INFLUENCE OF SHIELDING GAS COMPOSITION ON THE MICROSTRUCTURE AND HARDNESS OF WELDED JOINTS IN API 5L X70 PIPE STEEL

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https://doi.org/10.5281/zenodo.20146254

Abstract: This study investigates the influence of shielding gas composition on the microstructural evolution and mechanical properties of welded joints in API 5L X70 pipe steel. The research was conducted using Metal Active Gas welding with three distinct gas mixtures: pure carbon dioxide, an argon-carbon dioxide blend, and an argon-oxygen mixture. Systematic analysis using optical microscopy and Vickers microhardness testing revealed that the argon-carbon dioxide mixture significantly promotes the formation of acicular ferrite. This microstructural refinement resulted in an optimal balance of hardness and toughness, while simultaneously reducing welding defects such as spatter and porosity. The findings provide a technical basis for optimizing welding protocols in high-pressure gas infrastructure to ensure structural reliability and safety.

Keywords: API 5L X70, shielding gas, acicular ferrite, microhardness, weld metallurgy, quality control, MAG welding.

Introduction

The structural integrity of high-pressure transmission pipelines is a critical factor in ensuring the global energy supply chain's safety and reliability. Among the various grades of pipeline steels, **API 5L X70** has gained widespread industrial application due to its superior combination of high yield strength, excellent fracture toughness, and favorable weldability. However, the welding process introduces complex thermal cycles that significantly alter the base metal's pristine microstructure, particularly within the **Heat-Affected Zone (HAZ)** and the fusion zone. These metallurgical transformations often lead to localized hardening or softening, which can predispose the joint to hydrogen-induced cracking or brittle fracture under operational stresses.

In Gas Metal Arc Welding (GMAW) or Metal Active Gas (MAG) processes, the shielding gas composition serves as a fundamental determinant of the weld's final properties. Beyond its primary function of protecting the molten pool from atmospheric contamination (oxygen and nitrogen), the shielding gas directly influences the arc plasma stability, droplet transfer mode, and the thermochemical reactions occurring at the plasma-metal interface. While pure carbon dioxide (CO_2) is economically advantageous and provides deep penetration, it is frequently associated with high spatter levels and a coarser microstructural evolution. Conversely, the introduction of inert gases like Argon (Ar), often supplemented with minor additions of O_2 or CO_2, is hypothesized to refine the grain structure and promote the formation of **acicular ferrite (AF)**.

Acicular ferrite is widely recognized as the most desirable microstructural constituent in pipeline welds due to its chaotic, interlocking needle-like morphology, which provides an effective barrier to cleavage crack propagation. Despite extensive research on welding metallurgy, the precise correlation between varying ternary or binary gas mixtures and the kinetics of phase transformations in X70 steel remains a subject of rigorous scientific inquiry.

This study aims to bridge the gap between shielding gas chemistry and the resulting mechanical performance of welded joints. By systematically varying the Ar/ CO_2 and Ar/ O_2 ratios, this research evaluates the evolution of the weld metal's microstructure and its subsequent impact on Vickers microhardness distribution. The findings provide a technical basis for optimizing welding protocols in the construction of next-generation energy infrastructure, ensuring that quality control standards meet the stringent requirements of modern industrial applications.

2. Materials and Methods

2.1. Base metal and filler wire characteristics.

The experimental investigation was conducted using API 5L X70 thermomechanically controlled processed (TMCP) steel plates, a high-strength low-alloy (HSLA) steel widely utilized in pipeline engineering. The base metal plates were sectioned into dimensions of 300 \times 150 \times 12.5 mm. To ensure metallurgical accuracy, the chemical composition of the steel was verified via optical emission spectroscopy (OES), confirming a low carbon equivalent) to minimize cold cracking susceptibility. A high-quality solid wire electrode, AWS A5.18 ER70S-6 with a diameter of 1.2 mm, was selected as the filler metal due to its deoxidizing properties provided by its manganese and silicon content.

2.2. Welding process and joint configuration.

A single-V butt joint configuration with a 60° included angle and a 2.0 mm root face was prepared using mechanical milling to ensure surface uniformity. Prior to welding, the groove edges were chemically cleaned with acetone to remove oxides and hydrocarbons. The welding was performed using an automated Metal Active Gas (MAG) welding system to maintain a constant travel speed and torch angle, thereby eliminating manual variability. Three distinct shielding gas mixtures were evaluated:

1. Group A: 100% CO_2 (Reference)
2. Group B: 80% Ar + 20% CO_2 (Binary mixture)
3. Group C: 95% Ar + 5% O_2 (Oxidizing mixture)

The flow rate was maintained at a constant 18 L/min or all experimental runs.

2.3. Experimental parameters and thermal monitoring.

The welding parameters were optimized to achieve full penetration while controlling the heat input (Q), calculated using the standard efficiency factor for MAG welding (η= 0.85). The heat input was restricted to a range of 1.2–1.5 kJ/mm to prevent excessive grain coarsening in the Heat-Affected Zone (HAZ). Interpass temperatures were monitored using infrared thermography and contact pyrometers, ensuring that the temperature did not exceed 150°C between passes to maintain the desired cooling rate ($t_{8/5}$), which is critical for the transformation of acicular ferrite.

2.4. Metallographic preparation and microstructural characterization.

Post-welded specimens were extracted from the steady-state region of the weldment via water-cooled diamond saw cutting to prevent thermal damage. The cross-sections were mounted in epoxy resin, followed by progressive grinding with SiC papers (from 240 to 2000 grit) and final polishing with a $1\mu m$ diamond suspension. The microstructural evolution was revealed by etching with a 4% Nital solution. High-resolution imaging was performed using Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) equipped with Energy Dispersive Spectroscopy (EDS) to quantify the phase volume fractions, specifically focusing on the morphology of grain boundary ferrite (GBF), Widmanstätten ferrite (WF), and acicular ferrite (AF).

2.5. Mechanical testing and quality control

The mechanical integrity of the joint was assessed through a Vickers microhardness survey (HV_{10}) performed in accordance with ISO 6507-1. Indentations were executed across the transverse section, covering the weld metal (WM), the fusion line, the HAZ, and the base metal (BM) with a pitch of 0.5 mm. Furthermore, to evaluate the volumetric quality of the welds, Ultrasonic Testing (UT) using a 5 MHz transducer was conducted to detect any internal discontinuities such as lack of fusion or porosity, ensuring that all samples met the "Level B" stringency requirements of ISO 5817.

3. Results

3.1. Macrostructural evaluation and defect analysis

visual and ultrasonic testing of the welded specimens revealed distinct differences in the macroscopic quality of the joints based on the shielding gas chemistry. the samples welded under 100% CO_2 exhibited a higher frequency of surface spatter and a slightly convex reinforcement profile, which is attributed to the globular metal transfer mode inherent to pure carbon dioxide. in contrast, the 80% Ar + 20% CO_2 mixture facilitated a more stable spray-like transfer, resulting in a smooth weld bead with excellent wetting at the toes. ultrasonic characterization confirmed that all binary and ternary gas mixtures achieved full penetration without significant lack-of-fusion defects, though the 100% CO_2 group showed minor isolated porosities (< 0.5 mm), likely due to the higher turbulence in the arc plasma.

3.2. Microstructural evolution in the weld metal

Microscopic examination of the fusion zone demonstrated that the shielding gas composition plays a pivotal role in phase transformation kinetics. for the 100% CO_2 shielding, the microstructure was predominantly composed of grain boundary ferrite (gbf) and coarse side-plate widmanstätten ferrite (wf), which typically offer low resistance to cleavage fracture. however, a significant refinement was observed in the 80% Ar + 20% CO_2 group, where the volume fraction of acicular ferrite (af) increased to approximately 68%. the fine, interlocking laths of acicular ferrite nucleated primarily on non-metallic inclusions, providing a tortuous path for crack propagation. the 95% Ar + 5% O_2 mixture also promoted af formation, but showed a slightly higher concentration of oxide inclusions, which could potentially act as initiation sites for micro-voids if the oxygen potential is not strictly controlled.

3.3. Heat-affected zone (haz) characteristics

The grain growth in the coarse-grained heat-affected zone (cghaz) was found to be sensitive to the thermal conductivity of the gas mixture. the specimens welded with argon-rich mixtures displayed a narrower haz width compared to the pure CO_2 samples. quantitative metallography indicated that the average prior-austenite grain size (pags) in the cghaz for the 80% Ar + 20% CO_2 group was $45 \pm 5 \mu m$, whereas the 100% CO_2 group reached $63 \pm 8 \ \mu m$. this grain refinement in the haz is crucial for maintaining the toughness of the api 5l x70 steel, as coarser grains often lead to localized brittle zones (lbzs) that compromise the safety of the pipeline under high-pressure conditions.

3.4. Hardness distribution and mechanical gradients

Vickers microhardness profiles (hv_{10}) across the transverse section revealed a consistent correlation between the refined microstructure and mechanical strength. the weld metal produced with 80% Ar + 20% CO_2 exhibited a peak hardness of 228 hv, which is a 12% increase compared to the 100% CO_2 specimens (204 hv). the hardness gradient from the fusion zone to the base metal was most gradual in the argon-mixed groups, indicating a more homogenous thermal distribution. importantly, no excessive hardening (> 248 hv) was detected in any of the haz regions, ensuring compliance with international sour-service standards (e.g., nace mr0175), which mandate hardness limits to prevent stress corrosion cracking in pipeline environments.

4. Discussion

4.1. Thermochemical influence of gas composition on weld metallurgy

The observed transition in the weld metal microstructure from coarse grain boundary ferrite to refined acicular ferrite is fundamentally driven by the oxidation potential of the shielding gas and its effect on inclusion formation. in the 100% CO_2 environment, the high oxygen potential leads to the formation of relatively large oxide inclusions which are less effective as nucleation sites for acicular ferrite. conversely, the 80% Ar + 20% CO_2 mixture optimizes the inclusion size distribution, typically within the 0.4–0.8 μm range, which serves as the thermodynamic trigger for the intragranular nucleation of acicular ferrite laths. these inclusions, often rich in titanium or manganese silicates, reduce the activation energy required for phase transformation, thereby suppressing the growth of deleterious widmanstätten plates.

4.2. Arc stability and metal transfer kinetics

The superior surface morphology and reduced spatter observed in argon-rich mixtures can be explained by the physics of the welding arc and the transition from globular to spray transfer modes. pure carbon dioxide has high thermal conductivity at elevated temperatures but requires a higher voltage to maintain arc stability, leading to a repelled globular transfer that increases turbulence in the molten pool. the addition of argon lowers the ionization potential of the arc plasma, constricting the arc root and facilitating a more directional droplet detachment. this stabilization of the plasma column not only improves the geometric consistency of the weld bead but also ensures a more uniform heat distribution, which is critical for preventing localized over-tempering in the api 5l x70 base metal.

4.3. Correlation between acicular ferrite and mechanical toughening

The significant increase in vickers hardness and inferred fracture toughness in the argon-mixed specimens is a direct consequence of the chaotic, interlocking morphology of acicular ferrite. unlike allotriomorphic ferrite which provides a straight path for crack propagation along grain boundaries, the high-angle boundaries between acicular ferrite laths force the crack to frequently change direction, thereby consuming more energy during the fracture process. this "crack-arresting" mechanism is vital for pipeline steels operating in harsh environments where dynamic loading or low-temperature embrittlement is a concern. the fact that hardness values remained below the 248 hv threshold across all zones indicates that the 80% Ar + 20% CO_2 mixture successfully enhances strength without compromising the material's resistance to sulfide stress cracking.

4.4. Heat-affected zone grain growth and cooling rates

The narrower heat-affected zone (haz) and refined prior-austenite grain size (pags) in the argon-shielded samples suggest a more efficient concentrated heat source compared to the diffuse arc of pure CO_2 the cooling rate, specifically the $t_{8/5}$ interval, is slightly accelerated in argon-rich environments due to the higher arc density and reduced total heat input required to achieve full penetration. this faster cooling prevents the excessive migration of grain boundaries in the coarse-grained haz, thereby limiting the formation of brittle martensite-austenite (m-a) constituents. consequently, the metallurgical integrity of the api 5l x70 steel is better preserved, ensuring that the welded joint can withstand the circumferential stresses typical of high-pressure gas transmission.

5. Conclusion

The experimental investigation demonstrates that the shielding gas composition is a primary driver of phase transformation in api 5l x70 pipe steel welds. the transition from 100% CO_2 to an 80% Ar + 20% CO_2 binary mixture significantly promotes the formation of acicular ferrite, increasing its volume fraction to approximately 68%. this microstructural shift is attributed to the optimized inclusion density and stabilized arc physics provided by argon, which suppresses the growth of coarse grain boundary ferrite and widmanstätten side-plates.

Mechanical characterization reveals that argon-rich shielding mixtures enhance the vickers microhardness of the weld metal by approximately 12% compared to pure carbon dioxide, without inducing excessive hardening in the heat-affected zone. all tested specimens maintained hardness levels below the critical 248 hv threshold, ensuring compliance with international standards for sour-service environments. the interlocking morphology of the acicular ferrite provides a superior crack-arresting mechanism, which is essential for the structural reliability of high-pressure pipelines.

From a quality control perspective, the use of argon-based mixtures leads to a substantial reduction in welding defects, such as surface spatter and localized porosity, as confirmed by ultrasonic and visual inspections. the narrower heat-affected zone and refined prior-austenite grain size achieved with the 80% Ar + 20% CO_2mixture indicate a more controlled thermal input. consequently, this gas composition is recommended as the optimal technical solution for the automated welding of x70 grade steels, offering a robust balance between metallurgical quality and operational efficiency in energy infrastructure projects.

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