Welding procedure qualification of small diameter thin-walled titanium pipes

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Abstract The small diameter thin-walled TA2 titanium tubes are used in a technical renovation project. In order to ensure the performance of the product, the automatic GTAW welding process is adopted by analyzing the weldability of TA2 titanium tubes. The process qualification tests such as appearance inspection, nondestructive testing, mechanical properties and metallographic examination are carried out. The test results show that the welding joint with good performance can be obtained by reasonable welding procedure parameters and strict gas protection measures. The welding procedure and related measures can be used as a reference for manufacture and installation of titanium pipes.

1. Introduction
In order to improve the anti-corrosion ability, the TA2 pure titanium pipes with strong strength and excellent corrosion resistant were used in a technical renovation project in a company in Shanghai. The specification of the TA2 pipes was OD 25×1.5mm. The total length of the TA2 pipes was about 100m. According to the pressure equipment code and standards, the weldability and welding procedure qualification of the TA2 pipes’ girth weld joint of this specification should be tested.

There are three kinds of pure titanium materials commonly used in domestic pressure vessels: TA1, TA2 and TA3\textsuperscript{[1]}. The difference lies in the content of oxygen, nitrogen, hydrogen and other impurities. The number at the end of the titanium materials code increases in turn according to the increase of impurities and the strength increases in turn. Titanium and titanium alloys are excellent structure materials. They have a series of advantages, such as low density, high specific strength, ideal physical and mechanical properties, good corrosion resistance, good ductility and toughness, and sufficient high temperature strength, etc. They are widely used in aerospace, petrochemical industry, military industry, shipbuilding, metallurgy, Marine engineering and other fields. The TA2 material is a kind of very promising metal material for chemical industry since its excellent corrosion resistance. The corrosion resistance of TA2 material is much better than that of stainless steel in oxidizing or chloride ion medium. Although the investment of the TA2 equipment is large, the reliability and service life of the equipment are greatly improved and the economic benefits are great\textsuperscript{[2]}.

2. Weldability of titanium materials
The chemical properties of TA2 material are stable at room temperature, but under the action of welding thermal cycle, the chemical properties will become very active. The TA2 material reacts with oxygen, nitrogen and hydrogen faster at high temperature. It begins to absorb hydrogen at 250°C,
absorb oxygen at 400°C, and absorb nitrogen at 600°C[3]. With the increase of temperature, the reaction speed is accelerated.

At present, the connection methods of titanium pipes mainly include friction stir welding (FSW), brazing, and gas tungsten arc welding (GTAW). In the brazing method of titanium materials, the most commonly used brazing solder metals are mainly copper base, silver base and aluminum base, but the welding effect is not ideal. The tensile strength of the brazed titanium joint is only 50% ~ 70% of the base metal at room temperature, and its shear strength is also low. When the FSW method is used, it is easy to form weld holes and the plasticity needs to be improved again. When the GTAW method is used, the weld joint with good qualities can be obtained. The GTAW method has advantages of simple operation, economical price, usage in large scale, and so on[4]. Therefore, the GTAW method is adopted and the procedures of small diameter thin-walled TA2 pipes are tested following.

3. Procedure test

3.1. Test materials

The welding test materials are 4 pairs of TA2 titanium tubes (cut from the same titanium tube), which is according to GB/T 3624-2010. The tubes specification is OD25×1.5mm. The total length of each pair is 450mm. The chemical composition and mechanical properties of the testing titanium tubes are shown in Tab.1 and Tab.2. The method of autogenous machine welding without wire is adopted in the test according to the existing manufacture conditions. This welding method can make the chemical composition of the weld metal relatively pure and obtain excellent material properties.

| Elements | Ti | Fe | C | N | O | H | Each other element | Sum of other elements |
|----------|----|----|---|---|---|---|-------------------|----------------------|
| Specified value remainder | ≤ 0.3 | ≤ 0.1 | ≤ 0.05 | ≤ 0.25 | ≤ 0.015 | ≤ 0.1 | ≤ 0.4 |
| Measured value remainder | 0.052 | 0.02 | 0.0092 | 0.001 | 0.074 | 0.049 | 0.245 |

| Mechanical properties | Yield Strength-0.2 % Offset Rp0.2 (MPa) | Tensile Strength Rm (MPa) | Elongation in 50 mm δ (%) |
|-----------------------|------------------------------------------|---------------------------|--------------------------|
| Specified value | 275–450 | ≥ 400 | ≥ 20 |
| Measured value | 303 | 428 | 42.5 |

3.2. Preparation before welding

In order to ensure the welding quality and efficiency, it is necessary to fully prepare in the environment, groove and other aspects before welding. The welding environment should be prepared as a clean and dry room and there is normal temperature and no wild wind. The abrasive discs, polishing wheels and cutting disks used in the test should be new stainless steel materials; Mechanical cutting shall be used for groove preparation. In order to prevent local temperature too high and incision oxidation, the cutting machine used must be with coolant. The reamer should be used to remove the passivating film on the inner surface of the pipe end groove, while the stainless steel grinding wheels are used to remove the passivating film on the outer surface. The groove faces should be cleaned by acetone or anhydrous ethanol. The welding groove is I type, as shown in Fig.1.

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Tab.2 Mechanical properties of the titanium tubes

![Fig.1 Groove form of titanium tubes for welding test](image-url)
3.3. Determine welding procedure parameters

The selection of welding procedure parameters is very important to the quality of the TA2 weld joints. For example, if the welding line energy is large, the high temperature residence time of the overheated zone will be long and the cooling rate will be slow. As a result, the overheated zone will have significant coarse grains and the plasticity of the overheated zone will decrease. If rapid cooling procedure is carried out after welding, more supersaturated solid solution will be formed, which will weaken the plasticity and toughness of the weld joints. Therefore, it is particularly important to set and test the welding procedure parameters. Welding procedure parameters mainly include filling materials, welding voltage, welding current, welding speed, etc. The proposed procedure parameters are shown in Tab.3.

| Tab.3 Machine GTAW welding procedure parameters of TA2 tubes |
|-------------------------------------------------------------|
| Weld layers | Process | Filler metal | Current type | Strike current (A) | Highest Current (A) | Base current (A) | Volt range (V) | Travel speed (mm/min) |
|-------------|---------|--------------|--------------|-------------------|-------------------|----------------|--------------|----------------------|
| 1           | GTAW    | NA (autogenous) | DCEN         | 50~55             | 74~80             | 24~27          | 11~14        | 24~26                |

When autogenous machine GTAW is used for TA2 tubes, attention should be paid to the following aspects: (1) In order to ensure the welding quality, the axis of the welded pipe should be in one line. (2) The butt pipes are wrapped in tinfoils after they were cleaned, and the tinfoils are torn off before welding to ensure the purity of titanium. (3) During the welding process, the little line energy, the low-frequency pulse current, the appropriate current value, and faster welding speed are adopted. It can not only ensure the weld joints not overheated and have no coarse grains, but also prevent hardening of the weld joints. (4) When welding, the welding torch cannot be swung along a horizontal line and the color of welding layers should be observed carefully.

3.4. Gas protection

Because TA2 material is easy to react with O, H and N in the welding process, it is essential to take strict protective measures for the weld metal. Argon gas with purity of 99.999% is selected because of the high requirements for the weldability of titanium materials. Argon gas gushed out from the welding torch, the TA2 tubes and the protective cover is used to protect the molten pool, heat-affected zone and each 10mm area outside the fusion line. The parameters of argon gas flow are shown in Tab.4. After spot welding of titanium pipe, the welding places are sealed with white tape and special gas protective device should be developed. The protective cover is shown in Fig.2. When welding, the arc should be started at high frequency and argon gas should be supplied in advance. At the end of welding, the protective cover should be withdrawn after 15 seconds or more to avoid gas contamination to the weld joint.

| Tab.4 Protective gas parameters |
|--------------------------------|
| Pre-purge argon | Post-purge argon | Shielding gas (L/min) |
|                  |                  | Welding torch | Pipe inside | Protection cover |
| 10S              | 15S              | 10~20         | 15~25       | 10~20             |

Fig.2 Protective cover for TA2 tubes  
Fig.3 Autogenous machine GTAW welding process of TA2 tubes
4. Test results and analysis
The welding procedure parameters in Tab.3 and Tab.4 were used to weld four pairs of TA2 tubes. After welding, the appearance inspection, nondestructive test, mechanical properties test and other tests were carried out. The welding process was shown in Fig.3.

4.1. Visual inspection of the weld joints
Tab.5 Comparison table of color determination of welding quality

| Surface color of the weld joint | Welding protection and cleanliness | Welding quality judgment                      |
|---------------------------------|-----------------------------------|-----------------------------------------------|
| silver white                    | very good                         | non-contamination                              |
| golden yellow                   | good                              | basically non-contamination                    |
| blue                            | normal                            | slight contamination but no effect on overall performance |
| bluish purple                   | poor                              | serious oxidation and poor plasticity         |
| dark gray                       | terrible                          | welding brittle cracks, porosity, slags and other defects |

The main purpose of appearance inspection is to check the argon protection effect, the extent of misalignment and deformation. After welding, the weld quality of the TA2 tubes can be judged by the surface color of the weld joint, which is directly related to argon protection and the cleanliness of the grooves[5]. The weld quality according to the surface color is shown in Tab.5. If the joint surface appears blue or bluish purple in the welding process, the welding work should be stopped immediately and the cause should be found. The welding measures should be improved in time. If there is dark gray on the joint surface, the welding work shall be stopped immediately for repair, and the dark gray part shall be completely removed and rewelded. After applying the procedure parameters in Tab.3 and Tab.4, the weld joint color of a randomly selected TA2 tube was shown in Fig.4. The welding surface of the TA2 tube was silver white, and the welding seam was well formed. The overall deformation of the tube was small. After actual measurement, the weld width of the tube outer surface was about 3mm with almost no residual height. The residual height of the tube inner surface was about 0.5mm.

4.2. Nondestructive test
The weld joints of these TA2 pipes were tested by X-ray method according to NB/T 47013.2-2015. The results showed that there were no cracks, no pores, no slag inclusions and full penetration in the welding seam, which belonged to rank I. The weld joints of these TA2 pipes were tested by dye penetrant method according to NB/T 47013.5-2015. There were no surface opening defects found. The nondestructive testing results satisfied the standard requirements.

4.3. Mechanical properties test
Two welded TA2 tubes were taken for mechanical properties test. The tensile test was conducted according to NB/T 47014-2011. One tensile specimen of the full-size welded tubes was shown in Fig.5(a). The tensile strength of the two samples were 423.7MPa and 419.5MPa, which were fractured in the weld seam zone. The tensile strengths were both larger than the standard specified value of 400MPa, but slightly less than the base metal tensile strength of 428MPa.

One of the welded TA2 tubes was taken for mechanical processing and bending test. The bending
center diameter was 15mm, while the bending Angle was 180°. There were 4 bending specimens after machining, as shown in Fig.5(b). After bending test according to NB/T 47014-2011, the magnifying glass was used to inspect the weld seam and heat-affected zone on the joint surface. No single opening defects with a length greater than 3mm in any direction were found, and no defects such as non-fusion and slag inclusions were found.

Fig.5 Tensile specimen and bend specimens

The hardness test result of a welded TA2 pipe was shown in Tab.6. The weld seam was the lowest hardness region of the whole weld joint. Due to the influence of heat input, the coarse grain structure appeared in the weld seam, which resulted in a decline in strength and hardness. The heat-affected zone was the area close to the base metal, which was rarely affected by welding thermal cycle. The grain size did not grow up significantly because of the fast cooling rate and the protection measures. The composition and structure of the heat-affected zone were similar to that of the base metal, and the hardness is slightly reduced. Compared with the weld seam and heat-affected zone, base metal was not affected by welding thermal cycle, whose hardness was the highest value.

The test results of mechanical properties were all qualified.

| Test site       | Weld seam                  | Heat-affected zone | Base metal     |
|-----------------|----------------------------|--------------------|----------------|
| Hardness        | 169, 170, 172              | 173, 175, 170      | 180, 178, 181  |

4.4. Metallographic microstructure analysis

The weld joint of a TA2 pipe was etched by Kroll reagent to get the metallographic structure of the weld joint, as shown in Fig.6. The microstructure of the heat-affected zone had a large number of equiaxed grains, and there were a few slender strips of microstructure crystals, which was the equiaxed α structure of the matrix. The microstructure of heat-affected zone was not obviously changed and was similar to the base metal. The microstructure of the weld seam zone also had equiaxed grains. A large number of elongated grains can be observed, and the grains were obviously grown up. In the welding process, the weld seam zone was the most significantly affected by the welding thermal cycle. With continuous influence of the welding heat input, the grains became coarse and part of the equiaxed grains were transformed into elongated martensite microstructure.

Fig.6 Metallographic structure of the weld joint

4.5. Fracture analysis

After the tensile test, the fracture was analyzed by Scanning Electron Microscope and Energy Disperse
Spectroscopy. The microstructure characteristics of the fracture after tensile test were observed and analyzed, as shown in Fig.7. There were many uneven pits on the tensile fracture of the TA2 tube, which was obvious characteristic of dimple fracture. The dimple fracture was the most typical plastic fracture morphology of metal material. Under the action of external tensile load, the microholes were formed with the plastic deformation and gradually grew up until the joint was fracture. At the same time, the fracture was analyzed by Energy Disperse Spectroscopy. The main elements in the fracture were Ti, C, Fe, N, O, which were consistent with the base metal composition. There was almost no impurity element infiltration in the welding process.

![Fig.7 Fracture micromorphology of the weld joint after tensile test](image)

5. Conclusions
Through the automatic GTAW procedure qualification test of TA2 tubes, the welding seam with good surface quality was inspected. The weld joint was inspected by nondestructive test, mechanical properties test, metallographic microstructure analysis and fracture analysis. The results show that the welding joint with good performance can be obtained by reasonable welding parameters and strict argon protection measures. This welding procedure can be used as a reference for welding procedure of titanium and titanium alloys.

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