut, etc.

After welding, the weld joint surface of the sample was inspected by dye penetration test according to NB/T 47015.5-2015. There were no linear defects found. After processing, eight observation surfaces were inspected by a 10 times magnifying glass. The weld seam was

completely fused without defects. According to the geometric dimension measurement, the weld metal heights were all more than 2.0mm, which satisfied the minimum design requirement of 2.0mm. See Tab.5 for details.

Fig 3. Morphology of the tube-to-tubesheet weld joints

Table5. Weld metal heights (mm)

Joint No.	1			
Cross-section No.	1	2	3	4
Weld metal heights	2.55	2.67	2.52	2.72
Joint No.	8			
Cross-section No.	1	2	3	4
Weld metal heights	2.76	2.84	2.78	2.73

Table6. Test results of pull-off strength

Joint No.	Width (mm)	Thickness (mm)	Area (mm ²)	Total load (KN)	Pull-off strength R _m (MPa)	Fracture site
3	25	2	144.44	59.39	411.17	tube
6	25	2	144.44	57.05	394.97	tube

4.3 Metallographic examination

In the process of fusion welding, the infiltration of impurity elements will make the plasticity and corrosion resistance of the weld joint deteriorate. The microstructure of the weld joint can reflect the change of mechanical properties, so it is necessary to inspect the microscopic metallographic structure. After wire cutting and fine polishing of the sample, the test specimen was immersed in the etching agent of 4% nitric acid-alcohol solution for erosion. The microstructures of the weld joint was observed under metallographic microscope after drying and polishing, as shown in Fig.4.

4.2 Test of pull-off strength

The pull-off strength is the pull-off force per unit area applied to the welded or expanded perimeter of the tube when it is released from the tubesheet. When the heat exchanger is in use, the tube-to-tubesheet weld joint is under the combined action of fluid pressure and the differential temperature stress of the shell side and tube side. The two forces produce a tensile force to break the weld joint away. Therefore, the greater the pull-off force than the tensile force, the less likely the tube is to break away from the tubesheet. Lack of pull-off force may cause damage to the sealing of the joint and may result in breaking away in serious cases^[7]. In order to ensure a firm welding connection and good tightness of the tubes and the tubesheet, it is necessary to carry out the pull-out strength test.

The pull-off strength test was carried out by WE-60 Universal Tester, and the test results are shown in Tab.6. After the tubes were pulled off from the tubesheet, the fracture was found to occur on the tubes, which indicated that the strength of the weld joints is relatively large. By calculation, the test results satisfied the minimum requirement of 370MPa in the design document.

The microstructure distribution of the weld joint was uniform, and there had no phenomenon of obvious grain growth. The structure of base metal BFe30-1-1 was a single α structure with bright color, which belonged to face-centered cubic lattice. The microstructure of heat-affected zone was the same as that of base metal, but the microstructure of heat-affected zone was bigger than that of base metal. However, the grain size in heat-affected zone did not become too bulky. The microstructure of the weld seam was smaller than that of base metal, so there was no obvious growth of weld grains^[8]. It can be inferred that H, O and other impurity elements in the air were very little to enter the weld joint. The results showed that the metallographic structures of the joint were normal.

Fig 4. Metallographic structures of the weld joint

4.4 Test of joint hardness

Tetragonal diamond indenter of a Vickers hardness tester is pressed into the sample surface under the action of test force. The test force is maintained for a specified time and then withdrew. The length of the indentation diagonal line on the surface of the sample is measured, then the indentation surface area is calculated. Finally, the vickers hardness value is calculated by that the average pressure indentation on the surface area divided by gravitational acceleration.

The hardness values of the joint measured by a HVS-50 Vickers hardness tester were shown in Tab.7. The test results showed that the hardness of the weld seam were maintained at a high level, and the highest hardness was 152.1HV₁₀, which is higher than the heat-affected zone and base metal. The test results basically showed that the strength of the weld seam was larger than the heat-affected zone and the base metal. The test results are satisfied the requirements of JB/T 4755-2006.

Table7. Hardness test results of the sample joint

Test site	Base metal of tube	Heat-affected zone on tube side	Weld seam	Heat-affected zone on tubesheet side	Base metal of tubesheet
Hardness HV ₁₀	97.8, 103, 104.4	124.3, 128.1, 141.7	152.1, 149, 137.3	137.3, 102.2, 98.6	77.1, 73.5, 73

5 Product welding and conclusion

After the BFe30-1-1 tube-to-tubesheet sample was welded and the tests above were qualified, the procedure qualification record was formed and the welding procedure specification was formulated. The BFe30-1-1 tube-to-tubesheet weld joints of this heat exchanger were operated by a certified welder. The welding quality satisfied the code and vessel standards by nondestructive test and hydrostatic test. Through the helium leak test, the results of BFe30-1-1 tube-to-tubesheet weld joint satisfied the design requirements.

The test and manufacture results show that proper welding method, correct welding structure, reasonable welding procedures (including effective measures of argon gas protection) are the essential factors to ensure the quality of the BFe30-1-1 tube-to-tubesheet weld joints. This welding procedure can be adopted in actual production with Cu-4 type and has great significance to the manufacture of white copper heat exchangers.

BFe10-1-1 white copper joint by FSW. Hot working technology, 50 (7): 31-35.

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