Research on the welding performance of X70 longitudinal submerged arc welding ultra-abyssal pipeline steel

Jixiang Gao¹, Daobiao Liao¹, Liejun Li²*, Feng Zhou³*,¹
¹Guangdong Polytechnic Normal University, Guangzhou 510635, China
²National Engineering Research Center of Near-Net-Shape Forming Technology for Metallic Materials, South China University of Technology, Guangzhou 510640, P. R. China
³Foshan Polytechnic, Foshan 528137, Guangdong, China
¹gjx205@163.com, b1158070630@qq.com, cniliejun@scut.edu.cn, df3419822@qq.com

Abstract: In this paper, Gleeble 3800 was used to simulate the changes in microstructure and properties of X70 ultra-abyssal pipeline steel at room temperature under different welding line energies. The industrial welding test of X70 pipeline steel was also conducted by adopting the 4-wire Longitudinal Submerged Arc Welded process. By optimizing welding process parameters, a reasonable welding specification process was developed. The results show that at different welding line energies, when the cooling time \( t_{8/5} \) is 12 ~50s, the microstructure of the welding coarse crystal zone is mainly lamellar bainite and granular bainite, and the uniform distribution of granular bainite exists in the austenite, obtaining better impact toughness. Ultra-abyssal longitudinal submerged arc welding steel producing by the optimized 4-wire energy welding process has excellent mechanical properties and crack propagation resistance.

1. Introduction

With the growth of world energy demand, the exploitation of oil and gas is developing from the continent to the ocean. Now ultra-abyssal pipeline has been widely used in the transportation of oil and gas under the sea. However, the severe offshore construction and underwater environment put forward more and more stringent requirements for ultra-abyssal pipelines¹⁻³. The engineering safety requirements of ultra-abyssal pipelines are more stringent than those of land pipelines, requiring higher strength and thickness to improve the crushing performance, impact toughness at low temperature and DWTT index to improve the crack prevention performance of steel tubes⁴⁻⁶. The manufacture and laying of the steel pipelines mainly depend on the welding process, and welding quality is the crucial factor to determine the performance of conveying pipelines⁷,⁸.

In this paper, the Gleeble 3800 was used to simulate the changes of microstructure and properties of a pipeline steel under different welding line energies. Using and 4-wire longitudinal Submerged Arc Welding process to conduct industrial welding test on X70 pipeline steel, a reasonable welding specification was established by optimizing the welding process parameters.

2. Materials and test methods

2.1 Testing materials
Testing material was the ultra-abyssal pipeline steel produced by a steel plant, grade for X70, with a low C-Mn-Nb-Ti micro-alloyed designed and produced by TMCP technology, its chemical composition is shown in table 1[9,10].

| C   | Si | Mn  | P    | S    | Mo | Al | N    | Cr+Ni+Cr | Ti+V+Nb |
|-----|----|-----|------|------|----|----|------|----------|---------|
| 0.05| 0.21| 1.52| 0.007| 0.008| 0.122| 0.01-0.05 | 0.006 | ≤0.75 | ≤0.08 |

2.2 Simulate methods and Industrial test

A thermal simulation test was carried out using Gleeble-3800 thermomechanical processing machine to simulate different welding heat input. The standard sample is 10 mm×10 mm×55 mm in size. Figure 1 shows the welding thermal cycle of the sample heated up to 1350 ℃ by the rate of 150 ℃/s, then, cooled down at 8 different cooling rate of t8/5 = 6 s to 120 s.

Industrial test was on a longitudinal submerged arc welding machine, utilizing X-Groove forms, double-sided four-wire welding process, welding welding parameters as shown in table 2.

| Table2 Welding technology of ultra-abyssal pipeline steel |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| number          | voltage/V       | current/A       | v (m/min)       | q (KJ/cm)       | Weld silk       | Weld dose       |
| Inner weld      |                 |                 |                 |                 |                 |                 |
| 1               | 900-1000        | 35-37           |                 |                 |                 |                 |
| 2               | 750-820         | 40-45           |                 |                 |                 |                 |
| 3               | 600-660         | 41-46           |                 |                 |                 |                 |
| 4               | 500-550         | 42-47           |                 |                 |                 |                 |
| Outer weld      |                 |                 |                 |                 |                 |                 |
| 1               | 1000-1100       | 36-39           |                 |                 |                 | SJ102G          |
| 2               | 900-990         | 40-44           |                 |                 |                 |                 |
| 3               | 750-850         | 41-45           |                 |                 |                 |                 |
| 4               | 500-600         | 42-46           |                 |                 |                 |                 |

Sampling in pipeline steels and the welded tube, in accordance with ASTM A370-2011 standard used SHT4206 microcomputer control battery solution servo universal testing machines for tensile tests. The size of Sharp metal impact specimen was 10mm×10mm×55mm, grooves deep was 2mm, used PTM2200-B1 type of pendulum impact testing machine for impact testing. Hardness testing used
HV-10A a low load Vickers hardness tester in accordance with ASTM E384-2011 standard. With wire cutting method of sampling on welded joints in longitudinal seam submerged arc welding pipes, specimens were worn, mechanical polishing, 4% nitric acid alcohol solution of erosion in the LEICA DM 2500M metallographic microscope, metallographic picture were taken.

3. Results of experiment

3.1 Structure and mechanical properties of pipeline steel
Typical microstructure of the test plate is shown in Figure 1, which is mainly composed of acicular ferrite and a small amount of granular bainite. Grain size is comparatively small, the average grain size is 4.0~5.0 μm.

![Fig.2 microstructure of ultra-abysal pipeline steel (a, thickness of 1/4; b, Center)](image)

The mechanical properties of the manufactured steel plate meet the requirements of the DNV-OS-F101 steel plate mechanical performance standard.[11] The strength of the test material is relatively high, with a yield strength of 530 MPa and a tensile strength of 640 MPa. It also has excellent Charpy V-notch impact toughness, reaching 355 J at -30 °C.

3.2 Structure and mechanical properties of pipeline steel by using thermal simulation
Figure 3 shows SEM microstructure of the as-received sample and CGHAZ under different thermal cycles. Microstructure of the as-received sample is mainly composed of polygonal ferrite (PF) and acicular ferrite (AF). As shown in Figure 3(a) and 3(b), when t8/5=6s and 12s, CGHAZ is mainly composed of bainite ferrite (BF) and a small amount of M-A islands. Granular bainite is the main component of BF, in which a small amount of ferrite co-existing with lath bainite. The M-A island is bulk and disperses in the matrix. The granular bainite gradually enlarge, and quasi-polygonal ferrite appears with increasing t8/5. When t8/5= 40 s, as shown in Figure 3(c), granular bainite is the main component and a small amount of polygonal ferrite is visible. Compared with the sample obtained at t8/5=6 s, the number of M-A islands is significantly reduced. When t8/5=80 s, the M-A island gradually disappears and consists of larger polygonal ferrite and bainite.

![Fig. 3 SEM micrographs of X-70 pipeline steel](image)
The simulated sample in the welding coarse grain area was subjected to impact test at -30℃. The relationship between impact toughness value and cooling time $t_{0.5}$ is shown in figure 4. In the figure, the heat-affected coarse grain area (CGHAZ) of the pipeline steel has excellent impact toughness, and the impact toughness values under different heat input in the test are all greater than 200J. Due to the growth of the original austenite grain caused by the welding heat input, the impact toughness decreased compared with the base metal, and the impact toughness value gradually decreased with the cooling rate slowing down.

![Fig. 4 Relationship between cooling time $t_{0.5}$ and impact toughness (a)/ hardness(b)](image)

3.3 Experimental study on welding technology of steel tube

3.3.1 analysis of microstructure of weld

The macrophotograph of the joint structure of the ultra-deep sea steel pipe is shown in Figure 2a. The weld structure is composed of quasi-polygonal ferrite and acicular ferrite, with fine grains and clear grain boundaries; on the side of the weld metal, as the distance to the fusion line increases, the organization does not change significantly, while on the side of the base metal, as the distance to the fusion line increases, the organization changes significantly. The organization becomes thicker in the region of about 300 $\mu$m and gradually transitions to a fine organization.

![Fig.5 Micro structure of pipeline steel welded joint](image)

Figure 2b-d shows the metallographic structure photos of the welded joints of deep-sea welded pipes. The coarse-grained region(Figure5b shown) is mainly composed of granular bainite. The size of the MA island is larger, and austenite grains with a size greater than 100 $\mu$m are clearly seen; the austenite grains and MA in the coarse-grained region(Figure5c shown) far from the weld The size of the island is significantly reduced. The structure in Figure 5d is dominated by polygonal ferrite ferrite, and there are a small amount of pearlite and cementite, which is a fine-grained region. The matrix structure of the pipeline steel in Figure 5d is dominated by acicular ferrite, with irregular shapes, no complete and continuous clear grain boundaries, and a small amount of granular bainite and M-A island structure.
3.3.2 Performance analysis of steel tube welding

Take transverse and longitudinal tensile specimens from the end of the trial-produced steel pipe for tensile test. The test results show that:

a) The transverse yield strength of the steel pipe is between 530~570 Mpa, with an average of 544 Mpa; the transverse tensile strength is between 595~655 Mpa, with an average of 635 Mpa; the transverse yield ratio is between 0.82~0.87, with an average of 0.84;

b) The longitudinal yield strength is between 490~530 Mpa, with an average of 549 Mpa; the longitudinal tensile strength is between 590~655 Mpa, with an average of 625 Mpa; the longitudinal yield ratio is between 0.86~0.89, with an average of 0.88;

c) The tensile properties of the extracted steel pipes all meet the technical requirements. The yield strength of the entire steel pipe is evenly distributed, and it has excellent tensile properties in both the transverse and longitudinal directions.

Table 6 shows the toughness test results of the base metal, weld and heat-affected zone of steel pipe. It can be seen from the statistical results that the trial-produced Φ 691 × 40.5 mm X70 LSAW pipe base material, weld and heat affected zone have excellent impact toughness.

![Fig.6 Location of Vickers hardness measurement](image)

Crack Tip Opening Displacement Test (CTOD) is one of the most critical technical indicators for high pressure and high steel grade thick-walled submarine pipelines. The CTOD test temperature is 0°C, which is determined by BS7448 and DNV OS-F101 Appendix b. As shown in Table 4, both the base material, the weld and the HAZ coarse-grain zone have good CTOD values, and the characteristic CTOD values far exceed the BS7448 and DNV OS-F101 standards greater than 0.2 mm.
4. Summary
The matrix structure of deep-sea pipeline steel is dominated by acicular ferrite, with a small amount of granular bainite. The coarse-grained zone of the steel pipe weld structure HAZ is composed of granular bainite, and the size of the M-A island is larger. The structure of the fine-grained zone is dominated by polygonal ferrite, with a small amount of pearlite and cementite.

In different $t_8/5$ ranges, the microstructure of the X70 pipeline steel welding coarse grain zone is mainly bainitic ferrite and granular bainitic, with good impact toughness value. The right amount of granular bainite can divide bainite ferrite off, so that the strip bundle is small and the toughness is optimal. When the cooling time $t_8/5$ is 12 ~50s, the toughness of coarse grain area is the best. The decrease of $t_8/5$ will lead to the appearance of thick strip bundles and strip m-a islands. The increase of $t_8/5$ leads to the gradual increase of polygon ferrite, which leads to the decrease of impact toughness. Ultra-abyssal welding process of welded pipe is reliable, with high welding quality and well property, which meets the DNV-OS-F101 standard and user technical requirements.

Acknowledgements
The authors gratefully acknowledge the Natural Science Foundation of Guangdong Province (2017A030313276;2018A0303133287); Guangdong science and technology project (2017B090907015); and Major Project of Department of Education of GuangDong Province (2016KZDXM046 and 2017GZCZX003)

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