Mechanical properties and microstructure of longitudinal submerged arc welded joint of a new C–Mn steel sheet cladding fine grained ferrite in surface layer for a long distance transport pipeline

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Abstract

A new type of C–Mn pipeline steel plates with the ultra–fine grained ferrite in surface layer and the fine–grained ferrite in the central layer has been developed successfully. In order to manufacture the long distance oil pipelines using this new ultra–fine grain pipeline steel sheet, the microstructure and mechanical properties of the welded joints by the Longitudinal Submerged Arc Welding (LSAW), especially the impact toughness, need to be evaluated. Tensile tests, impact tests, are used to study the mechanical properties in this paper according the Chinese National standards. The metallographic technique and SEM are adapted to analyze the microstructure and impact fracture morphology of the LSAW joint. The research results show that the HAZ near the fusion line is a weak part of impact toughness of LSAW joint. However, the base metal is of the fine–grained and ultra–fine grained microstructure itself, and the heat treatment effects between the post–process welding seam and pre-process welding seam on the multi–layer and multi–pass submerged arc welding process, the impact toughness of the HAZ is greatly improved. The whole welded joint is better than the performance of ordinary pipeline steel, which is satisfied with the welding performance requirements of steel sheet engineering application, and can be used in long distance pipeline manufacturing projects.

1. Introduction

Longitudinal submerged arc welded pipes use for long–distance transport of oil and gas [1], especially in harsh seismic zone [2], tundra, and high drop terrain [3]. At present, the development of the pipeline steel strength is meaningless only by the improvement of the toughness, weldability, and corrosion resistance of the steel correspondingly increases. Also oil and gas pipelines such as the Second West-East Gas Pipeline, the Shaanxi–Beijing Railway, and the Sino–Russian East Line [4] need to have stable performance, especially the Sino–Russian East Line crossing the extremely cold regions, which has higher requirements for the low-temperature toughness of pipeline steel [5]. For longitudinal submerged arc welded fine-grained steels such as X70 and X80 which the most commonly used steels for oil and gas transportation pipelines at present [6]. However, the straightness is not easy to meet the standard owing to the welding thermal stress or equipment precision limitation [7]. The relationship between the heat input and the heat affected zone of the joint is studied, and found that excessive heat input will cause the grain size to be severely rough [8–10]. The deterioration of the properties caused by grain coarsening in the heat-affected zone and the joint softening caused by improper welding heat input is the main problem [9–13]. The microstructure of the LSAW joint is mainly made up of the coarse martensite phase and the bainite phase. These researches show that the size of prior austenite grain, the volume fraction of bainitic ferrite, and M/A constituent increase with increasing the cooling time, moreover the martensite’s volume
fraction decreases [14–18]. Remarkable of toughness decrease observes with increasing the size of austenite grain and the volume fraction of M/A constituent. This kind of metal-filled zone’s phases is characterized by a brittle microstructure that greatly hinders the mechanical properties of the welded joint. The ferrite phase generally exhibits a lower strength than that of the bainite and martensite phases [16–20]. As the Hall-Petch relationship suggests, a reduction in grain size will improve mechanical properties, including hardness and yield stress.

In this case, the ferrite is the most desirable phase microstructure in the weld metal because of its excellent toughness. Since the end of the twentieth century, many materials research projects have focused on ultra-fine grain (UFG) steel. Some research results of the laboratory have applied in the metallurgical industry [14–18]. The smallest ferrite grain size approaches 5.5 μm in the surface layers, and can reaches 6.5 μm on average in the whole thickness of the plates. While for usually rolled plates, the grain size is 15 μm on average in the whole thickness of the plates, without a significantly difference between surface layer and central layer. Previous studies show that fatigue characteristics achieve a large improvement by ferrite grain refinement. On the similar stress conditions, the fatigue life of the special plates is more than ten times that of ordinary plates, which can prolong the first stage of fatigue crack growth [19–22]. As you know, the welding technology is a necessary and important manufacture procedure for the fine-grained microstructures material application, especially for the heavy thick steel plates, such as a shipbuilding, pipe making and pressure vessel fabrication. The LSAW is one of basic welding technology for the pipeline duo to its low cost, high efficiency, and good applicability [1]. However, because the characteristics of the LSAW, the properties of the metal-filled zone and the heat-affected zone are more difficult to control than that of the base metal, so the welding seam or welding joint is a weak for manufacturing the pipeline [10–24].

There have two methods to improve the quality of welding joint recently. One is the addition of small alloying element or reactive elements can have a significant effect on metal-filled zone, which is very expensive and complicated manufacturing process. The other is the post welding heat treatment method, which is low-cost and have a significant effect on all welding joint [10–16]. On the other hand, it is necessary to analyze the microstructure and fracture in different areas of LSAW joints. In order to provide an adequate safety pipeline and improve transportation efficiency by the fine-grained microstructure material application in oil, natural gas, and other transportation industries, the welding properties of the material need evaluated whether it can fit for the requirements of mechanical properties for transportation pipeline [21–26]. At present, the welding evaluated work for the new fine-grained microstructure material is not enough. In this paper, the new steel plates with ultra-fine grained ferrite in surface layers and fine-grained ferrite in central layers have developed and manufactured successfully. The welding properties of the plates has analyzed by the impact test method and other. The research result will shows if welding properties of the LSAW joint can meet satisfy the demands of the practical application of the new fine-grained metal material by the post welding heat treatment method.

### 2. Experimental material and method

The composition of the new C-Mn steel plate used in this experiment shows in table 1.

China Shougang Group uses a 3300 mm four rolling mill to produce the new C-Mn steel plate (Containing Balance Fe, 0.14%–0.18% C, 0.2%–0.40% Si, 0.80%–0.90% Mn, 0.02%–0.05% Al, P < 0.015%, S < 0.005%, wt%) with the thickness of 25.4 mm and the surface layer (special steel plate) as fine grained ferrite by a special TMCP process. The 220 mm thick, 140 mm wide and 1700 mm long’s C-Mn steel continuously casting slabs is reheated at 1200 °C for more than 3.5 h. The C-Mn steel slab is rough-rolled in the range of 1150–1000 °C to reduce the thickness from 220 mm down to 80 mm. Then final rolling passes of the C-Mn steel plate is performed in the range of 860 °C–800 °C from 80 mm to 25.4 mm. This is followed by an accelerated cooling process immediately with the start cooling temperature of about 780 °C–800 °C and the final cooling temperature of 600 °C–640 °C. Finally, the hot rolled steel plate goes through the hot leveling process. The mechanical properties of the new C-Mn steel plate are presented in the table 2.

Compared with the conventional adding Nb and Ti alloying design and manufacture method (also need refining processing) for the same type special steel plate, the cost of the new C-Mn steel plate obtained in this paper saves about 400 RMB/T, could be controlled in 3200 RMB/T, which costs reduce about 12.5%, and the mechanical properties of new C-Mn steel plate is greatly improvement shown in table 2.

### Table 1. Composition of new C-Mn steel plate.

|   | C       | Si      | Mn      | Al      | S       | P       | Fe     |
|---|---------|---------|---------|---------|---------|---------|--------|
|   | 0.14 – 0.18 | 0.20 – 0.40 | 0.80 – 0.90 | 0.02 – 0.05 | <0.005 | <0.015 | margin |

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[1] C. Shoufang et al. (2020) Mater. Res. Express 7 (2020) 046513
The surface layer of the new C-Mn steel plate is ultra-fine-grained and the middle layer is fine grain. The surface ferrite grain size of the new C-Mn steel plate is 5–7 μm (Grain size level 11.5–12.5 assigned in Chinese National Standard GB/T6394-2002, and eqv. ASTM E112: 1996), and the middle ferrite size is 10–15 μm (grain size number 10-9) as shown in figure 1. Ferrite grain size and level of the new C-Mn steel plate are presented in the table 3.

The workpieces are manufactured by the process developed by our research group. All the plates have made into pipes by a series of standardized processing, which including edge trimming, bending and forming, and pretreatment before welding, backing welding, inner submerged arc welding, cap/outer welding processes, and so on.

The four-wires double-sides single-layer LSAW method with a diameter of 6 mm are used in the pipeline welding process, and the welding speed is 1.6–1.8 m min⁻¹. The inner and outside welding current is 680 A–1050 A, the inner and outside welding voltage is 32–46 V. The double groove is X shape, the angle of groove is 80°, and length of root face is 6 mm. The welding wire is H08M2SiA, the flux is HJ431. The internal welding is first pass and external current is second procedure shown in the figure 2(a). The wire spacing is 30 mm, the length of welding pool is about 150 mm.

The workpiece cut from the welded tube, which makes into test and measurement sample. The tensile tests have performed according to Chinese National Standard GB/T228-2002 (eqv. ISO6892:1998) for both the base metal and the welded joint. According to the Chinese National Standard GB/T229-2007 (eqv.ISO148-1:2006), the Charpy V-notch impact test is carried out at −10 °C for different welding joint areas (including metal-filled weld seam zone, fusion line zone, heat affected zone, base metal, upside weld seam and bottom weld seam, etc.). Finally, the S360 scanning electron microscope is used to observe the fracture morphology.

In order to ensure the reliability and accuracy of the sample preparation, these samples cut from the based metal, meal-filled weld seam zone, fusion line zone, and HAZ (Heat affected zone) of the LSAW joint using a WEDM (Wire Electrical Discharged Machining). Before the Charpy impact specimen and the metallographic...
specimen are processed, the cross-section of the WEDM sample is machined to produce a bright surface through milling and polishing along the latitude of welding area. Because the position of the fusion line and the boundary of welding seam can be clearly seen, the V-shaped opening of Charpy impact specimen can be remarked easily in the desired position of welded joint or the contours of different welding areas. Mark and fix the position so that the final machined impact specimen V-notch is exactly aligned with the desired position. For example, to check the impact performance of the fusion line of welded joint, the V-notch is just open on the fusion line of welded joint. The V-notch impact sample and metallographic sample show in figure 2(b).

3. Results

3.1. Mechanical properties of tensile test

The results of 27 tensile tests including the tensile strength, yield strength, and elongation of LSAW samples are shown in figure 3.

Figure 3 shows the minimum and maximum tensile strength of welded joint are 415 MPa and 515 MPa respectively. The average value of the tensile strength of the LSAW welded joint is 483 MPa. The average value of tensile strength of base metal is 483 MPa shown in the table 2 and figure 3. These test data comes from 27 different lots with some different production batches of steel plates, the variation of tensile strength can eliminate the standard deviation between the base metal and the welding joint. The tensile test results of multi-samples show that the welded joints have a small fluctuation range for tensile strength, which indicating that the LSAW welding process is stable and the quality consistency of the welded joint is good. The tensile strength of the welded joint is very good to that of the base metal. The average tensile strength of the welded joint is about 20 MPa higher than the tensile strength of the base metal (shown in the table 2), and the difference is obvious. In addition, a bending test was performed on the LSAW welded joint, and the results showed that no crack occurred in the welding area. So the welding joint is satisfied to the technical requirement.
3.2. Microstructures of welding joint

The microstructure of welding joint including the base metal, HAZ, weld seam zone of LSAW samples are shown in figure 4.

The welded joint is designed the weld seam (metal-filled zone), HAZ and based metal. The fusion zone is the transition zone where partial melting occurs at the junction of the weld seam and the HAZ. This zone is rather narrow, it is also called the fusion line. Because the fusion line is difficult to distinguish it in metallographic analysis, so the fusion line are discussed usually with the Coarse Grained HAZ (CGHAZ) together. The HAZ is a very important part of welding joint, which is also a weak part of welding joint generally. The HAZ has many different categorized regions in different ways. In this paper, the HAZ includes the sub-critical HAZ (SCHAZ), inter-critical HAZ (ICHAZ) and upper-critical HAZ (UCHAZ) from the base metal to weld seam zone can be observed in turn. Further micro categorizes, the UCHAZ includes the Superheated Coarse Grained HAZ (SCGHAZ) in the fusion zone, the Coarse Grained HAZ (CGHAZ) and Fine Grained HAZ (FGHAZ). The UCHAZ is the most likely to cause failure in performance in the HAZ. Figure 4(a) shows that the microstructure of the welding seam area (metal-filled zone) is composed of a typical cellular structure. The flake-like ferrite and strip ferrite are distributed along the grain boundary of the cellular structure. The microstructure of the Widmanstätten ferrite, and also containing a small amount of pearlite.

Figure 4(b) shows the microstructure near the fusion line. The left side of the figure 4(b) is the coarse-grained structure of the HAZ, which is mainly composed of Widmanstätten ferrite, flake-like upper bainite and granular bainite structure. There is a clear dividing line between the upper left and lower right of the figure, namely the fusion line, which is also the boundary between the welding seam and HAZ. The area on the right side near the fusion line is the metal-filled zone (weld seam center zone), which is composed of a cellular structure. In the cellular grain boundary, there are flake-like or strips of ferrite, while a small amount of Widmanstätten structure grows into the cellular grain from the crystal boundary. The inside of the cellular grain is mainly acicular ferrite and a very small amount of pearlite. The size of the cellular grain near the fusion line is larger than that of the metal-filled center zone, which is related to the dilution of the alloying elements for grain refinement. The width of the large-size cellular structure is about 300–400 μm across the fusion line toward the inside of the welding seam.

Figure 4(c) is a superheated coarse microstructure in the UCHAZ, which is located the left side of the fusion line. The pro-eutectoid ferrite precipitates along the original austenite grain boundary, and the Widmanstätten ferrite grows into the prior austenite grain. The black part is pearlite. The overheated grain growth near fusion line changes very coarse due to the temperature arrive the fusion point, so it is called Superheated Coarse Grained HAZ (SCGHAZ). The left of the figure 4(c) shows the initiation of coarse grain microstructure in the HAZ.

Figure 4(d) is a coarse grained microstructure in the UCHAZ similar to superheated zone, where the temperature reached the AC3 temperature. Because of the rapid cooling of the austenite, the microstructure was almost fully ferrite with larger grains compared to the base materials. It is also composed of a coarse Widmanstätten ferrite and pearlite, but size of grain microstructure is thinner than that of the superheated microstructure near the fusion line. It is also called CGHAZ.

Figure 4(e) shows a fine grained microstructure near CGHAZ in the HAZ center and also belongs to UCHAZ. The Widmanstätten ferrite and pearlite are formed during rapid cooling of the joint. The microstructure of the Widmanstätten ferrite and pearlite is gradually shortened from the top right to the bottom left in the figure, and the segmented pearlite region becomes smaller, reflecting that the trend of superheated austenite grain coarsening is gradually weakened. The coarse Widmanstätten ferrite gradually disappears and a small amount of equiaxed ferrite appears, which shows a relative homogeneous microstructure. The grain size of this microstructure is thinner than that of the coarse microstructure in the CGHAZ. It is also called FGHAZ.

Figure 4(f) shows the completely recrystallized grained homogeneous microstructure in the ICHAZ and the appearance of banded ferrite and pearlite Because the temperature of this area rises to near austenitization temperature (AC3) for a short time but the residence time is short, the austenite grains formed are basically not grown, and carbon diffusion is hardly carried out on the welding process. During the subsequent cooling process, most of the areas containing a small amount of C element form ferrite, and some areas containing a high amount of C element form pearlite, and finally distributes in a band shape. It is also called Recrystallized Grained HAZ (RGHAZ), where the temperature is below the AC3, but above the AC1 temperature.

Figure 4(g) shows the very fine grained homogeneous microstructure in the SCHAZ near the base metal, which also appears as a uniform size’s strip ferrite and pearlite. During the welding process, the temperature of the areas is below the AC1 point, therefore the austenite grains do not grow obviously and the dissipation of carbon seldom carries out. During the cooling process after the welding, the carbon content in majority of the area is low and ferrite occupies majority. In contrast, banding pearlite forms and distributes intermittently in the minority of the area with the high carbon content. It is called as phase transfer Uncompletely Recrystallized Grained zone (URGHAZ). The fine grain size of this zone is smaller than that of UCHAZ.
Figure 4. Microstructure of welding joint: (a) metal-filled zone; (b) fusion zone; (c) SCGHAZ near fusion line; (d) CGHAZ; (e) FGHAZ; (f) ICHAZ; (g) SCHAZ; (h) base metal made by hot rolling.
Figure 4(h) shows a homogeneous original microstructure of hot rolling for the base metal.

3.3. Impact test results of welding joint

The impact test results of welding joint and base metal show in table 4. The table 4 show that the impact energy value of base metal varies from a small range of 188 to 200 J with 100% shear area. The impact energy value of metal-filled zone changes from 204 J to 273 J, which is higher than those of base metal, but with a very small brittle zone. The impact energy value of the fusion zone changes from 138 J to 270 J in a large range, which is the worst part of welding joint. The energy value of the HAZ varies from a range of 208 J to 261 J. The impact test result shows the energy value of specimens changes little when the shear area is little, which is correspondent to the coarse-grained microstructure as shown in figure 4. The SCHAZ has a refine-grained microstructure, about 1.5–2 mm far from base metal, the impact energy value is the highest among the four different zones (including base metal, fusion zone, HAZ, metal-filled zone) of LSAW joint. It should be pointed out that the test data in the figure 4 is these results of different production batches steel plates, not these results of different locations on the same steel plate. The impact test results of welding joint and base metal also show the quality control of the new C-Mn steel processing is more effective, the consistency of the product has been a great guarantee. The new C-Mn steel plate and welding joint meet the requirements of API 5 L B standard for line pipe (Yield strength up to 300 MPa), the low temperature impact toughness performance of welding joint and base metal is very well shown in the table 4.

The impact energy of sample is affected by the impact load and deformation, and is roughly equal to the area integral value formed by the impact load-displacement curve. In the table 4, an interesting phenomenon arises here. The HAZ has a high impact toughness values than other regions (such as base metal and fusion zone), but these grains in the HAZ are coarser than those of base metal according to the figure 4. The impact energy of welding joints or base metals is related to two main factors: (1) The shape of microstructure of base metal or welding joint (including grain size and shape, etc); (2) The property of microstructure of base metal or welding joint (including phases, components, element, etc). On some similar conditions, the microstructure or phases factor will play a dominant role generally about impact energy. Although the HAZ grains are coarse, the Widmanstätten ferrite, bainite and pearlite phases are formed in the HAZ, these phases’ strength/hardness is higher than that of the base metal (including pre-eutectoid ferrite and little pearlite only).

On the other hand, the four-wires double-sides single-layer LSAW method is adopted in this paper, the HAZ is subjected to heat treatment by the subsequent welding operation, it can normalize and temper microstructure in the HAZ, which is conducive to the improvement of its toughness. The grain size and phase compose of welding seam or fusion zone are different from the HAZ and base metal completely. It is difficult to compare them with one same simple standard. At last, this SCHAZ has gone through a recrystallization heat cycle and the residual stress has decreased with a slow cooling rate in the welding CCT process. So the impact energy value of HAZ is higher than that of base metal. However, the mechanical properties of the whole welding joint is almost similar to those of base metal, which is caused by the characteristic of fusion zone with an almost 1–3 mm width. So the key for improving mechanical properties of welding joints is property of fusion zone.

In the table 4, the alphabet ‘O’ in ‘O1’ refers to the specimen from the Outer welding part of the joint and ‘I’ in ‘I7’ refers to that from the Inner welding part. SA refers to shear area, NF refers to non-fracture.
3.4. Impact fracture morphology of welding joints

The impact fracture morphology of outer surface sample and inner surface sample for LSAW joint of new C-Mn steel plates cladding ultra-fine grained ferrite in surface layer is issued in figures 5 and 6 respectively.

The macrostructure of impact fractograph on metal-filled (Specimen O2, shown in table 4), fusion zone (Specimen O1) and HAZ (Specimen O8) of outer surface sample is shown in figure 5(#1), figure 5(#2) and figure 5(#3) respectively.

The cracks of outer surface sample on metal-filled zone begin at the point of the parabolic tear pit and extend toward the bottom in figure 5(b1). The shallow dimples mean a limited toughness for welding joint, but the strength and hardness of the metal-filled joint are high. The cracks initiate from the coalescence of voids. The voids may appear on the grain boundaries as shown in figure 5(c1). The particles or defects appearing at or near the grain boundaries would give rise to crack initiation points.

There exists the radial zone in fusion zone of outer surface sample (Specimen O1, shown in table 4) in figure 5(a2), but a rectangular protrusion appears below the fibre zone near the bottom of the notch. The rectangular protrusion with a crack radial character belongs to CGHAZ. The shape of shallow dimple is elliptical or parabolic, which means high strength and hardness. Figure 5(b2) shows the ductile dimple fractograph of the fiber zone. The rectangular protrusion in the radial zones shows in figure 5(c2), the cleavage fracture occupies a major portion and looks like rosette pattern. There is a torn ridge between the rosette patterns.

The fracture profile of the outer surface between metal-filled zone sample and fusion zone sample is similar to the parabolic dimple shows in figure 5(#1) and figure 5(#2) respectively. The CGHAZ region adjacent to the external fuse has a significant warp crack. In addition, the rosette cleavage fracture and the plastic fracture ridge in Fig. Figure 5(#2) are thinner than that in figure 5(#1), which appear in the interior of the parabolic dimple in the figure 5(#2).

Figure 5(a3) is macrostructure of impact fractograph on the HAZ of outer surface sample (Specimen O8, shown in table 2). It is typical fractograph in impact test for HAZ far from fusion line. Figure 5(b3) shows the dimples in the ferrite and pearlite and figure 5(c3) shows the tearing ductile dimples.

The macrostructure of impact fractograph on metal-filled (Specimen O2, shown in table 2), fusion zone (Specimen O1) and HAZ (Specimen O8) of inner surface sample is shown in figure 6(#1), figure 6(#2) and figure 6(#3) respectively.

Figure 6(a1) is macrostructure of impact fractograph on metal-filled zone of inner surface sample (Specimen I4, shown in table 4). Fine dimples appear on the surface of the fractograph slightly away from the notch shown.
Some secondary precipitated particles are located at the bottom of the dimples. A cleavage fracture or a quasi-cleavage fracture occurs in the center portion of the specimen, as shown in figure 6(c1), which looks like tongue patterns on the quasi-cleavage surface. Among the rosette cleavage planes, there are some tearing ridges. The impact fractograph of inner surface samples on fusion zone shows a small protrusion with an irregular shape in the radial region below the fiber region in figure 6(c2), which is different from that in figure 6(c1). The crack in the radial region begins with the connection between the shear region and the radial region. In the small protrusion region, there has a 4 mm elongated space between the fiber region and the radial region. The space may just be the location of the fusion line. The upper part belongs to the metal-filled zone and the lower part belongs to the CGHAZ along the fusion line.

Figure 6(a3) is also typical fractograph of inner surface sample impact test for HAZ far from fusion line. Figure 6(b3) shows the fractograph close to the root of the impact notch and the radial region including the ductile dimples initiating from the ferrite and pearlite. Figure 6(c3) shows the tearing ductile dimples.

Comparing with the characteristics of impact fractograph for the inner surface sample and outer surface sample of welding joint respectively shown in figures 5 and 6, some ductile dimples scatter among the cleavage fracture in the figure 5(c1), which is different from that in figure 6(c2). If the tearing ridge is thinner, so the ductile area is larger in the fusion zone, which shows in figures 5(c2) and 6(c2) respectively.

The outer and inner portions of the metal-filled zone joint exhibit different fracture mechanisms. A tough contour parabolic dimple appears in the outer surface sample shown in figure 5(b1). At the bottom of the dimple, small particles and pits caused by particles can be seen in figure 5(c1). At the beginning of the crack formation, the small particles promote the initiation of the parabolic dimple until the occurrence of cracks. A signature outline for tongue-shaped pattern of Cleavage fracture appears in the inner surface sample shown in figure 6(b1), and in the initial stage of crack formation, small particles promote the generation of cracks to form a tongue-shaped crack as shown in figure 6(c1).

The fractograph in figure 6(b2) is similar to that in figure 5(b2). However, the dimples are relatively shallow and appear the grain boundary position, and the second precipitated particles on or near the grain boundaries can promote the formation of ductile pits. The fractograph in figure 6(c2) is similar to the that in figure 5(c2).

Tough torn ferrite and pits in pearlite appear in both the inner and outer HAZ regions, as shown in figures 5(c3) and 6(c3). The impact test results also show that the fractograph in the CGHAZ adjacent to the
| Specimen | Chemical contents, wt% | Grain Size Number | 0 °C CVN | −10 °C CVN | References |
|----------|------------------------|-------------------|---------|-----------|------------|
|          | C | Si | Mn | P | S | Surface | 1/4 | Centre | L | T | T |
| 1        | 0.16–0.19 | 0.10–0.25 | 0.50–0.60 | 0.020 | 0.020 | 7–7.5 | 7–7.5 | 7–7.5 | 39 | 31 | — | [21] |
| 2        | 0.14 | 0.15 | 0.55 | 0.015 | 0.022 | 10 | 8.5 | 8–8.5 | 114 | 51 | — | [21] |
| 3        | 0.15 | 0.23 | 0.65 | 0.011 | 0.005 | 9.8 | 9.8 | 8.7 | 180 | — | 150 | [22] |
fusion line is cleavage and that in the metal-filled zone is ductile or pseudo cleavage, and that in the HAZ are ductile. It illustrates that the CGHAZ near the fusion line is the most serious position for the LSAW joint. Therefore, the CGHAZ region near the fusion line is the worst region where the crack is most likely to occur.

4. Discussion

There are several major factors affecting the impact toughness of LSAW joints of new C-Mn steel plates cladding ultra-fine grained ferrite in surface layer, such as the microstructures, uniformity and cleanliness of base metals, the welding process, and the addition of trace elements to the base metals, and so on. In order to ensure the required toughness of base metal, the P and S element’s contents are usually controlled at a lower degree. In addition, the thermo-mechanical control process is used to obtain the ultra-fine grained microstructure in the surface layer and fine-grained one in the intermediate layer during steel plate rolling. The strength and toughness of steel plate can be satisfied by controlling the cleanliness and microstructure.

The table 5 shows that the toughness of Specimen 2 has improved by the method of grain refinement compared with that of Specimen 1. On the condition of fine-grained microstructure, the toughness of Specimen 3 has also improved by high cleanliness of steel in comparison with Specimen 2. The toughness of base metals with a high cleanliness and ultra-fine grained microstructure in this paper shown in table 1 is superior to the results in table 5.

In the table 5, L refers to the rolling direction; and T refers to the transverse direction.

In the lower austenite transformation temperature range near the AC3 point, the austenite can be recrystallized by large deformation austenite to refine ordinary C-Mn steel, and the retained austenite can be pancaked with appearance of dislocation cellar microstructures and lattice distortion bands in the micro-alloyed steel. No matter what kind of austenite status, the γ phase converts to α phase at the appropriate cooling rate, the final refinement and superfine microstructure of steel can be obtained at room temperature.

The coarse microstructure of the central region of the steel is remelted into austenite during the LSAW heating process. The austenite transforms into a relatively fine microstructure on the condition of LSAW CCT, which improves the toughness of the welding fusion region. And then, the fine grain and ultrafine grain microstructure near the fusion line will become large during the LSAW heating process. During the high-speed unbalanced LSAW CCT, the HAZ microstructure of fine-grained steel plate transforms into a relatively fine microstructure because of a large number of small dispersed nucleated particles, so that the grain size of the CGHAZ is smaller than that of ordinary C-Mn steel, and the toughness in the HAZ can be improved. Therefore, the fine grain and ultra-fine grain microstructure can not only improve the strength and toughness of the base metal, but also improve the mechanical properties of whole welded joints.

As the results of tables 4 and 5, the toughness of the refined steel by the component cleanliness controlling and grain size refining is much better than that of the ordinary steel. Although the toughness of HAZ near the fusion line is the worst in the whole welded joint shown in table 4, the toughness of HAZ of the refined steel’s welded joint is much better than that of the ordinary steel’s base metal shown in table 5.

The multi-layer and multi-pass LSAW has an important heat treatment effect characteristic. That is, the front welding pass has a heat treatment effect on the subsequent welding pass. So the outer surface welding seam has a great influence on the inner surface welding seam caused by multi-pass welding heat cycles. The microstructure of whole welding joint including the HAZ near fusion line is refined and the toughness of welding joint can be improved, especially for the HAZ near the fusion line. The results of table 4 show the conclusion is correct. It seems the toughness of the HAZ near the fusion line of the last pass will be the worst in the multi-layer and multi-pass LSAW, but don’t forget the new steel plates cladding ultra-fine grained ferrite in surface layer can make up for this defect. On the other hand, there has other effective method for toughness improvement of the whole welded joint beside the PWHT method. Some fine second phase particles with a high dissolution temperature can be stably present in the welded joint by the wire addition, which can prevent the microstructure of the HAZ and the metal-filled zone become coarse. The toughness of the welded joint improve observably. The base metal also can improve the toughness by the addition of small alloying element or reactive elements, such as, the fine particles will formed by adding Al, Ti, Mg, or Zr at the end of the secondary refining steel procedure. So that the recrystallization can occur and the relative fine grained microstructure of steel plate can be obtained.

5. Conclusion

A new C-Mn steel plates with an ultra-fine grained ferrite in surface layer and fine-grained ferrite in the central layer have successfully processed. The ultra-fine grained steel is used to manufacture long distance transport
pipeline practically for oil or gas by the LSAW. The microstructure and mechanical properties of the LSAW joints have analyzed. The research results are concluded as the following:

(1) The HAZ near the fusion line is a weak part of impact toughness of LSAW joint. In metal-filled zone of the welded joint is cellular structures which consist of granular bainite, Widmanstätten ferrite, and a little pearlite. The fusion zone changes into coarse Widmanstätten ferrite and pearlite. In the center of HAZ, the pearlite blocks segmented by Widmanstätten ferrite gradually become small, and some ferrite grains appear. The recrystallization zone in HAZ is near base metal, which appears continuous pearlite banding pattern. Finally, the base metal consists of axial ferrite grains and in which the pearlite islands randomly distribute.

(2) The tensile strength of the LSAW joints is superior to the base metal, and the fracture position of the tensile specimen appears in the base metal side. The impact energy value of the HAZ changes relatively large by the Charpy V-notch impact test, but which still keeps at a high value, and the fracture shear area is small. The results show that the impact performance of the fusion zone is the worst, the impact toughness of the HAZ better than that of the metal-filled zone. A brittle cleavage fracture pattern appears the inner surface specimens in metal-filled zone and the fusion zone, and the HAZ and the base metal are ductile dimple fractures during the impact test.

(3) The overall performance of LSAW joints of the new C-Mn steel plate cladding ultra-fine grained ferrite in surface layer is satisfying and meets the engineering requirements for manufacturing a long distance transport pipeline.

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