Microstructure and Low-Temperature Toughness of Double-Sided Submerged Arc Welded Joints in Low-Carbon Bainitic Steel (Postprint)

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Abstract

Double-sided submerged arc welding was performed on low-carbon bainitic steel, and the welded joints were characterized using optical microscopy and a PSW750 oscilloscope impact testing machine to investigate the steel's microstructure and low-temperature toughness. The results show that after double-sided submerged arc welding of low-carbon bainitic steel, the weld zone microstructure consists of acicular ferrite and granular bainite; the HAZ microstructure comprises bainitic ferrite and granular bainite; the hardness near the HAZ fusion line is the highest, decreasing with distance from the fusion line and gradually approaching the base metal hardness; as temperature decreases, solidification segregation during welding, highly concentrated dislocation sources that cannot relax stress concentration in time, and carbonitrides formed by microalloying elements such as Ti and Mo distributed on grain boundaries lead to reduced toughness in the welded joint's weld zone and HAZ, with ductile-to-brittle transition occurring at -20°C and -60°C.

Full Text

Preamble

Microstructure and Low Temperature Toughness of Weld Joints Prepared by Double-sided Submerged Arc Welding for Low Carbon Bainite Steel

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Abstract

Low carbon bainite steel was welded using double-sided submerged arc welding, and the microstructure and low temperature toughness of the joints were characterized using optical microscopy and a PSW750 instrumented impact testing machine. The results show that the weld seam microstructure consisted of acicular ferrite and granular bainite, while the heat-affected zone (HAZ) exhibited a microstructure of bainite ferrite and granular bainite. The hardness was highest near the fusion line in the HAZ and gradually decreased with distance from the fusion line, approaching the hardness of the base metal. Compared with the base material, both the weld seam and HAZ exhibited lower toughness, with ductile-brittle transition temperatures at -20℃ and -60℃, respectively. This reduction in toughness may be attributed to solidification segregation, highly concentrated dislocations, and the formation of carbonitrides from alloying elements such as Ti and Mo at grain boundaries during rapid cooling after welding.

KEY WORDS metallic materials, low carbon bainite steel, submerged arc welding, microstructure, low temperature toughness

With increasing demand for oil and natural gas, high-pressure, large-diameter, long-distance pipelines have become the main development trend for hydrocarbon transportation. Low carbon bainite steel offers excellent comprehensive properties including high strength, high toughness, and versatility, leading to its widespread application in pipeline construction. Since welding is the primary method for pipe fabrication, the welding process often degrades the microstructure and properties of welded joints, making them the weakest link in the entire pipeline and susceptible to crack initiation, propagation, and even unstable fracture. While considerable research has been conducted on ferritic bainitic steels, studies on the microstructure and low temperature toughness of submerged arc welded joints in bainitic steels remain limited. Therefore, this work investigates low carbon bainite steel subjected to double-sided submerged arc welding under specific process parameters, examining the microstructure of welded joints and conducting instrumented impact tests from -60℃ to 20℃ to analyze the low temperature toughness and ductile-brittle transition mechanisms in different regions of the welded joints.

1 Experimental Methods

The base material used in this study was low carbon bainite steel with dimensions of 500 mm × 155 mm × 15.3 mm. The main chemical composition is listed in . Welding was performed using a Lincoln twin-wire automatic submerged arc welding machine with double-sided welding and double-sided forming. The leading wire diameter was 4.0 mm and the trailing wire diameter was 3.2 mm. A double-Y groove was employed with the following specifications: root face of 2 mm, internal groove angle of $60 \pm 3°$, and external groove angle of $90 \pm 3°$. The welding consumables consisted of XAUTSJ101ZC flux matched with H03MnNi3 wire. Prior to welding, the test plates were cleaned with acetone to remove oil contamination and achieve a metallic luster. After completing the front side welding, slag was removed from the back side before welding the reverse side. The detailed welding parameters are listed in .

Welded joints were sectioned and prepared as metallographic specimens, which were etched with 4% nital solution. Microstructural examination and grain morphology observation were conducted using a GX71 OLYMPUS metallographic microscope at various magnifications. Microhardness measurements were performed using an HV-120 Vickers hardness tester, with indentations made every 2 mm from one side of the base metal, across the weld center, to the other side of the base metal. Impact test specimens were prepared according to GB/T2650-2008 "Impact Test Method for Welded Joints" and tested using a PSW750 instrumented impact testing machine at temperatures ranging from -60℃ to 20℃ at intervals of 20℃. After impact testing, fracture surfaces were examined using a JSM-6700F scanning electron microscope (SEM).

2 Results and Discussion

2.1 Macroscopic Morphology of Joints

The macroscopic appearance of the welded joint is shown in [Figure 1: see original paper]. The etched joint exhibits clear boundaries between the base metal, weld zone, and heat-affected zone. No porosity, inclusions, or lack of fusion were observed, and the weld edges showed good fusion with neat formation. The weld employed single-sided welding with double-sided forming, and the grains in the weld zone were significantly coarser than those in the HAZ. Columnar grains on both sides grew nearly perpendicular to the fusion line and met at the weld center.

2.2 Microstructure of Joints

The microstructure of the low carbon bainite steel base metal is shown in [Figure 2: see original paper]a, revealing a microstructure of granular bainite and ferrite. Granular bainite serves as the strengthening phase in low carbon bainite steel with high strength, while an appropriate amount of ferrite as the toughening phase can improve toughness, reduce the grain size of granular bainite to some extent, increase grain boundary area, and enhance the ductility and toughness of the steel.

The microstructure of the weld zone is presented in [Figure 2: see original paper]b, consisting of acicular ferrite, granular bainite, a small amount of M-A islands dispersed in the ferrite matrix, and black inclusion particles distributed at grain boundaries. The acicular ferrite structure is distributed in a random, interlocking pattern that effectively prevents crack propagation and enhances the toughness of the weld zone. The ferrite is uniformly distributed without a specific orientation relationship and exhibits high dislocation density, which can further improve weld toughness through a dislocation strengthening mechanism. However, compared with the base metal, intermetallic compounds and brittle phases precipitate at grain boundaries in the weld zone, and micro-pores and inclusions exist in the weld, making it a weak region for both strength and toughness.

Figures 2c and 2d show that the HAZ microstructure consists of granular bainite and bainite ferrite. Granular bainite initially forms as lath-shaped ferrite with high dislocation density, while fine M-A island hard phases are dispersed and interact with dislocations, hindering dislocation movement. This indicates that granular bainite improves strength through both dislocation strengthening and dispersion strengthening. M-A islands can reduce stress concentration and avoid low-energy diffusion paths for cracks during fracture. The dispersed distribution of M-A islands with certain spacing between them impedes crack propagation, thereby increasing strength without significantly reducing ductility and toughness. Different points in the HAZ experience different thermal cycles during welding, resulting in significant microstructural and property variations across HAZ regions. As shown in [Figure 2: see original paper]c, the region near the weld side forms a coarse-grained zone due to large welding heat input and grain coarsening, which reduces ductility and toughness. The region near the base metal undergoes recrystallization, forming a normalized zone with uniform and fine microstructure ([Figure 2: see original paper]d), equivalent to a normalized heat treatment structure that significantly improves ductility and toughness. Consequently, the mechanical properties of the HAZ are intermediate between those of the base metal and weld zone.

2.3 Hardness of Joints

The hardness distribution across the joint is shown in [Figure 3: see original paper]. The hardness is highest near the fusion line and decreases with distance from the fusion line, gradually approaching the hardness of the base metal. This occurs because, under submerged arc welding conditions, the welding wire and flux transfer different types of alloying elements to the weld zone, forming nucleation sites. The low carbon bainite steel contains relatively high Mn content, and the (δ+γ) phase transformation occurs near the fusion line. Since Mn has lower solubility in δ-ferrite, segregation occurs at boundaries. During subsequent cooling, the segregated Mn increases boundary damping, reducing the tendency for grain growth and increasing hardness near the fusion line.

2.4.1 Impact Toughness

Instrumented impact testing provides the energy distribution at each stage of the fracture process, accurately reflecting fracture characteristics and the degree of ductile-brittle behavior. The impact energy (AK) can be decomposed into crack initiation energy (Ai) and crack propagation energy (AP), such that AK = Ai + AP. The measured impact energy, crack initiation energy, and crack propagation energy from this study are listed in . Research indicates that material embrittlement is first manifested by a reduction in crack propagation energy.

As shown in , when the temperature of the weld zone decreased to -20℃, the AP value sharply decreased to 30.5835 J, indicating obvious embrittlement. For the HAZ, when the temperature decreased to -60℃, the AP value abruptly changed to 35.5244 J, indicating embrittlement. [Figure 4: see original paper] shows the variation trend of total impact energy and crack propagation energy with temperature for both the weld zone and HAZ. Figures 4a and 4b clearly demonstrate that the HAZ exhibits higher toughness than the weld zone. The crack propagation energy changes at different rates in different temperature ranges for the weld zone and HAZ. The HAZ shows the maximum slope between -40℃ and -60℃, while the weld zone exhibits the maximum rate of change between 0℃ and -20℃ ([Figure 4: see original paper]b). This indicates that as temperature decreases, the crack propagation energy of the material decreases, causing a substantial reduction in toughness. At a certain critical temperature, the crack propagation energy drops abruptly, resulting in a ductile-brittle transition.

In this study, the ductile-brittle transition temperature (Tk) was defined as the temperature at which AK = 0.5(AKmax + AKmin). Therefore, when the impact energy of the weld reached 133.02 J, a significant reduction in toughness occurred, corresponding to a ductile-brittle transition temperature of -20℃. For the HAZ, when the impact energy was 172.34 J at -60℃, the welded joint exhibited obvious embrittlement, manifested as a sudden change in impact toughness, establishing -60℃ as the ductile-brittle transition temperature for the HAZ.

2.4.2 Fracture Surface Morphology

SEM examination of impact fracture surfaces revealed the micro-morphology of weld and HAZ specimens at different temperatures, as shown in [Figure 5: see original paper]. For the weld zone, the fracture surface at 20℃ consisted almost entirely of dimples formed by concave micro-voids, exhibiting ductile fracture with generally small dimples ([Figure 5: see original paper]a) that effectively hindered crack propagation. Figures 5b and 5c show short and curved river patterns with few tributaries and small cleavage planes, surrounded by numerous tear ridges characteristic of quasi-cleavage fracture. This results from the relatively high content of pro-eutectoid ferrite that precipitates along austenite grain boundaries in a network pattern and grows into the grains in a lath morphology, combined with numerous oxide particle inclusions in the weld that easily form micro-voids. Local slip at secondary crack tips leads to rapid shear tearing, reducing the toughness of the weld zone.

As shown in [Figure 5: see original paper]d, the HAZ fracture surface at 20℃ exhibits dimples of various sizes and uneven distribution, accompanied by tear ridges, indicating obvious ductile fracture. Large dimples form from large, dense second-phase particles and inclusions under impact loading, generating dislocation pile-ups that create micro-voids. As the load increases, these micro-voids coalesce to form dimples. Smaller second-phase particles and inclusions dispersed throughout the matrix create small dimples. Figure 5e also indicates ductile fracture, but the small and densely distributed dimples reduce toughness at 20℃. When the temperature decreased to -60℃, the fracture surface showed obvious "river patterns," where each tributary in the river pattern corresponds to a step between parallel cleavage planes at different heights, exhibiting cleavage fracture ([Figure 5: see original paper]f).

2.5.1 Solidification Segregation

The experimental results demonstrate that both the weld and HAZ exhibit good impact toughness at higher temperatures. However, when the temperature decreased to -20℃ and -60℃, the toughness of the weld zone and HAZ severely deteriorated, decreasing by 82% and 75% compared with the values at 20℃, respectively, with the fracture mode changing from ductile to brittle. To investigate the ductile-brittle transition mechanism, chemical analysis was performed on the weld zone, with results listed in .

Compared with the base metal composition in , elements such as Mn, Si, and Mo were significantly burned off during transfer, while Ni and B were transferred to the weld through the welding wire. According to metal solidification principles, assuming no composition gradient exists ahead of the solid-liquid interface at the beginning of solidification in the weld pool, and that no diffusion occurs in the solid phase while convection and some diffusion occur in the liquid phase:

Cs = k0C0(1 - fs)^(k0-1)

where Cs is the mass fraction of solute in the solidified weld metal within a micro-region, C0 is the original mass fraction of solute in the entire weld deposit, k0 is the solute distribution coefficient, and fs is the solidification fraction.

The welding solidification process is dynamic, with insufficient time for solute diffusion in the solid phase. However, the submerged arc welding pool has a relatively long solidification time, allowing some diffusion and convection in the liquid phase. As the solid-liquid interface advances during weld pool solidification, solute enrichment inevitably occurs near the interface. Since the composition in the solid phase cannot homogenize through diffusion, the composition of the initially solidified weld metal (Cs) should be k0C0. Because k0 $<$ 1, Cs $<$ C0, and the fusion zone is at the edge of the weld pool where liquid metal solidification begins first. The initially solidified solid phase contains lower solute concentration, while the later solidified solid phase contains higher solute concentration, resulting in a relatively pure microstructure with fewer inclusions near the fusion zone, while the later-solidified weld center region becomes enriched with more inclusions. This condition leads to composition inhomogeneity during the continuous phase transformation in the weld pool. Observation of the macroscopic morphology in [Figure 1: see original paper] clearly shows that coarse columnar grains formed during solidification due to composition inhomogeneity, and as temperature decreased, material segregation intensified, causing embrittlement of the weld zone.

2.5.2 Weld Inclusions

EDS analysis of inclusion distributions in the base metal and weld is shown in [Figure 6: see original paper]. Spherical inclusions are clearly visible in both the base metal and weld, with inclusions in the base metal being smaller than those in the weld. The analysis reveals that Ti and Mo alloying elements were introduced into the weld during welding. These microalloying elements readily form fine carbonitride particles that disperse along grain boundaries, significantly increasing stress concentration. The distribution of larger inclusions increases the number of microcracks, reducing material toughness. Fracture originates from coarse compounds, particularly those at grain boundaries, which facilitate crack initiation and propagation. Although the grain size in the weld zone was significantly refined compared with the base metal, the non-uniform distribution of inclusions makes the weld zone a weak region in the welded joint. Moreover, the relatively large compounds in the weld zone play a decisive role in crack initiation and propagation. As temperature decreases, these microalloying elements further diffuse to form carbonitrides distributed along grain boundaries, becoming brittle phases that reduce material toughness. Consequently, toughness gradually decreases with temperature, and at a certain temperature, the impact energy and crack propagation energy drop sharply, resulting in a ductile-brittle transition.

2.5.3 Other Factors

For body-centered cubic metals or alloys, the reduction of slip systems makes slip difficult, resulting in a significantly increased yield point. When loaded at a stress higher than the material yield strength, the metal does not yield immediately, and the yield delay time increases with decreasing temperature. Due to longer yield delay times at low temperatures, microscopic slip and highly concentrated dislocation sources cannot relax these stress concentrations before yielding, accelerating crack initiation and propagation. Consequently, material toughness deteriorates as temperature decreases, and a ductile-brittle transition occurs at a certain temperature. The weld zone and HAZ experience different thermal cycles during welding, and large welding heat input leads to coarse grains and deteriorated uniformity, forming massive granular bainite that significantly reduces material toughness.

2.6 Improving Low Temperature Toughness

Alloy element burn-off during welding substantially reduces the amount of transferred alloying elements. To compensate for these losses, required alloying elements can be transferred to the weld metal through the welding wire to improve weld toughness based on microalloying principles. Adding Mn, Ni, and Mo can control phase transformation temperature and expand the γ-phase region, thereby improving the strength and low temperature toughness of the weld zone. Transferring appropriate amounts of Al, Ti, B, and rare earth elements can suppress pro-eutectoid precipitation and form Al2O3, AlN, TiO, and TiN as nucleation sites to refine the microstructure and improve the strength and low temperature toughness of the weld zone.

Under the premise of adequate penetration and good fusion, reasonable control of welding process parameters can effectively control weld microstructure and refine grains, ensuring the toughness of both the weld and HAZ. Post-weld cooling rate can also be controlled through heat treatment to promote the transformation of acicular ferrite and granular bainite, thereby improving the low temperature toughness of the weld zone and HAZ.

3 Conclusions

1. The microstructure of the weld zone in low carbon bainite steel welded joints consisted of acicular ferrite and granular bainite, while the HAZ microstructure consisted of bainite ferrite and granular bainite. The hardness was highest near the fusion line and gradually decreased with distance from the fusion line, approaching the hardness of the base metal.
2. The toughness of low carbon bainite steel gradually decreased with decreasing temperature, and a ductile-brittle transition occurred after reaching a certain temperature. The ductile-brittle transition temperature was -20℃ for the weld zone and -60℃ for the HAZ, with impact energy decreasing by 82% and 75%, respectively, compared with the values at 20℃.
3. The fracture surface of the weld zone at 20℃ consisted almost entirely of dimples formed by concave micro-voids, exhibiting ductile fracture. When the temperature decreased to -20℃, the fracture mode became obvious quasi-cleavage fracture. The HAZ also exhibited ductile fracture at 20℃, but obvious brittle fracture characteristics appeared only when the temperature decreased to -60℃.

References

1. Yang J R, Huang C Y, Wang S C, The development of ultra-low-carbon bainitic steels, Materials & Design, 6(1), 335(1992)
2. I. A. Yakubtsov, P. Poruks, J. D. Boyd, Microstructure and mechanical proprieties of bainitic low carbon high strength plate steels, Materials

Science and Engineering A, 480(1), 109(2008)

3. Vassilaros M G, Czyryca E J, The development of high strength cooling-rate insensitive ultra-low carbon steel weld metals, Key Engineering Materials, 84(3), 587(1993)
4. Hillenbrand H G, Development of high strength material and pipe production technology for grade X120 line pipe, Proceedings of IPC 2004-International Pipeline Conference, Calgary, Canada, 1 (2004)
5. TAO Peng, ZHANG Chi, YANG Zhigang, The microstructure and mechanical property of X70, X80 and X100 grade pipeline steel, Welded Pipe and Tube, 19(2), 31(2008)
6. LI Jiwei, LIU Qinsuo, The research status on ULCB steel, Journal of Tianjin University of Technology, 24(1), 57(2008)
7. HUO Lixing, Welding Structure and Engineering Strength, (Beijing, China Machine Press, 1995) p13
8. LI Jihong, YANG Liang, CHENG Feichou, ZHANG Min, Microstructure and mechanical properties of welding joints of X100 line pipe by double submerged arc welding, Welding Journal, 34(10), 27(2013)
9. ZHOU Hongchen, DAI Shujuan, GAN Cuihua, JIANG Haitao, Study on fractal of impact properties of materials, Material for Mechanical Engineering, 18(6), 31(1994)
10. YANG Caifu, ZHANG Yongquan, The research of 10Ni5CrMoV steels with high toughness, Journal of Materials Processing Technology, 12(6), 2(1997)
11. DUAN Linna, LIU qingyou, JIA Shujun, Microstructure characteristics and strength-toughness of X100 pipeline steel, Chinese Journal of Materials Research, 26(4), 443(2012)
12. ZHANG Min, YANG Liang, LI Jihong, Effects of welding heat input on properties of joints of X100 pipeline steel, Chinese Journal of Materials Research, 26(6), 1(2012)
13. WANG Yong, ZHANG Min, Welding Metallurgy, (Beijing, China Machine Press, 2011) p185

Note: Figure translations are in progress. See original paper for figures.