Microstructure and Impact Toughness of X70–L245 Butt Girth Weld in Natural Gas Station

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Abstract. At present, the numerical simulation and safety evaluation of girth welds are based on the properties of tubular materials, which cannot truly reflect the properties of girth welds. Based on the investigation results of girth weld in the station, this paper took X70 (21mm) and L245 (12mm) joints with large material and wall thickness gap in the station as research objects, prepared girth weld according to the welding process in the project site, and studied the structure and impact toughness of the joints. The microstructure of weld zone was analyzed by optical microscope. Charpy impact toughness increased from the center of weld to both sides, and the center of weld was the lowest. On X70 side, the impact toughness of FGHAZ is the highest and the impact energy is about 200 J, which is significantly higher than the weld center. The impact toughness near the fusion line on side L245 is the highest, but significantly smaller than that on side X70. Grain refinement, interlacing structure and M/A structure are conducive to the improvement of impact toughness. In this kind of girth weld, the center of the welding seam is the weakest area, and the X70 side has a significantly higher toughness.

1. Introduction

After long service of oil and gas transmission pipeline, many cases of oil and gas transmission pipeline failure were caused by weld defects. In China, the failure of pipelines caused by the welds is particularly prominent. In recent 10 years, with the construction and production of high-steel large-caliber pipelines, more than 30 girth weld cracking and leakage accidents occurred in the pipeline pressure testing stage and the initial operation stage, more than 70% of which were caused by girth weld defects. In addition, girth weld failure accidents occur frequently in storage and transportation facilities of oil and gas transmission stations [1-3]. In 2011, girdle-weld butt joint between flange and process pipelines of the compressor import and export in a natural gas pipeline compressor station burst during the pressure test. The whole workshop almost be destroyed, causing serious economic losses. It can be seen that the in-service safety and failure prevention and control technology of girth weld has become an important engineering problem facing the current pipeline safety in service. It can be seen that the in-service safety and failure control technology of girth weld in natural gas station yard has become an important link of current pipeline system safety.

Different from the girth welding joints of long-distance pipelines, the girth welds in the natural gas station have the characteristics of different steel grades, different wall thickness and different pipe fitting types due to a large number of joints between different pipes [4]. The investigation results show
that the difference between the two butt joints of the reduced tee -- straight pipe butt girth weld is relatively larger, and the X70–L245 joint is one of the typical forms of the larger difference [5]. Compared with the same material and the same wall thickness butt joint, this butt joint form will cause different thermal fields on both sides under the same heat input condition, which will lead to different performance of heat affected zones (HAZ) on both sides. However, there are few researches on the strength and toughness of girth weld.

Impact toughness can better reflect the strength and toughness characteristics of girth weld. Based on the investigation results, this paper prepared the butt joint with different wall thickness X70–L245, investigated the distribution rule of impact toughness of girth welds, and analyzed it in combination with the organization structure. The results can provide a basis for failure analysis, numerical simulation and safety evaluation of girth weld in natural gas station.

2. Experimental Procedure

2.1. Welds Preparation
The girth weld was prepared by welding X70 pipe to a L245 pipe. Table 1 shows the details specifications of the materials. The butt joint was welded according to Q/SY GJX 0221-2012 “Welding specification for station pipes of West - east gas transmission third line” [6] with groove angle of 60 degree. The welding was done by manual semi-automatic welding using ER50-6 welding rod (Φ 2.5 mm) on the root welding and the E6015-Ga welding rod (Φ 2.5 mm) on the filling and cover welding.

| Materials          | X70       | L245     |
|--------------------|-----------|----------|
| Pipe diameter      | Φ1016 mm  | Φ1016 mm |
| Wall thickness     | 21 mm     | 12 mm    |
| Manufacturing standards | API Spec 5L | GB/T 9711 |

2.2. Test
Because the weld seam area, especially the heat-affected area, has a small width in the pipeline axial direction, in order to better obtain the performance distribution in these areas, charpy impact test samples adopted a smaller thickness of 3.3mm, so as to minimize the occupation of grooves in different structure areas. The samples were cut from three positions of near outer surface, middle of pipe wall and near inner surface. The metallographic analysis were carried out with a Leica MeF3A metallographic microscope and a Olympus confocal laser microscope.

3. Results and Discussion

3.1. Metallographic Analysis
Figure 1 shows the macroscopic metallographic picture of the welded joint. It can be seen that there are obvious background welding, filling welding, cover welding layer and HAZ at the girth weld joint. The metallographic structure photos of welding seam backing weld, filling weld and covering weld layer are shown in Figure 2.
In order to study the properties of different areas in the heat-affected zone, the microstructure of the heat-affected zone of girth weld joints was observed. Figure 3 shows the metallographic structure of the HAZ on both sides of the weld. It can be seen that the HAZ can be divided into coarse crystal zone, fine crystal zone and two-phase zone according to the microstructure. The width of L245 side HAZ (Figure 3(a)) is about 2 mm, among which the coarse crystal zone is about 1.1 mm, the fine crystal zone is about 0.6 mm, and the two-phase zone is about 0.3 mm. The coarse grain area is large, the fine grain area is small, and the two-phase area is the mixed structure of the fine grain and the original structure of the parent material. It can be seen from Figure 3(b) that the width of heat affected zone on the side of X70 is about 1.5 mm, which can also be divided into the following areas: the coarse crystal area is about 0.7 mm, the fine crystal area is about 0.6 mm, and the two-phase area is about 0.2 mm.
The high magnification metallographic photos of the coarse grain area, fine grain area of the weld seam and the base metal area are shown in Figure 4. It can be seen that the metallographic structure of the coarse grain area on L245 side is mainly granular polygon ferrite (PF) + pearlite (P) + bainite (GB), of the fine grain area is mainly ferrite (F) + P, and of the base metal is F + P. The coarse grain area on the side of X70 is mainly composed of GB, while the fine grain area is composed of PF + m-a island, and the parent material is composed of granular bainite B grains + polygonal ferrite PF.

![Figure 4. Metallographic structure of Coarse crystal zone, fine crystal zone and base material.](image)

(a) L245 side coarse grained region; (b) L245 side fine grained region; (c) L245 base material; (d) X70 side coarse grained region; (e) X70 side coarse grained region; (f) X70 base material

3.2. Impact Toughness

In order to study the distribution of toughness in different parts of the heat-affected zone, charpy impact toughness was tested and analyzed. The schematic diagram of sampling and grooving position is shown in Figure 5, according to the research objectives and operability. In order to make charpy impact samples reflect the performance of a certain area as much as possible, the impact samples with a thin thickness of 3.3 mm were selected according to ASTM A370-17 “Standard test methods and definitions for mechanical testing of steel products” [7]. M represent grooves at the center of the weld seam. When sampling at the outer wall side and the wall thickness center, grooves are notched on the L2 (R2) at the intersection of the fusion line and the lower surface of the sample, that is, charpy impact performance at the fusion line is tested. L1 (R1) represent grooves at the position between the center and the fusion line, L3 (R3) groove represent that notched at the intersection of the fusion line and the upper surface of the sample, that is, to test the performance of the heat-affected zone, L4 (R4) groove represent that notched at the intersection of the upper surface of the sample and the boundary line between the heat-affected zone and the base material, which aimed to test the performance of two-phase tempering zone.

When notching grooves on the inner wall side samples, L1 (R1) and L2(R2) were abandoned could not be notched because the distance between the welding seam center and the fusion line is too close.
According to the linear relationship of between impact absorption work and sample area (width) [7], $A_{kv(3.3)}/A_{kv(10)} = 3.3/10$, the impact absorption work value of $3.3\times10\times55$ sample is converted into the value of $10\times10\times55$ sample.

Charpy impact absorption work results are shown in Figure 6 shows. It can be seen that the impact absorption energy at the weld seam center is the lowest, which is mainly due to the structure characteristic (as shown in Figure 2(b) and Figure 2(c)) of coarse grain at the weld seam center and the presence of some harmful phases (Widmannstatten structure (WF)). Compared with both the filling welding and cover welding layers, the backing welding layer shows higher impact absorption work, because there is basically no harmful phase (e.g. WF) at the backing weld.

Compared with R2, L2 has a larger increase relative to the weld center, which is mainly affected by the structure. Due to the melting and diffusion during welding, the characteristics of the fusion line near the two joint sides are almost similar to that of the coarse crystal zone, so the microstructure of the coarse crystal zone can be used to infer the fusion line (L2/R2). By comparing Figure 4(a) and Figure 4(d), it can be seen that compared with X70 side, the coarse crystal zone on side L245 is mainly PF+P+GB, with interlaced structures and smaller grains, while the grain size on side X70 is significantly larger, so the impact toughness of L2 is higher than that of R2.

In L3 (R3) and L4 (R4) position, the impact toughness of X70 side of L245 side show different changes. Compared with R2, R3 and R4 continues to increase, but compared with L2, L3 and L4 decrease. This is mainly because of X70 side fine grain zone (as shown in Figure 4(e)) contains clearly grain refinement, obvious structure crisscross martensite/austenite (M/A) islands structure, while grain refinement, interlacing structure and M/A structure are conducive to the improvement of impact toughness [8]. Relatively, grain size of L245 side fine crystal zone is larger (as shown in Figure 4(b)), staggered characteristics is not obvious, the presence of P, which are not conducive to the improvement of toughness. Therefore, the impact toughness of the L245 side fine crystal zone and the two-phase zone is lower.

As shown in Figure 4(c), structure of L245 side base material is F + P. Grain size is relatively large, grain boundary is clear, and there is linear pearlite structure, which are not conducive to the improvement of toughness. Structure of X70 side base material is GB + PF (Figure 4(f)). Grain size is relatively small, the two structure intersect each other, which are the mainly reason for its higher toughness.

On X70 side HAZ, impact toughness of the fine-grained zone is the highest, and the impact energy is about 200 J, which is significantly higher than the weld seam center. On L245 side HAZ, the impact toughness near the fusion line is the highest, but significantly smaller than that on side X70. The difference in the microstructure of the HAZ on both sides is the reason for the performance gap. Grain refinement, structure crisscross and martensite/austenite islands (M/A) structure are conducive to improvement of impact toughness, coarse grains, clear grain boundaries, Widmannstatten structure and pearlite are adverse factor. In the L245–X70 girth weld, the center of the welding seam is the weakest area, and the X70 side has a significantly higher toughness.
4. Conclusion
Charpy impact toughness increased from the center of weld to both sides, and the weld seam center is the lowest. On the X70 side, Impact toughness of FGHAZ is the highest and the impact energy is about 200 J, which is significantly higher than the weld center. Impact toughness near the fusion line is the highest of in the L245 side HAZ, but significantly smaller than that on side X70. The main reason for the difference of the highert position in HAZ between L245 side and X70 side is that grain size of L245 side FGHAZ is larger, staggered characteristics is not obvious and the presence of P.

Grain refinement, interlacing structure and M/A structure are conducive to the improvement of impact toughness. In this kind of girth weld, the center of the welding seam is the weakest area, and the X70 side has a significantly higher toughness. The value of impact toughness in weld zone would provide technical basis for the numerical simulation and safety evaluation of real girth weld in the station. The results of metallographic analysis agree with the performance distribution.

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