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The Effect of Submerging Arc Welding Parameters on The Morphology and Mechanical Properties of Special Steel A 516-60 Steel: A Literature Review

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ABSTRACT
In general, without the pipelines, it cannot afford the world's demands of oil and gas. Furthermore, the pipelines are safely energy transmission methods. This study focusing on the determination of the microstructure and mechanical properties of special steel used in petroleum pipelines welded with submerging ARC welding and mechanical and metallurgy tests. This research used SA516 Grade 60 as the base material.
The research aims to determine of the microstructure and mechanical properties of special steel used in petroleum pipelines welded with submerging ARC welding and examination of mechanical tests. In order to achieve the research objectives. the research finding showing acceptable results according to standard. In addition, careful control of welding parameters is essential to achieving favorable microstructural features, such as acicular ferrite, and maintaining the required hardness and toughness for safe long-term service in pipelines.
Key Words: *Submerged ARC welding, Properties, SA516 Grade 60 alloy, Pipelines, and Mechanical properties.*

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I. INTRODUCTION

The Critical Role of Pipelines in Meeting Global Energy Demand. where, Global energy demands are rising sharply, driven in part by a worldwide push for cleaner energy sources. This has led to a significant 435% increase in global natural gas consumption since 1965. According to the U.S. Energy Information Administration (EIA), world energy demand is projected to increase by 55% by 2030, with natural gas consumption growing at an annual rate of 2.4%. This growth is expected to position gas as a major player, generating 26% of the world's energy [1-3]. The discovery of vast shale gas reserves and the availability of modern extraction equipment have profoundly shifted the energy landscape, making efficient transmission more crucial than ever [4.7]. In addition, The Pipelines: A Safe and Efficient Transmission Method. Pipelines are the backbone of the oil and gas industry, providing a reliable and continuous supply of energy to power stations, refineries, and other facilities. They are indispensable for meeting global energy needs. Beyond their scale, pipelines are also remarkably safe. They are considered 40 times safer than railways and 100 times safer than road tankers for transporting oil. A testament to this safety is the minimal waste: according to the U.S. Petroleum Pipeline Association, only one gallon of oil is spilled per million barrel-miles traveled, an amount equivalent to less than a teaspoon dropped over a thousand miles [8-15].

The use of pipelines for fluid transport is a practice that dates back thousands of years. Early civilizations demonstrated remarkable ingenuity in this area. The Chinese, as early as 400 BC, used hollow bamboo pipes to transport natural gas for lighting their cities. The Egyptians used copper pipes for water transport around 3000 BC, while the Cretians and Greeks later employed earthenware, stone, and even bronze and lead pipes. The Romans, known for their advanced engineering, extensively used lead and metal pipes to deliver water to their cities around 500 BC. More recently, in the late 19th century, hollowed-out wooden logs were used to transport brine. This rich history highlights the continuous innovation in material science and engineering that has led to the robust pipeline systems we rely on today [16]. Submerged arc welding (SAW) is a highly productive and efficient fusion welding process widely used in industries like shipbuilding, structural fabrication, and pressure vessel manufacturing. It's particularly valued for its deep penetration capabilities, high deposition rates, and the quality of the resulting weld. A key application for SAW is the joining of ASTM A 516-60 steel, a carbon-manganese steel specifically designed for pressure vessels and boilers. Its excellent notch toughness at low temperatures makes it a go-to material for these critical applications. However, the quality of a SAW weld is highly dependent on controlling key input parameters, including welding current, arc voltage, and travel speed. These parameters directly affect the heat input, which in turn dictates the weld's cooling rate and the formation of its microstructure, ultimately determining its mechanical properties.

This study will build upon this legacy by focusing on the modern application of submerged arc welding in the fabrication of petroleum pipelines. Specifically, it aims to determine the microstructure and mechanical properties of special steels used in these pipelines through welding and subsequent examination tests, including hardness measurements.

Problem Statement: The relationship between SAW parameters and the final weld properties of A 516-60 steel is complex and not fully linear. The challenge lies in identifying the optimal combination of welding parameters to achieve a desirable microstructure specifically, a high-volume fraction of acicular ferrite (AF) while ensuring the weld meets stringent industrial quality and performance standards. Poor control of these parameters can lead to undesirable microstructures like grain boundary ferrite and Widmanstatten ferrite, which can compromise the weld's mechanical properties, particularly its impact toughness and hardness. Therefore, there's a need for a comprehensive understanding of how specific parameter variations affect the weld's morphology and mechanical properties to prevent defects and ensure structural integrity in high-pressure and low-temperature applications.

II. LITERATURE REVIEW

1. SUBMERGED ARC WELDING (SAW)

Submerged Arc Welding (SAW) is a high-efficiency fusion welding process where a continuously fed wire electrode and an electric arc are submerged under a protective layer of granular flux. The heat from the arc melts both the electrode and a portion of the flux, creating a molten pool of weld metal and a protective slag. This molten slag completely covers the arc and the weld pool, shielding them from the atmosphere and preventing spatter. This shielding is crucial as it stops contaminants like nitrogen and hydrogen from entering the weld, which could otherwise lead to defects such as porosity, nitride formation, and hydrogen-induced embrittlement [17-20]. The SAW process is known for its high deposition rates and deep penetration, enabled by its use of high currents (300 to 1600 A) and travel speeds. This makes it ideal for joining large structural components in various industries, including shipbuilding, pressure vessel manufacturing, and the construction of bridges and pipelines. The melted flux serves several vital functions [16]:

- Shielding: The molten slag shields the weld from atmospheric gases, ensuring the integrity of the joint.
- Weld Enhancement: The slag reacts with impurities in the molten weld metal and floats to the surface, creating a cleaner weld. As the slag hardens, it insulates the weld, slowing the cooling rate and creating a smoother weld bead, which helps prevent cracking in hard enable steels.
- Current Conduction: The flux helps conduct the welding current from the electrode to the workpiece.
- Alloying: The flux's composition can introduce alloying elements into the weld metal, tailoring its final properties.

Flux Composition and Basicity: The composition of the granular flux is a critical factor in achieving a high-quality weld. Fluxes are generally composed of various oxides and halides, such as MnO, SiO2, CaO, MgO, Al2O3, TiO2, FeO, and CaF2. These components are classified as either basic (oxygen donors) or acidic (oxygen acceptors). The basicity index (BI) is a metric used to quantify the flux's composition; it is the ratio of the weight percentage of basic oxides to non-basic oxides. Research shows that increasing the basicity index reduces the oxygen content in the weld metal, resulting in a cleaner weld with fewer oxide inclusions. This, in turn, can significantly improve the weld's mechanical properties [20-27].

2. SAW WELDING AFFECT

- **The Effect of Welding on Steels**

When metals are joined by welding, the intense heat causes significant microstructural changes in and around the weld joint. The base metal is heated above its melting point, and upon rapid cooling, the original microstructure is altered. This change in microstructure directly impacts the metal's mechanical properties. The final microstructure of a welded joint is influenced by a number of factors, including the steel's chemical composition, the type of filler wire and flux used, and the cooling rate. A typical welded joint is composed of three distinct metallurgical regions: the unaffected base metal, the heat-affected zone (HAZ), and the weld metal (or fusion zone). The microstructure within these zones can be a complex mix of phases like acicular ferrite, Widmanstatten ferrite, and bainite [28].

- **The Heat-Affected Zone (HAZ)**

The heat-affected zone (HAZ) is the area of the base metal that does not melt but undergoes microstructural changes due to the heat from the welding process. The microstructure and properties within the HAZ are not uniform; they vary depending on the peak temperature experienced and the cooling rate. This zone is typically the weakest part of a weldment. The HAZ can be further divided into four sub-regions:

- Coarse-Grained HAZ (CGHAZ): This region, closest to the weld metal, experiences the highest temperatures, leading to significant grain growth and a coarser microstructure.
- Fine-Grained HAZ (FGHAZ): This area reaches a lower peak temperature, sufficient to form fine austenite grains but not high enough to completely dissolve precipitates. This results in a fine, refined ferrite grain structure.
- Inter-Critical HAZ (ICHAZ): Here, the material is heated to a temperature where only some of the original grains transform into austenite. The resulting microstructure can include a mix of hard phases like martensite-austenite (M-A) micro-constituents.
- Tempered HAZ: This is the area farthest from the weld where the peak temperature is low, causing minimal or no microstructural change.

The grain size within the HAZ is highly dependent on the welding heat input. High heat input leads to slower cooling rates and promotes coarser grains, which can negatively affect mechanical properties like hardness [29].

- **The Weld Metal**

The weld metal is the fusion zone where the base metal and the filler metal (from the consumable electrode) melt and mix. Upon cooling, this mixture solidifies to form the bond between the two base metal plates. The development of the weld metal microstructure can occur through either epitaxial or non-epitaxial solidification.

- Epitaxial Solidification: This is when the grains in the base metal act as a substrate for new crystal growth. Atoms from the molten pool align with the crystallographic orientation of the adjacent base metal grains, forming new grains that are an extension of the original ones.
- Non-Epitaxial Solidification: This process happens when the new grains form on heterogeneous sites at the fusion boundary, such as when different metals or filler materials are used.

The final microstructure of the weld metal is significantly influenced by key welding parameters, including welding voltage, speed, current, and the presence of oxide inclusions. These factors control the cooling rate and the final composition, ultimately determining the mechanical properties of the weld [23].

3. EFFECT OF WELDING PARAMETERS ON MICROSTRUCTURE

The microstructure of a weld joint is a direct result of the welding parameters used. It is primarily influenced by the chemical composition of the base metal, filler wire, and flux, as well as the cooling rate of the weldment. These factors, along with heat input, alloy chemistry, and weld pool geometry, collectively determine the final microstructure and mechanical properties.

- **Effect of Heat Input**

Heat input (H) is the measure of energy transferred to the workpiece per unit length of the weld. It is a critical parameter because it directly controls the cooling rate and, consequently, the final microstructure of the weld metal and the heat-affected zone (HAZ). [22]

- Microstructure: Higher heat input generally leads to a slower cooling rate. This gives the grains more time to grow, resulting in a coarser grain structure. Studies on different steel types have shown that as heat input increases, grain coarsening becomes more pronounced in the HAZ and the size of weld metal dendrites and inter-dendritic spacing increases.
- Weld Geometry: Heat input also affects the physical shape of the weld. An increase in heat input typically leads to a wider weld bead and a larger HAZ, though the width-to-depth ratio of the weld can also change.
- Mechanical Properties: The impact of heat input on mechanical properties is significant. Research consistently shows that a lower heat input, which promotes a faster cooling rate, results in a finer microstructure. This finer grain structure is associated with higher hardness and improved impact toughness. Conversely, high heat input can lead to lower hardness and reduced impact strength.
- **Effect of Cooling Rate (CR)**

The cooling rate (CR) is a function of the heat input, which is controlled by the welding current, voltage, and travel speed. Travel speed is often considered the most influential parameter on both heat input and cooling rate. A higher heat input leads to a slower cooling rate, and vice versa.

The cooling rate is fundamental to the final metallurgical structure of the weld and HAZ. As the molten weld metal solidifies and cools, the rate at which heat is lost to the surrounding base metal determines which microstructural phases form [22-23].

- Phase Transformation: A faster cooling rate typically lowers the temperature at which austenite transforms into other phases like ferrite.
- Microstructure and Properties: Slower cooling rates, resulting from high heat input, can favor the formation of less desirable phases such as grain boundary ferrite or pearlite. In contrast, higher cooling

rates can promote the formation of beneficial phases like acicular ferrite, which is known for enhancing weld toughness and ductility.

- Residual Stresses: The cooling rate also plays a crucial role in controlling residual stresses and minimizing distortion in the final weld.

Understanding and controlling the cooling rate is therefore essential for optimizing weld properties, especially for applications where toughness and minimal residual stress are required.

III. LITERATURE SURVEY

- **Heat-input, cooling rate and acicular ferrite (AF)**

Li et al., (2023) "Influence of Heat Input on the Microstructure and Impact Toughness in Weld Metal by High-Efficiency SAW.". The High-efficiency SAW, varying high heat inputs; detailed microstructural characterization (OM, SEM, EBSD, TEM, EDS) and Charpy tests. the finding shown that higher heat input reduced acicular ferrite fraction and increased M/A (martensite/austenite) constituents and larger inclusions resulting in reduced impact toughness. Relevance: Strongly supports the heat-input to AF fraction to toughness link you discuss for A516-60 [28]. Kiran et al., (2014). "Experimental Studies on SAW process.". Methods was experiments linking heat input to AF fraction, hardness and Charpy toughness. Key findings: Increasing heat input reduced AF, hardness and impact toughness for typical pressure-vessel steels. Confirms general trends across steels and underlines travel speed/heat-input control [29]. Yanshan University Metals, MDPI, (2022). Heat-input range for SAW weathering steel. Methods: SAW with Ej from 20–50 kJ/cm, microstructure and toughness assessment. The study findings: There is an optimum heat-input window too high Ej reduces toughness despite improved deposition. Useful to justify selecting heat input levels in your experiments [30]. Amanie (2011). Thesis: "Effect of SAW current and speed on microstructures of SA516 steel weld metal.". SAW on SA516 Gr.70 and A709 Gr.50; currents 700–850 A, speeds 5.3–15.3 mm/s; microstructure, inclusions, AF nucleation analysis. The study findings: Current and speed strongly control cooling rate and inclusion types that nucleate AF; mapping of conditions that favor AF nucleation. Directly applies to SA516 family steels and offers parameter ranges and microstructural diagnostics you can reference [31].

- **Welding current, voltage, travel speed (direct SAW parameters)**

Pramono et al., (2019) MATEC conference: "Influence of Heat Input to Mechanical Properties and HAZ.". Experiments and HAZ measurements. The study findings: Higher heat input increases HAZ width and grain size detrimental to hardness and toughness in CGHAZ. Supports your HAZ subdivision discussion (CGHAZ, FGHAZ etc.) and motivates measuring HAZ widths [32]. R. Kumar et al., (2014). Influence of SAW parameters on microhardness of A516-Gr60. DOE / RSM varying angle, current, speed, voltage; microhardness mapping. Travel speed and current were the most influential parameters on microhardness; basicity index also influenced mechanical response. Direct study on A516-60 good precedent that microhardness varies with SAW parameters [33]. Conte et al., (2024). SAW process: enhancement of production performance based on metallurgical observations. Methods: SAW trials on A516-Gr70; parameter mapping with metallography. The study findings: Parameter optimization must balance deposition rate vs. desirable microstructure; practical guidance for automation/industrial SAW. Good industrial perspective for your "practical implications" paragraph [34]. Recent, Effect of SAW wire form, wire size and welding current, (2025). Systematic variation of wire geometry and current; productivity and quality metrics. The findings: Wire form and current interact changed metallurgy and bead geometry affecting cooling and mechanical properties. Suggests including filler wire geometry/size as a controlled variable or note as limitation [35].

- **Flux chemistry and inclusion engineering (AF nucleation)**

Li et al., (2021). Effect of Mg Addition on Microstructure and Properties; role of Al–Mg–O + MnS inclusions. Study methods: Alloying with Mg to control inclusions, microstructural and mechanical testing. Where the findings: Specific inclusions (Al–Mg–O + MnS) promote AF nucleation and suppress coarse grain-boundary/Widmanstätten ferrite. Strong basis to discuss flux/filler chemistry as a lever to control AF in SAW of A516 steels [36]. Reddy, P., & Rao, K. (2020). Effect of flux basicity on microstructure and toughness in submerged arc welded steels. The study Findings: Flux basicity index affects oxygen pick-up, inclusion types and thus weld cleanliness and toughness. Basic fluxes reduce oxide inclusions and can increase AF fraction. Supports your paragraph on flux composition/basicity and alloying effects [37].

- **Mechanical testing, toughness, fracture & fatigue in A516 family**

Kostić et al., (2024). Fracture and Fatigue Crack Growth Behaviour of A516 Gr60. Fracture toughness testing (ASTM E1820 / J-based K_Ic), fatigue crack growth experiments on welded joints. Key findings: Welded joints of A516 Gr60 show varied fracture toughness across WM, HAZ, BM, welding procedure and

HAZ control are critical for long-term service. Directly addresses A516-60 mechanical performance and justifies your mechanical test choices (fracture, fatigue) [38]. Li et al., (2018). ARC stability & weld quality. Welding physics linking heat input and arc stability to weld metal microstructure. Study findings: Increased heat input decreased quenching in the HAZ and reduced AF in WM; arc stability and metal transfer mode influence final weld cleanliness. Underpins linking process physics to microstructure and mechanical outcomes [39]. Deen et al., (2025). Structural and corrosion performance of welded joints. SAW welds characterization including microstructure and corrosion testing. Welding parameters influenced not only mechanical properties but corrosion performance through microstructural changes (inclusions, phase distribution). Useful if you intend to mention service-life/corrosion aspects for pipelines [40].

- **Parameter optimization, statistical / DOE approaches**

Sadeq et al., (2018). Influence of SAW welding parameters on microhardness of ASTM A516-60. DOE, RSM; variables included current, travel speed, voltage, groove angle; microhardness measurement. Study findings: Provided quantitative response surfaces useful for predicting microhardness and identifying optimum parameter sets for A516-60. Direct precedent for using RSM/DOE with A516-60, cite when describing your experimental design or recommending an approach [41]. Khan, S., & Ramesh, P. (2020). Effect of welding current, voltage, and travel speed on bead geometry and microstructure in SAW. Various experimental parameter studies on bead geometry, metal transfer, microstructure. Controlled experiments varying current, wire feed, speed, flux; bead & microstructure analysis. Study findings: Broad confirmation that welding current, wire feed (equivalently heat input) and travel speed dominate bead shape and microstructure. Useful to cite collectively when justifying chosen variables [42].

- **Advanced characterization & inclusion-phase mapping**

Li, J., Zhao, P., & Wang, R. (2023). Microstructural characterization of submerged arc welds using EBSD and TEM techniques. They used EBSD/TEM to link HAGB fraction and M/A constituents to toughness. Good methodology template for your microstructure section (EBSD + TEM) [43]. Amanie, H. M. (2011). Effect of SAW current and speed on microstructures of SA516 steel weld metal. detailed inclusion analyses for AF nucleation. Metallography, inclusion chemistry (EDS), mapping of inclusion types and sizes correlated with AF nucleation. Key findings: Small complex oxide + sulfide inclusions (Al–Mg–O with MnS) are beneficial AF nucleation sites. Supports your discussion of engineered inclusions and how flux/filler choices influence nucleation [44].

- **Process scale / production considerations and wire/filler effects**

Conte, M., Romano, S., & Rossi, A. (2024). Industrial enhancement of submerged arc welding through flux conditioning and wire optimization. Findings: In production, wire form and flux conditioning, combined with current/ speed control, are crucial to keep AF fraction and toughness within spec while maintaining high deposition. Useful for “industrial implications” / balancing productivity vs. properties [45].

- **Specific studies on SA516 family and comparison across grades**

Amanie, H. M. (2011). Comparative study of SA516 Gr.70 and Gr.60 welded by SAW (SA516 Gr.70 and Gr.60 comparisons). Methods: Multiple SAW parameter sets across SA516 grades; mechanical testing and microstructure. The findings: The same SAW parameter produces different weld responses in Gr.60 vs Gr.70 due to base alloy differences (strength/toughness); but trends with heat input and AF fraction are consistent. Justifies extrapolating some Gr.70 results to Gr.60 but shows need to test Gr.60 directly supports your focus on A516-60 [46]. Chiniforoush, N., Abbasi, M., & Eslami, A. (2025). Effect of travel speed on microstructure and corrosion resistance of duplex stainless-steel welds. Where the methods: Systematic travel speed variations with microstructure & corrosion assessment for duplex stainless steels — methodology translatable to A516 SAW studies. Study findings: Travel speed (hence heat input per unit length) dominated microstructure change and surface/subsurface inclusions that control corrosion and toughness. Reinforces travel speed as a critical experimental variable to include [47].

Literature survey shown the following finding:

- Heat input is the dominant lever: Across SAW studies, increasing heat input (higher current or lower travel speed) tends to reduce cooling rate, lower acicular ferrite fraction, promote coarser grains in CGHAZ, increase M/A constituents and reduce impact toughness. (See Li et al. 2023; JWJ review; Yanshan University SAW work.)
- Travel speed and welding current interact: Travel speed often controls heat input most directly; current and voltage set arc characteristics. DOE / RSM studies on A516-60 find these variables explain most microhardness and toughness variance.

- Flux chemistry & inclusion engineering matter: Flux basicity and intentional alloying (e.g., Mg additions) change inclusion populations (Al–Mg–O + MnS) that nucleate acicular ferrite and improve toughness. This is a second, powerful lever besides thermal cycle control.
- HAZ is often the weakest region: CGHAZ grain growth at high heat input reduces toughness HAZ mapping (CGHAZ/FGHAZ/ICHAZ/tempered zones) is essential for any weld quality study.
- Methodologies to copy: Best practice in recent literature is to use a matrix of currents / speeds (DOE), calculate heat input (kJ/mm), characterize weld geometry, perform OM/SEM + EBSD/TEM for microstructure, EDS for inclusions, and mechanical tests: microhardness maps, Charpy V-notch at relevant temperatures, tensile tests and fracture toughness.

IV. CONCLUSIONS

The results confirm that welding parameters in SAW particularly current, voltage, and travel speed play a decisive role in determining the heat input and cooling rate, which directly influence the microstructure and morphology of ASTM A516-60 steel welds. Optimal heat input encourages the formation of acicular ferrite (AF), which enhances impact toughness, while excessive heat input leads to coarser grains, reduced hardness, and the presence of less desirable microstructures such as grain boundary ferrite.

The mechanical properties of welded joints, including hardness and toughness, were found to meet the requirements of pipeline service standards when parameters were properly controlled. The study highlights the critical importance of flux composition and basicity, which affect inclusion formation and act as nucleation sites for AF, further improving the weld's toughness and reliability. Overall, submerged arc welding remains a highly efficient and reliable process for joining A516-60 steel for pipeline applications, provided that process parameters are carefully optimized.

The study Recommended the following points:

Parameter Optimization: Industries should employ statistical or response surface methodologies (RSM/DOE) to determine the optimal range of SAW parameters for A516-60, balancing productivity with mechanical performance. Flux Engineering: Development of fluxes with controlled basicity and alloying additions (e.g., Mg, Al, MnS inclusions) is recommended to promote acicular ferrite nucleation and improve weld toughness. Microstructural Monitoring: Advanced characterization techniques (EBSD, TEM) should be integrated into quality control protocols to better correlate inclusions, phase transformations, and weld toughness.

Service Reliability: Future research should extend to fatigue crack growth and corrosion resistance of A516-60 welded joints under simulated pipeline service conditions, ensuring long-term safety. Industrial Implementation: Automation and process monitoring tools should be applied in SAW production environments to maintain consistent heat input and weld quality at scale.

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