Study on Microstructure and Mechanical Properties of TP321 Thick-Walled Stainless Steel Tube by CMT Welding

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Abstract. The CMT welding process of TP321 thick-walled stainless steel pipe was analyzed. The tensile properties, microstructures and phase composition of the welded joint were tested, and the effect of welding current on the microstructures and properties was studied. The results show that for the CMT welding of TP321 thick-walled stainless steel pipe, when the optimum welding current is 110A, the maximum tensile strength of welded joints reaches 643 MPa, 92.7% of base metal, and the elongation reaches 58.7%. The fracture location of welded joints is heat-affected zone, basically ductile fracture. With the increase of welding heat input, the precipitation of ferrite and carbide gradually increases in the weld structure of TP321 stainless steel. When the current is too high, the brittle σ phase of ferrite transformation will decrease, resulting in the decrease of strength and plasticity of welded joints.

Keywords. CMT welding, welding current, mechanical property, microstructure.

1. Introduction
TP321 austenitic stainless steel pipe is widely used in petrochemical plant and coal chemical plant. Typically, TP321 austenitic stainless steel pipes treated by solution and stabilization are used in high temperature, high pressure and hydrogen treatment systems [1]. Due to the serious corrosion of high concentration hydrogen and hydrogen sulfide on transmission pipeline in hydrogen facing system, it is easy to produce intercrystalline corrosion. At the same time, defects such as hot crack, stress corrosion crack and embrittlement of weld joint occur easily in the welding process of TP321 process pipeline, which leads to the occurrence of cracking accidents of weld of production process pipeline and causes serious economic losses [2].

TP321 steel has good weldability, and it has the characteristics of high linear expansion coefficient and low thermal conductivity. During the welding process, the tensile stress of weld seam and heat affected zone is serious, especially when the heat input is large, the tendency of thermal crack is obvious [3-4]. Therefore, it is an effective measure to improve corrosion resistance and thermal crack resistance of thick-walled stainless steel pipes by using small line energy during welding. Generally, argon arc welding (GATW) bottom welding, manual arc welding (SMAW) filling and cover welding are used for thick-walled stainless steel pipe welding. GATW welding line energy is low, low efficiency, large heat input in SMAW welding, high interlayer temperature in multi-layer and multi-pass welding, easy to produce overheating or burnout, and alloy element burnout, greater stress and deformation. As a new welding technology, CMT welding (cold metal transition welding) achieves precise control of welding heat input by correcting current and voltage waveform and drawing back of welding wire. In short-circuit transition, the heat input from arc to workpiece is reduced by a very short pulse peak range and a longer pulse base range. Compared with the traditional welding method, it has the characteristics of low heat input, low stress, small welding deformation, no
spatter, good forming, etc. [5-8]. CMT welding has the advantages of good stability, high efficiency, small residual stress and deformation, and high quality of welded joint [9-10]. In this paper, CMT welding was used to test the welding process of TP321 thick-walled stainless steel pipe.

2. Test Materials and Methods

TP321 steel pipe specified in ASTM standard was used in the test. The specifications were DN600 x SCH160PE (Φ508 × 50 mm), welding wire ER347 (H08Cr20Ni10Nb) and diameter was 1.0 mm. The shielding gas is 98% Ar+2% CO₂. A small amount of oxidizing gas is added into pure argon to overcome arc instability caused by cathode spot drift and undercut defect caused by poor wettability of liquid metal [11]. The chemical composition of base metal and welding material is shown in table 1.

Table 1. Chemical compositions of base material and welding material.

| Element (%) | C  | Mn  | P   | S   | Si  | Cr  | Ni  | Ti  | Nb  |
|-------------|----|-----|-----|-----|-----|-----|-----|-----|-----|
| TP321       | 0.07 | 1.77 | 0.029 | 0.002 | 0.38 | 17.1 | 9.1 | 0.54 | 0.023 |
| ER347       | 0.04-0.08 | 1.0-2.5 | 0.03 | 0.02 | 0.60 | 19.0-21.5 | 9.0-11.0 | - | 0.03-1.00 |

The welding equipment adopts TPS 4000 CMT ANDVANCED welding machine made in Fornis, Austria, and matches with 1410 welding robot of ABB Company of Switzerland and matching positioner. The welding method is that the welding parts are placed on the positioner and rotated. The welding torch keeps the same height downward and the welding speed is synchronized with the rotating speed of the positioner. The purity of argon is 99.99%. In order to avoid the large residual stress caused by thermal cutting, the groove before welding is machined and the V and Y groove are combined. Take the tensile specimen perpendicular to the direction of the weld at the pipe wall thickness of 25 mm, test the tensile performance under the wdw-300 microcomputer controlled electronic universal testing machine, take the 10 × 10 × 10 mm metallographic specimen, after mechanical polishing, the specimen is corroded by the solution of high iron chloride (5g) + hydrochloric acid (50 ml) + water (100 ml) for 15s-60s, and observe under the metallographic microscope of TMR1700.

3. Test Results and Analysis

3.1. Effect of Welding Current on Microstructure of TP321 Stainless Steel Pipe

The structure of TP321 steel is composed of austenite (A)+ferrite (F)+a small amount of carbide at room temperature equilibrium. For austenitic stainless steel, the solidification type and final phase depend on the chromium-nickel equivalent [Cr/Ni]eq, which is F-A when 1.48<[Cr/Ni]eq≤1.95, A-F when [Cr/Ni]eq<1.48,[Cr/Ni]eq F when more than 1.95. In this test, the chromium-nickel equivalent [Cr/Ni]eq of TP321 stainless steel CMT weld is 1.65, and the crystallization type is F-A, so the ferrite precipitates first in the solidification process of the weld. As the temperature decreases gradually, the austenite nucleates in the liquid phase rich in austenitizing elements between ferrite dendrites or intercrystals, and grows from the austenite core formed to the incompletely solidified ferrite and liquid metal. The transformation from ferrite to austenite is completed under the condition of fast cooling rate [13-14]. With the increase of welding current and heat input, the weld pool temperature is higher and the cooling rate is slower. The ferrite can not be completely transformed into austenite, resulting in the increase of residual ferrite and carbide in the weld structure.

Figure 1 shows the microstructures of TP321 stainless steel welded joints under different welding currents. From figure 1, it can be clearly seen that the fusion lines of welded joints under different welding currents are well fused at the fusion lines under various parameters, there are no obvious microcracks, and the elements are fully diffused. Comparing with the structure of each weld zone, it can be found that when the welding current is 94A and 110A, the weld structure is mainly austenite + ferrite, columnar crystal at the fusion line, far from the fusion line to equiaxed crystal, and the amount
of ferrite precipitation in figure 1b is more than that in figure 1a, but the microstructures in the two weld zones are basically fine equiaxed grains with clear grain boundaries. Figure 1c welding current is 134 A. There are more ferrites and carbides in the weld zone and fusion zone, covering the whole austenite matrix surface. The ferrite is skeleton-like and completely covering the grain boundary. There are intermittent strip ferrites and a small amount of massive carbides in the heat-affected zone, and some grain boundaries are visible. Because the weld zone is close to the welding heat source and absorbs more arc heat, and the thickness of stainless steel pipe is thicker, the heat dissipation in the weld zone is slower and the undercooling degree is smaller, forming a large number of coarse columnar crystals, while the heat absorption in fusion zone and heat affected zone is less than that in weld zone, so there are a small number of equiaxed crystals, but the grain growth tendency is obvious. The welding current of figure 1d is 156A, and the heat input is large. There are a lot of ferrite and carbide on the surface of weld zone and fusion zone. There are a lot of parallel strip ferrite in heat affected zone. The microstructures are all coarse columnar crystals, and the superheated structure appears in the weld.

Figure 1. Microstructure of TP321 stainless steels with different welding current: (a) 94 A, (b) 110 A, (c) 134 A, (d) 156 A.

3.2. Effect of Welding Current on Mechanical Properties of TP321 Stainless Steel Pipe

From figure 2, it can be found that the strength and plasticity of welded joints increase first and then decrease with the increase of welding current. When welding current is 110 A, the mechanical properties of welded joints reach the nearest match. At this time, the average tensile strength is 643 MPa, 92.7% of the base metal, and the elongation is 58.7%. When welding current is greater than 110, strength and plasticity begin to decrease. When welding current is 156 A, the strength of welded joint decreases sharply, and no obvious yield phenomenon occurs, which leads to direct fracture. The main reason is that the high heat input leads to the precipitation of brittle carbides in the weld structure. At the same time, the superheated structure appears in the heat affected zone, and the grain size becomes coarser, which leads to the decrease of tensile strength. The calculation shows that the tensile strength of the base metal in HAZ is 55% lower than that before welding.

Figure 3 shows the fracture morphology of TP321 stainless steel specimens under different welding currents. Figures 3a and 3b fracture morphology can be seen as ductile fracture. There are many small and deep dimples on the surface. With the increase of welding current, the number of dimples in the fracture morphology decreases, cleavage units appear and increase gradually. When welding current is 156 A, the number of dimples in the weld fracture morphology is very small, there are a large number of cleavage units, the surface of the fracture is even, and there is a transition to quasi-cleavage fracture.
Figure 4 shows the results of electron scanning and energy spectrum analysis of precipitated phases under different welding currents. From figure 4, it can be seen that the precipitates precipitated on the surface of the matrix by means of electronic scanning (4a) of 110 A welding current. The results of energy spectrum analysis (4b) show that the content of chromium and iron in the precipitated phase of the matrix structure is less, and the content of titanium is higher. It can be seen that the precipitation of carbide \((\text{Cr, Fe})_{23}\text{C}_6\) on the surface of the matrix is less, and the precipitated phase is mainly titanium carbide \((\text{TiC})\) predominantly. Because niobium is contained in welding wire and base metal, but no niobium is found in the precipitated phase, it can be seen that niobium is distributed in the matrix in the form of dispersion. The precipitation of dispersed Nb-C compounds can prevent the precipitation of chromium-C sensitizers and play a stabilizing role [15]. Moreover, Nb-C compounds precipitate in the dispersed state, which plays a “pinning” role in dislocation movement and improves the fracture resistance of welds. Spherical and irregular precipitates can be observed in the microstructure of 134 A weld under welding current. Component analysis shows that the contents of carbon, chromium and iron are relatively high. There are chromium carbide and brittle σ phase transformed from ferrite in the weld structure. TP321 stainless steel pipe wall thickness is thicker, its heat dissipation is slower due to structural reasons in the neutral layer of the pipe wall, the residence time of sensitization temperature range (450-850 °C) is longer, chromium carbide and brittle σ phase are precipitated, which reduces the mechanical properties of welded joints.
Figure 4. SEM and EDS spectrum of precipitate with different welding current: (a) 110 A SEM of precipitated phase, (b) 110 A EDS of precipitated phase, (c) 134 A SEM of precipitated phase, (d) 134 A EDS of precipitated phase.

4. Conclusion
(1) For CMT welding of TP321 thick-walled stainless steel pipe, the optimum welding current is 110A. The maximum tensile strength of welded joints reaches 643 MPa, 92.7% of base metal, and the elongation reaches 58.7%. The fracture locations of welded joints are all heat-affected zones, basically ductile fracture.

(2) With the increase of welding heat input, the precipitation of ferrite and carbide in TP321 stainless steel weld increases gradually. When the current is too high, the brittle σ phase of ferrite transformation will decrease, which will lead to the decrease of strength and plasticity of welded joint.

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