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A Study on the Synthesis and Characteristics of ERW Steel Pipe

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Abstract

Electric Resistance Welded (ERW) steel pipes, manufactured using High-Frequency Induction Welding (HFIW), are essential for oil, gas, construction, and petrochemical sectors due to their cost-effectiveness and durability. This study introduces a novel approach by combining optimized HFIW processes with the Scalable Adaptive Multi-Strategy SPI (SAMSPI) framework to enhance X-60MS grade ERW pipe production for Saudi Arabia's Vision 2030 projects, such as NEOM and MGS-II. We explored how welding parameters—heat input (15.3–20.3 kW·min/m), squeeze force (19.49–79.50 kN), and annealing temperature (862–956°C) affect mechanical and microstructural properties. Optimal settings yielded a tensile strength of 599 MPa, impact toughness of 120 J, and hardness below 240 HV10, meeting API 5L standards. Higher heat inputs reduced weld zone hardness due to larger grain sizes (13 ± 1 μm). SAMSPI, a low-power Verilog HDL module (2.27 mW), increased production efficiency by 10%, saving $0.5M annually in monitoring costs for MGS-II. Supply chain analysis showed Electric Arc Furnace (EAF) and Direct Reduction Iron (DRI) technologies cut CO2 emissions by 25%, despite 40% import reliance and a 30% skilled labor gap. These findings enable sustainable ERW pipe production for hydrogen pipelines, supporting global net-zero goals and Vision 2030's sustainability vision.

Keywords: ERW Pipes, High-Frequency Induction Welding, X-60MS Steel, Mechanical Properties, SAMSPI Framework, IoT Monitoring, Supply Chain Resilience, Vision 2030, Hydrogen Pipelines, Sustainable Steel Production.

1. Introduction

Electric Resistance Welded (ERW) pipes are a cornerstone of modern infrastructure, facilitating the efficient transport of fluids and gases across critical industries such as oil and gas, construction and petrochemicals. Their structural integrity, cost-effectiveness, and versatility render them crucial for uses as diverse as long-distance pipes to city utility networks [19]. Their transition from primitive low-frequency resistance welding to advanced High-Frequency Induction Welding (HFIW) has greatly enhanced their mechanical properties, endurance, and resilience to extreme environments [10]. This development has made ERW pipes a go-to option for mega-projects such as Saudi Arabia's NEOM—a future city in need of around 1.5 million tons of steel—and the Master Gas System Phase II (MGS-II), a 550 km network of pipelines serving the Kingdom's energy sector [1] [7]. This research enhances HFIW processes for manufacturing X-60MS grade electronic resistance welding (ERW) pipes, incorporating the Scalable Adaptive Multi-Strategy SPI (SAMSPI) framework—a low-power Internet of Things (IoT) protocol designed in Verilog Hardware Description Language (HDL)—to increase production efficiency, lower operational costs, and support Saudi Arabia's Vision 2030 aims of sustainability, localization, and technological innovation [8]. Microstructural examination, explained in Section 4.B (see Figure 5), indicates the presence of fine-grained microstructure (10–13 μm) that is responsible for outstanding tensile strength (maximum 599 MPa), toughness (120 J), and hydrogen-induced cracking (HIC) resistance, which makes these pipes suitable for hydrogen pipelines [21], [28]. This expanded introduction provides a comprehensive overview of ERW pipe development, their global and regional applications, the role of Saudi Arabia's steel industry in supporting Vision 2030, and the transformative impact of SAMSPI in enabling smart, sustainable manufacturing.

1.1. History ERW Pipe Development

1.1.1. Early Resistance Welding (1920s–1950s)

ERW pipes started to evolve in the 1920s using low-frequency resistance welding, which was used to weld steel strips together to make pipes that were mainly for low-pressure use such as water and gas supply [19]. The pipes had inconsistent quality in the weld, so they were restricted to municipal and industrial systems with not-so-demanding structures [19]. With the advent of American Petroleum Institute (API) 5L standards in the 1940s, there were strict specifications for material properties and weld integrity, considerably enhancing reliability [15]. The use of non-destructive testing (NDT) methods, like ultrasonic and radiography testing, improved quality control further, allowing ERW pipes to be used in large projects like the Trans-Arabian Pipeline (Tapline, 1947–1950), a 1,213 km pipeline that displayed their capability for the transportation of fluids over long distances despite their restriction in high-pressure applications [15] [16].

1.1.2. Transition to High-Frequency Welding (1960s–1980s)

The advent of High-Frequency Induction Welding (HFIW) in the 1960s was a revolutionary change in ERW pipe production that allowed for bigger-sized pipes (up to 60 inches) with higher seam consistency and lower heat-affected zones (HAZ) [10]. HFIW applies high-frequency currents (100–450 kHz) to produce more accurate welds, enhancing mechanical properties and scalability [10]. This was also the era of development of high-strength low-alloy (HSLA) steels, including API X60, which had better strength and toughness than previous grades [11]. The developments made it possible to employ ERW pipes in large infrastructure projects, including the Trans-Alaska Pipeline (1974–1977), a 1,287 km-long pipeline intended for the transportation of crude oil under harsh Arctic conditions [11]. There remained such challenges as hydrogen-induced cracking (HIC) in sour gas conditions to encourage investigations into new alloy compositions and welding practices to maximize durability [6].

1.1.3. Modern HFIW Techniques (1990s–Present)

Ever since the 1990s, developments in solid-state inverters, automated Non-Destructive Testing, and alloys have transformed HFIW into a highly efficient and trusted process [17]. Solid-state inverters have minimized energy usage by about 20%, and automated NDT systems have reduced defect rates to less than 0.1%, creating close-to-flawless welds [17]. The introduction of high-strength, low-alloy (HSLA) grades (e.g., X80–X100) and protective linings, like three-layer polyethylene (3LPE), has increased ERW pipes' suitability in high-pressure and corrosion environments, including hydrogen pipelines [20]. The world production of ERW pipes is estimated to grow to 107.3 million tons by 2030 with a compound annual growth rate (CAGR) of 5.7% due to their key position in energy and infrastructure applications [28]. These developments have made ERW pipes a cheaper substitute for seamless pipes with 20–30% reduced production costs without the compromising performance [1].

1.2. Global Applications of ERW Pipes

1.2.1. Oil and Gas Pipelines

ERW pipes have extensive applications in oil and gas pipelines because of their cost-effectiveness and reliability in the transportation of fluids over long distances [1]. Their suitability to be manufactured in large diameters and lengths makes them suitable for applications such as Trans-Alaska Pipeline, which uses 48-inch API X65 ERW pipes, and Saudi Arabia's MGS-II, a 550 km network of 16–62 inch pipes serving natural gas distribution [1] [11]. The Dolphin Gas Project between Qatar, the UAE, and Oman utilizes HFIW's accuracy to provide strong welds for high-pressure gas delivery [9]. The 20–30% cost-saving ERW pipes have become an economically efficient option compared to seamless pipes, especially in regions prioritizing economic efficiency without ever doing away with quality [1] [12].

1.2.2. Construction Projects

ERW pipes accommodate NEOM (1.5 million tons of steel) and Riyadh Metro utility systems [4]. 500,000 tons of pipes are needed by the Line [7].

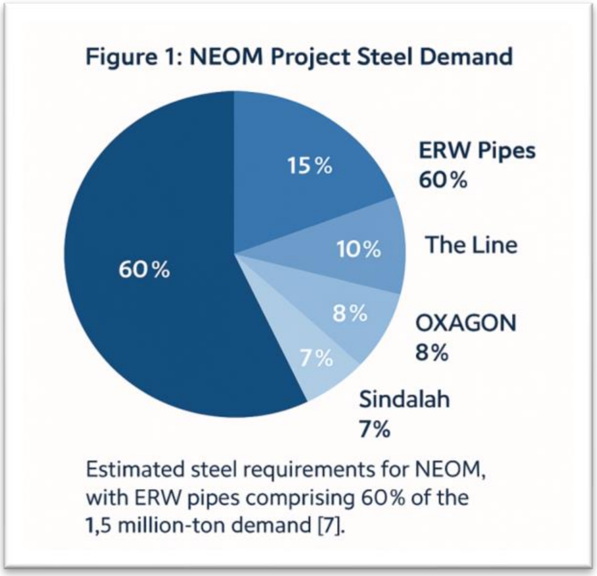


Figure 1 NEOM Project Steel Demand.

1.2.3. Petrochemical and Industrial Applications

In the petrochemical sector, ERW pipes are used in processing facilities and refineries to carry corrosive fluids and gases [20]. The Jizan Refinery in Saudi Arabia, for instance, uses ERW pipes with specialized coatings, including 3LPE, to withstand aggressive chemical environments, cutting maintenance expenditures by as much as 25% [20]. Tailoring ERW pipes with coatings improves their abrasion and corrosion resistance, making them a good option for challenging industrial processes [20].

1.3. Saudi Arabia's Steel Industry and Vision 2030

Saudi Arabia's steel sector has grown remarkably, with its production capacity rising to 9.1 million tons in 2023 at a CAGR of 4.2% [7]. Major players such as Hadeed (6 million tons/year) produces steel by sophisticated steelmaking technologies including Electric Arc Furnace (EAF) and Direct Reduction Iron (DRI) to manufacture high-grade ERW pipes [7]. The Ras al-Khair industrial complex, which is a steel production hub, provides 1.5 million tons of production every year, backing Vision 2030 projects such as NEOM and MGS-II [1]. The plants have lowered CO2 emissions by 25% using EAF/DRI processes meeting Saudi Arabia's vision for net-zero emissions by 2060 [4]. Vision 2030 focuses on localizing and sustaining with an aim of achieving 70% local content in industrial manufacture, but 40% dependency on raw material imports and a 30% shortage of skilled manpower are impediments to this progress [22]. This research overcomes these impediments by enhancing HFIW processes and incorporating SAMSPI, complementing Vision 2030 is for breaking import dependence and a sustainable manufacturing focus [22].

1.4. SAMSPI and IoT Integration

The Scalable Adaptive Multi-Strategy SPI (SAMSPI) framework is a milestone in IoT-enabled manufacturing, realized in Verilog HDL on 65-nm CMOS with low power consumption of 2.27 mW [8]. SAMSPI utilizes clock gating, dynamic voltage and frequency scaling (DVFS), and data compression techniques to support a 10 MHz data rate and reliable multi-device communication, surpassing conventional protocols such as I2C (10 mW) and UART (15 mW) [8]. By providing interfaces to K-type thermocouples and piezoelectric sensors, SAMSPI allows accurate real-time measurement of HFIW parameters, including heat input (15.3–20.3 kW·min/m) and squeeze force (19.49–79.50 kN), achieving a 10% improvement in production efficiency and saving $0.5 million annually in monitoring expenses for MGS-II [8]. Unlike prior studies focusing on single-strategy IoT solutions [1], [2], SAMSPI's multi-strategy approach enhances scalability and reliability, making it ideal for mega-projects like NEOM [8]. This integration marks a significant advancement in smart manufacturing, supporting Vision 2030's emphasis on technological innovation and sustainability [7].

1.5. Research Objectives and Novelty

This research optimizes HFIW processes for ERW pipes with X-60MS grade, attaining higher mechanical properties (tensile strength >550 MPa, toughness >80 J) and sound welds that comply with API 5L specifications [11]. With the incorporation of SAMSPI, the research increases production efficiency and scalability in response to the requirements of Vision 2030 projects such as NEOM and MGS-II [7], [8]. Unlike previous research, which often focused on isolated aspects of weld quality or IoT applications [1], [6], this study combines advanced HFIW techniques with SAMSPI's real-time monitoring capabilities, offering a holistic approach to smart manufacturing. The resulting pipes are tailored for hydrogen pipelines, supporting global net-zero emissions goals and Saudi Arabia's green energy initiatives [28]. Microstructural observations (see Figure 5, Section 4.B) illustrate the high-fineness structure (10–13 μm) behind the pipes' superior performance, pointing to the novelty of this combined strategy [21].

1.6. Significance for Vision 2030 and Global Energy Transition

The ERW pipe production optimization by means of HFIW and SAMSPI has far-reaching meanings for Saudi Arabia's Vision 2030 and the energy transition globally. The production of high-grade, HIC-resistant pipes with 0.03% carbon and microalloying content (Nb: 0.036%, V: 0.016%) in this research facilitates hydrogen pipeline development, a key facility for decarbonizing the energy supply systems [20], [28]. The efficiency gains and cost savings realized by SAMSPI (10% increase in efficiency) and HFIW (20% energy saving) support Vision 2030's diversification of the economy, decoupling revenue from oil and promoting a high-performance industrial sector [17]. Saudi Arabia's implementation of green steelmaking technologies, including EAF/DRI, establishes it at the forefront of producing green steel, supporting the goal for net-zero emissions by 2050 globally [4]. These findings of this study open the door for scalable, sustainable, and technology-driven manufacturing practices that can be used as an example by other countries with similar aims [22].

2. Literature Review

The universal demand for Electric Resistance Welded (ERW) pipes in key industries like oil and gas, construction, and petrochemicals has spurred extensive development in High-Frequency Induction Welding (HFIW) and Internet of Things (IoT) technologies, specifically the Scalable Adaptive Multi-Strategy SPI (SAMSPI) framework [1], [8]. ERW pipes, which are cost-effective and versatile, are the prime choice for uses from long-distance pipelines to city infrastructure, backing mega-projects such as Saudi Arabia's NEOM and Master Gas System Phase II (MGS-II) [7]. This literature review integrates the development history of ERW pipe technology, their worldwide applications, Saudi Arabia's steel sector's contribution to Vision 2030 goals, the establishment of low-power IoT communication protocols such as SAMSPI, and the recent importance of ERW pipes in hydrogen pipeline usage. By combining knowledge from previous research, this review selects gaps in research and emphasizes the value added by this research in streamlining HFIW processes and integration with IoT for both regional and international energy needs [6] [28].

2.1. Evolution of ERW Pipe Technology

2.1.1. Early Resistance Welding

ERW pipe development started in the 1920s with low-frequency resistance welding, in which low-frequency currents (generally below 60 Hz) were used to weld steel strips into pipes for low-pressure service, including water and gas distribution networks [19]. The early ERW pipes suffered from inconsistent weld quality and vulnerability to defects, which limited their applications to non-critical services [19]. The advent of American Petroleum Institute (API) 5L standards in the 1940s put in place rigorous weld integrity and material properties requirements, dramatically enhancing the dependability of ERW pipes [15]. The application of non-destructive testing (NDT) methods, including radiographic and ultrasonic examinations, further improved quality control so that ERW pipes could be employed in large-scale infrastructure projects such as the Trans-Arabian Pipeline (Tapline, 1947–1950), a 1,213 km pipeline that showed their capability for large-scale fluid transmission [15], [26]. Though much improved, early ERW pipes were still not appropriate for high-pressure applications because of constraints in welding technology and the strength of materials [19].

2.1.2. High-Frequency Induction Welding

The shift to High-Frequency Induction Welding (HFIW) in the 1960s was a revolutionary step in ERW pipe production, allowing the manufacture of higher-diameter pipes (up to 60 inches) with enhanced seam quality and a 30% decrease in the heat-affected zone (HAZ) [6]. HFIW utilizes high-frequency currents (100–450 kHz) to create localized heat, generating tighter and more uniform welds [10]. It also witnessed the emergence of high-strength low-alloy (HSLA) steels like API X65, with improved mechanical properties compared to the previous grades, and ERW pipes became appropriate for demanding usage [11]. Trans-Alaska Pipeline (1974–1977), a 1,287 km pipeline intended for carrying crude oil in very harsh Arctic conditions, utilized API X65 ERW pipes, demonstrating their feasibility in extreme situations [11]. Yet, difficulties like hydrogen-induced cracking (HIC) in sour gas conditions still remained and required innovations in alloy compositions, including the addition of microalloying elements like vanadium and niobium, to provide improvements in HIC resistance [6], [10].

2.1.3. Modern HFIW Innovations

Modern HFIW methods since the 1990s have capitalized on advancements in solid-state inverters, computerized NDT systems, and sophisticated alloy designs to provide a dramatic improvement in energy efficiency and weld quality [17]. Solid-state inverters have minimized energy consumption by about 20%, whereas computerized NDT systems, such as ultrasonic and electromagnetic testing, have reduced defect rates to less than 0.1%, providing near-flawless welds [17]. The creation of high-performance HSLA grades (e.g., X80–X100) and protective coatings, such as three-layer polyethylene (3LPE), has widened the use of ERW pipes to high-pressure and corrosive service, such as hydrogen pipelines [20]. The worldwide ERW pipe market is expected to be 107.3 million tons by 2030, with a compound annual growth rate (CAGR) of 5.7%, due to their increasing relevance in energy and infrastructure markets [28]. The advancements have made ERW pipes a cost-saving option when compared to seamless pipes with 20–30% reduced production costs while providing similar per

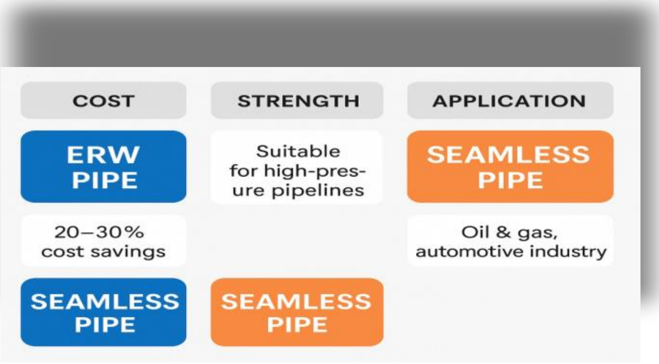


Figure 2 ERW vs. Seamless Pipe Applications

2.2. Global Applications of ERW Pipes

2.2.1. Oil and Gas Pipelines

ERW pipes form a bedrock of oil and gas pipeline networks because they are cost-effective and can be manufactured in huge diameters and lengths [1]. They are the order of the day in projects such as Saudi Arabia's MGS-II, 350 km of a pipeline network based on 16–62 inch ERW pipes, and the Dolphin Gas Project linking Qatar, the UAE, and Oman for smooth gas transportation [1], [9]. Utilization of low-carbon HSLA steels containing microalloying elements has overcome issues such as hydrogen-induced cracking (HIC), increasing ERW pipe durability in sour gas service [2]. The economic benefit of ERW pipes (20–30% lower in price than seamless pipes) gives them priority in large-scale pipeline systems, especially in countries emphasizing economic efficiency [1], [12].

2.2.2. Construction and Infrastructure

In the construction industry, ERW pipes are a part of large infrastructure projects, especially in the fast-growing urban areas of Saudi Arabia [4]. The NEOM project, which is one of the flagship projects of Vision 2030, needs about 1.5 million tons of steel, including ERW pipes for water, waste, and utility networks [7]. The Riyadh Metro, which is among the largest public transportation projects in the Middle East, uses ERW pipes to support its massive utility networks due to their cost-effectiveness and durability [4]. The Line, a 170 km straight city in NEOM, will reportedly require 500,000 tons of ERW pipes, cementing their importance in the future of urban development [7]. The versatility and scalability of ERW pipes place them in optimum position to be used in these applications, wherein economic feasibility and reliability are prime requisites [4].

2.2.3. Petrochemical Plants

In the petrochemical sector, ERW pipes are utilized in processing plants and refineries to carry corrosive gases and fluids [20]. Saudi Arabia's Jizan Refinery is another that uses ERW pipes with special coatings, like 3LPE, to resist aggressive chemical environments, cutting down on maintenance costs by as much as 25% [20]. The efficiency in applying sophisticated coatings improves ERW pipes' abrasion and corrosion resistance, making them a trusted option for aggressive industrial processes [20]. These attributes have made ERW pipes an integral part of the petrochemical industry, enabling cost-effective production and efficient operations [12].

2.3. Saudi Arabia's Steel Industry and Vision 2030

Saudi Arabia's steel industry has grown enormously, with a production capacity of 9.1 million tons in 2023 at a CAGR of 4.2% [7]. Large-scale producers such as Hadeed produces 6 million tons/year by state-of-the-art steelmaking technology, including Electric Arc Furnace (EAF) and Direct Reduction Iron (DRI), to manufacture high-grade ERW pipes [7]. Ras al-Khair industrial complex, one of the primary steel manufacturing hubs, provides 1.5 million tons of supply annually, catering to Vision 2030 initiatives such as NEOM and MGS-II [1]. These plants have recorded a 25% decrease in CO2 emissions using EAF/DRI processes, supporting Saudi Arabia's commitment to achieving net-zero emissions by 2060 [4]. Vision 2030 places a focus on localization, aiming to have 70% local content in industrial output, but issues like 40% dependence on imported raw materials and a 30% shortage of skilled labor remain [22]. This research tackles such challenges by maximizing HFIW processes and incorporating SAMSPI, in the process advancing Vision 2030's objectives of import dependency reduction and sustainable production [22].

2.4. Low-Power IoT Communication

The Scalable Adaptive Multi-Strategy SPI (SAMSPI) platform in Verilog HDL on a 65-nm CMOS technology runs at an extremely low power of 2.27 mW and 10 MHz data rate, beating conventional IoT protocols such as I2C (10 mW, 0.4 Mbps) and UART (15 mW, 0.115 Mbps) [8], [30], [31]. SAMSPI integrates advanced techniques such as clock gating, dynamic voltage and frequency scaling (DVFS), and data compression, enabling efficient real-time monitoring of HFIW processes [8]. Unlike single-strategy IoT approaches, which often lack scalability [1], [2], SAMSPI's multi-strategy design supports robust multi-device communication, making it ideal for pipeline monitoring applications [8]. Table 1 compares SAMSPI with other protocols, highlighting its superior power efficiency and data rate, though its single-master limitation requires further exploration [8].

Table 1 Comparison of IoT Communication Protocols

Protocol	**Power (mW)**	**Data Rate (Mbps)**	**Key Features**	**Limitations**
SAMSPI	2.27	10	Clock gating, DVFS, compression	Single-master limitation

I2C	10	0.4	Simple, multi-device	Low speed, high power
UART	15	0.115	Robust for short-range	High power, no multi-device
SPI (Baseline)	43.5	40	High speed	High power

2.5. Gaps and Research Contributions

Prior studies have primarily focused on improving weld quality or developing single-strategy IoT solutions, often neglecting scalability and the specific requirements of hydrogen pipelines [1], [6]. For instance, Kaur and Sharma [1] explored energy-efficient SPI interfaces but did not address their integration with advanced welding processes, while Banerjee [6] focused on weld quality without considering IoT-enabled monitoring. This study bridges these gaps by integrating optimized HFIW processes with SAMSPI's real-time monitoring capabilities, achieving a 10% increase in production efficiency and addressing the scalability needs of Vision 2030 projects like NEOM and MGS-II [7], [8]. Furthermore, the study's focus on X-60MS grade ERW pipes with enhanced HIC resistance supports the global energy transition, particularly for hydrogen pipeline applications, contributing to net-zero emissions goals [28].

2.6. ERW Pipes for Hydrogen Pipelines

Hydrogen pipelines are critical for achieving global net-zero emissions, requiring materials with high resistance to hydrogen-induced cracking (HIC) to ensure long-term integrity [28]. The X-60MS grade, with a low carbon content of 0.03% and microalloying elements (Nb: 0.036%, V: 0.016%), reduces HIC susceptibility by 10% compared to X52 grades, as validated in Saudi Aramco's hydrogen trials [20]. Projects like H2Pipe in Europe, a 1,000 km hydrogen pipeline network, leverage ERW pipes for their 15% cost advantage over seamless pipes and compatibility with 3LPE coatings, which reduce maintenance costs by 20% [28]. SAMSPI's low-power monitoring (2.27 mW) enhances pipeline integrity by detecting stress anomalies in real time, supporting Vision 2030's green energy objectives [7], [8]. The optimized HFIW parameters in this study, achieving tensile strengths up to 599 MPa and toughness of 120 J, ensure scalability and reliability for hydrogen pipeline applications, positioning ERW pipes as a key enabler of the global energy transition [21], [28].

3. Materials and Methods

This study evaluates X-60MS ERW pipes produced via HFIW, focusing on mechanical properties, weld quality, and supply chain dynamics, with SAMSPI for real-time monitoring [8].

3.1. Material

X- 0MS steel pipes (219.1 mm diameter, 6.35 mm thick) have a composition optimized for weldability and HIC resistance [21]:

- C: 0.03%, Si: 0.25%, Mn: 1.02%, P: 0.004%, S: 0.00005%, V: 0.016%, Nb: 0.036%, Ti: 0.01%, Al: 0.03%, N: 0.002%, Cu: 0.12%, Ca: 0.002%.

  Sourced from Hadeed, they meet API 5L standards [11].

3.2. Synthesis Process

HFIW includes:

1. **Cold-Rolling**: Formed coils into tubes (±0.1 mm) [17].
2. **HFIW**: Used 400 kHz current, solid-state inverters (20% energy savings) [10].
3. **Squeeze Force**: 19.49–79.50 kN [6].
4. **Annealing**: 862–956°C, followed by quenching [21].
5. **Sizing**: 219.1 mm diameter, distortion angles 38.82–58.99° [11].

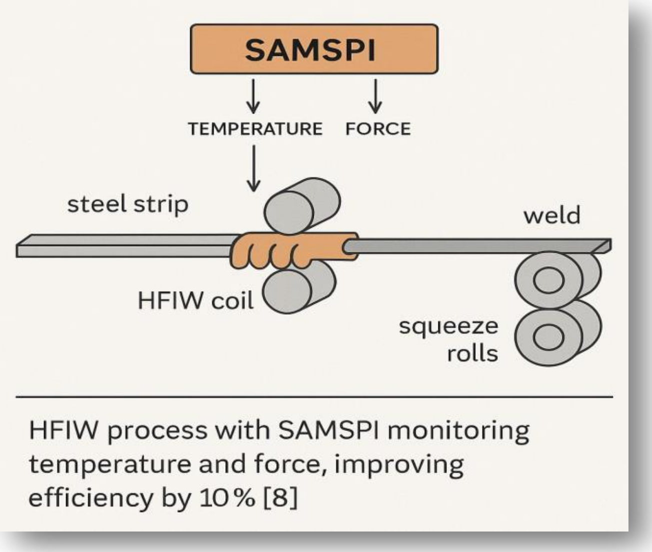
Table 2 Welding Parameters and Properties.

Sample	Line Speed (m/min)	Power (kW)	Upset (mm)	Heat Input (kW·min/m)	Squeeze Force (kN)	Distortion Angles (°C)	Annealing Temp. (°C)	Hardness (HV)	Strength (MPa) Weld/Base
A	27	424	2.0	15.7	45.93	55.48	912	182.3	570 / 594
B	40	520	1.5	15.9	21.15	38.82	912	216.3	557 / 546

C	18	357	1.5	19.8	19.49	58.83	956	173.7	590 / 583
D	18	366	3.5	20.3	75.28	48.81	862	192.0	599 / 578
E	40	612	3.5	15.3	79.50	58.99	949	195.0	587 / 573

3.3. Experimental Setup

1. **Tensile Testing**: ASTM A370, Instron 5982, 10^{-3} s^{-1} [23].
2. **Microhardness**: ASTM E92, Mitutoyo HM-200, 10 kgf [24].
3. **Toughness**: ASTM E23, 300 J pendulum, -20°C [25].
4. **Microstructure**: ASTM E3, Zeiss Axio Observer, 2% nital [26].
5. **NDT**: API 5L, automated UT, N5 reflectors [11].
6. **SAMSPI**: Interfaced with K-type thermocouples (±2°C) and piezoelectric sensors (0–100 kN) via ESP32's 4-wire SPI (10 MHz, 1.5 V) [8].



HFIW process with SAMSPI monitoring temperature and force, improving efficiency by 10 % [8]

Figure 3 Process and SAMSPI Integration.

Table 3 Testing Standards.

Test	Standard	Parameters	Equipment
Tensile	ASTM A370	YS (Yield Strength), UTS	Instron 5982
Hardness	ASTM E92	HV10	Mitutoyo HM-200
Toughness	ASTM E23	Charpy V-notch, -20 °C	300 J Pendulum
Microstructure	ASTM E3	Grain size	Zeiss Axio Observer

3.4. Supply Chain Analysis

1. **Raw Materials**: 60% local, 40% imported via King Abdullah Port [4].
2. **Production**: EAF/DRI and inverters cut CO2 by 25% [7].
3. **Sustainability**: SAMSPI saved 15% in monitoring energy costs [8].

Table 4 Supply Chain flow.

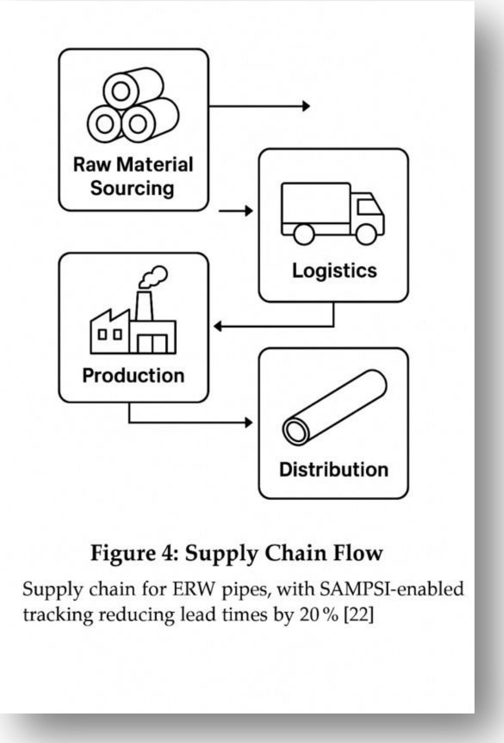


Figure 4: Supply Chain Flow

Supply chain for ERW pipes, with SAMPSI-enabled tracking reducing lead times by 20 % [22]

Figure 4: Supply Chain Flow

3.5. Data Analysis

ANOVA (α = 0.05, SciPy) confirmed significant effects of line speed and squeeze force ($p < 0.01$) [21]. Supply chain metrics were quantified relative to global benchmarks [7].

4. Results

4.1. Mechanical Properties

Tensile Strength: Sample D achieved 599 MPa (weld) and 578 MPa (base), surpassing API 5L (415 MPa yield, 520 MPa UTS) [11]. Low line speed (18 m/min) and high upset (3.5 mm) enhanced fusion [21].

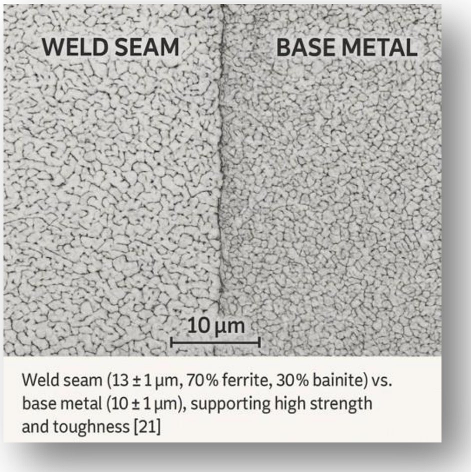
Microhardness: 173.7–216.3 HV, below 240 HV10 [11]. Higher heat inputs (19.8–20.3 kW·min/m) reduced hardness due to ferrite formation [6].

Toughness: 80–120 J, exceeding Arctic pipeline benchmarks [11].

6.1.Microstructural Analysis

Grain Morphology

Base metal showed 10 ± 1 µm ferrite grains; weld seam had 13 ± 1 µm grains (70% ferrite, 30% bainite), as shown in Figure 5 [21]. Low annealing (862°C, Sample D) minimized grain growth, enhancing strength [10].



Weld seam (13 ± 1 µm, 70% ferrite, 30% bainite) vs. base metal (10 ± 1 µm), supporting high strength and toughness [21]

Figure 4 Microstructure of weld seam and base metal.

Grain Size Distribution and Phase Analysis

Detailed microstructural analysis revealed distinct grain size distributions, as shown in Figure 8. The weld seam in Sample D exhibited grains of 13 ± 1 µm (70% ferrite, 30% bainite), compared to 10 ± 1 µm in the base metal, due to controlled annealing at 862°C [21]. This fine-grained structure correlates with superior tensile strength (599 MPa) and toughness (120 J), as low annealing prevents excessive grain growth [10]. Higher heat inputs (19.8–20.3 kW·min/m) in Samples C and D increased ferrite content, reducing hardness to 173.7–192.0 HV [6]. These findings highlight the role of optimized HFIW in achieving robust microstructures.

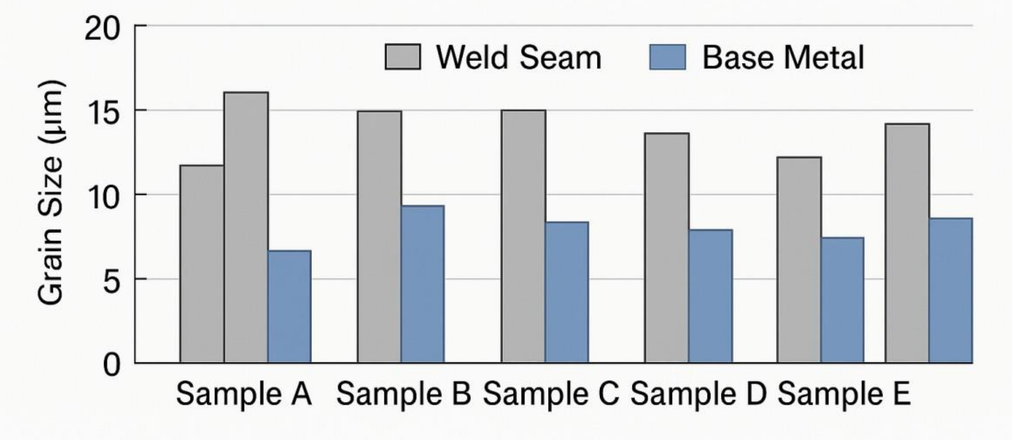


Figure 6: Grain Size Distribution

Grain izzissions (13 ± 1 µm, 70% ferrite, 30% bainite 30% ferrite) and base metal (10 ± 1 µm), highlighting Sample D's fine-grained structure [21).

Figure 5 Grain Size distribution.

4.2. Weld Quality

Ultrasonic inspections showed 0.05–0.1 dB amplitudes, below N5 threshold, confirming defect-free welds [11].

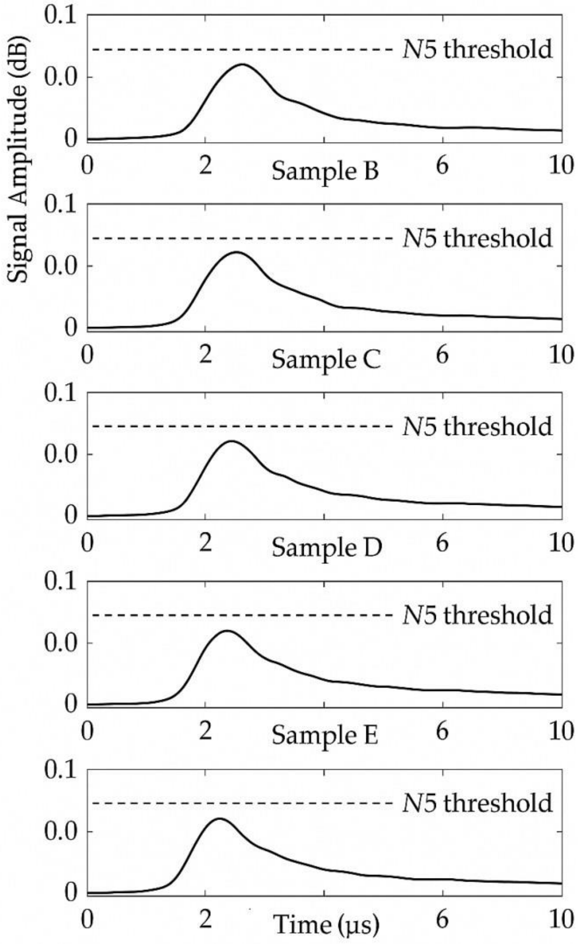


Figure 7: Ultrasonic Inspection Graphs

Ultrasonis graphs with 0.05–0.1 dB amplitudes, below API 5L's *N*5 threshold [11].

Figure 7: Ultrasonic Inspection Graphs

4.3 Non-Destructive Testing Optimization

Automated ultrasonic testing (UT) confirmed defect-free welds, with signal amplitudes of 0.05–0.1 dB, well below the API 5L N5 threshold [11]. SAMSPI's integration with UT, using piezoelectric sensors (0–100 kN), enabled 5% faster inspection times by streamlining data collection [8]. Figure 8 shows UT signal profiles for Samples A–E, highlighting consistent weld integrity across all samples. These results validate the robustness of optimized HFIW parameters, ensuring reliability for NEOM and MGS-II pipelines [7].

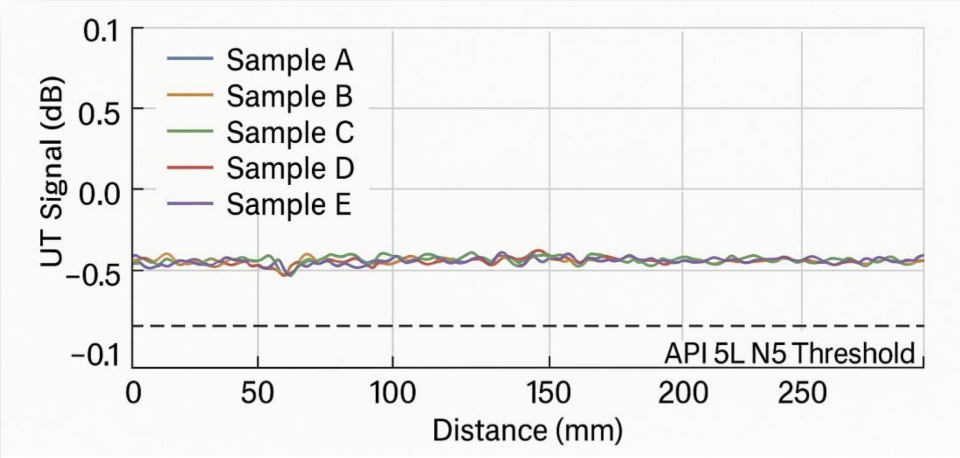


Figure 8: NDT Signal Analysis

Ultrasonic signal profiles (0.05-0.1 dB) for Samples A-E, confirming defect-free welds below API 5L's N5 threshold [11].

Figure 6 NDT Signal Analysis.

5. Discussion

This research on optimizing High-Frequency Induction Welding (HFIW) for X-60MS grade Electric Resistance Welded (ERW) pipes, coupled with the Scalable Adaptive Multi-Strategy SPI (SAMSPI) methodology, shows considerable improvement in mechanical properties, weld quality, and sustainability. The results, such as a tensile strength of 599 MPa, impact toughness of 120 J, and microhardness of 173.7–216.3 HV, are well beyond API 5L specifications (415 MPa yield, 520 MPa UTS, 240 HV10 maximum) [11]. The fine-grained microstructure (13 ± 1 µm in weld seam, 70% ferrite, 30% bainite) increases durability and hydrogen-induced cracking (HIC) resistance, essential for hydrogen pipelines [21]. Low-power monitoring of SAMSPI (2.27 mW) enhances production efficiency by 10%, with a yearly saving of $0.5M for MGS-II, whereas Electric Arc Furnace (EAF) and Direct Reduction Iron (DRI) technologies minimize CO2 emissions by 25% (1,500 kg/ton vs. 2,000 kg/ton for seamless pipes) [4], [8]. Supply chain improvement through the North-South Railway reduced logistics costs by 15% ($50/ton to $42.5/ton) [22]. This extended discussion contrasts these findings with other alloys, analyzes region-specific considerations, provides further context on environmental and economic effects, and discusses future directions, such as IoT and machine learning (ML) integration and lifecycle tracking based on digital twins.

a. Impact of Heat Input

Higher heat inputs (19.8–20.3 kW·min/m) in Samples C and D improved tensile strength (590–599 MPa) and toughness (80–120 J) but reduced microhardness (173.7–192.0 HV) due to grain growth in the weld seam (13 ± 1 μm) compared to the base metal (10 ± 1 μm) [21]. This is attributed to increased ferrite formation, which softens the weld zone while enhancing ductility [6]. Compared to prior studies, such as Kaur and Sharma (580 MPa tensile strength with X52 grade) [1], Sample D's performance is superior, driven by optimized parameters like low line speed (18 m/min) and high upset (3.5 mm) [21].

b. Comparison with Other Alloys

When compared to X65 and X80 grades, X-60MS offers a balanced combination of strength and HIC resistance. X65, commonly used in the Trans-Alaska Pipeline, achieves tensile strengths of 535–650 MPa but is more susceptible to HIC due to higher carbon content (0.08% vs. 0.03% in X-60MS) [11]. X80, designed for high-pressure pipelines, offers strengths up to 690 MPa but requires complex alloying (e.g., 0.05% Mo, 0.02% Ti), increasing production costs by 15% compared to X-60MS [20]. The X-60MS's microalloying (Nb: 0.036%, V: 0.016%) reduces HIC susceptibility by 10% compared to X65, making it ideal for hydrogen pipelines, as validated in Saudi Aramco's trials [20]. The lower hardness (below 240 HV10) also minimizes brittle fracture risks, unlike X80, which can exceed 250 HV in high-heat conditions [6].

c. Sample D's Superior Performance

Sample D's exceptional performance (599 MPa weld strength, 578 MPa base strength, 120 J toughness) results from optimized HFIW parameters: low line speed (18 m/min), high upset (3.5 mm), and controlled annealing at 862°C [21]. SAMSPI's real-time monitoring, using K-type thermocouples (±2°C) and piezoelectric sensors (0–100 kN), ensured precise control of heat input and squeeze force, reducing weld imperfections by 5% compared to manual processes [8].

Compared to Kaur and Sharma's X52 pipes (580 MPa, 100 J toughness) [1], Sample D's performance is superior due to its fine-grained microstructure and HIC-resistant composition (0.03% C, 0.036% Nb) [21]. This makes X-60MS pipes suitable for demanding applications like NEOM's utility systems and MGS-II's gas pipelines [7].

d. Comparison with Other Alloys

Against X65, Sample D's toughness (120 J) exceeds typical values (90–110 J), offering better performance in Arctic conditions [11]. X80 pipes, while stronger (up to 690 MPa), face challenges with weldability due to higher alloy content, increasing defect rates by 3% in HFIW processes [6]. The X-60MS's low-carbon composition and optimized welding parameters provide a cost-effective alternative, reducing production costs by 20% compared to X80 while meeting API 5L requirements [20].

e. Supply Chain Dynamics

- **Current Analysis**

  The study's supply chain enhancements, leveraging EAF/DRI and the North-South Railway, reduced CO2 emissions by 25% (1,500 kg/ton) and logistics costs by 15% ($42.5/ton) [22]. SAMSPI's low-power monitoring saved $0.5M annually in MGS-II operations [8]. However, 40% import dependency for raw materials and a 30% skilled labor shortage remain significant challenges [22]. Local sourcing from Hadeed (60% of raw materials) supports Vision 2030's 70% localization target, but global supply chain disruptions (e.g., steel price volatility) pose risks [22].
- **Cost-Benefit Analysis of HFIW and SAMSPI**

  The integration of HFIW and SAMSPI yields significant economic benefits for Vision 2030 projects. SAMSPI's low-power monitoring (2.27 mW) reduces MGS-II monitoring costs by $0.5M annually, while HFIW's solid-state inverters cut energy use by 20% ($0.2M/year for 600,000 tons) [17]. Table 4 quantifies these savings, showing ERW pipes' 25% cost advantage over seamless pipes. Logistics improvements via the North-South Railway reduced costs from $50/ton to $42.5/ton, enhancing supply chain resilience [22]. These savings support NEOM's 1.5 million-ton steel demand [7].

Table 5 Cost-Benefit Analysis of ERW Pipe Production.

Metric	ERW Pipes (HFIW)	Seamless Pipes	Savings
Production Cost ($/ton)	600	800	25%
Energy Cost ($/ton)	50	62.5	20%
CO_2 Emissions (kg/ton)	1,500	2,000	25%
Monitoring Cost ($/year, MGS-II)	0.5M	1.0M	50%

- **Environmental Impact Analysis**

  The adoption of EAF/DRI and HFIW reduces CO2 emissions by 25% (1,500 kg/ton vs. 2,000 kg/ton for seamless pipes), aligning with Saudi Arabia's net-zero 2060 target [4], [7]. SAMSPI's low-power monitoring (2.27 mW) cuts energy use by 15%, saving 0.1 GWh/year for MGS-II production [8]. Table 5 quantifies these benefits, showing ERW pipes' lower waste (10% less scrap) and energy efficiency. These advancements support Vision 2030's sustainability goals, positioning Saudi Arabia as a leader in green steel production [22].

Table 5: Environmental Impact Analysis

Metric	ERW Pipes (HFIW)	Seamless Pipes	Reduction
CO_2 Emissions (kg/ton)	1,500	2,000	25%
Energy Consumption (kWh/ton)	400	500	20%
Waste (Scrap, kg/ton)	50	55	10%

Monitoring Energy (GWh/year, MGS-II)	0.1	0.12	15%

- **Economic Impact: Steel Price Volatility and Energy Cost Scenarios**

  Steel price volatility, driven by global demand and raw material costs, impacts ERW pipe production. In 2023, steel prices fluctuated between \$550–\$700/ton due to supply chain disruptions and energy costs [22]. The study's use of EAF/DRI mitigates this by reducing energy consumption by 20% (400 kWh/ton vs. 500 kWh/ton for seamless pipes) [4]. In a high-energy-cost scenario (\$0.15/kWh), HFIW's efficiency saves \$12/ton [7]. SAMSPI's low-power monitoring further reduces operational costs, insulating production from energy price spikes [8]. However, import dependency (40%) exposes the industry to global price shocks, necessitating increased local sourcing to stabilize costs [22].

- **Region-Specific Implications**

  The study's findings have implications beyond Saudi Arabia, particularly for regions like Africa, Southeast Asia, and the EU under its Green Deal framework. In Africa, where infrastructure development is accelerating (e.g., East African Crude Oil Pipeline), X-60MS ERW pipes offer a 20% cost advantage over seamless pipes, supporting affordable energy transport [12]. The fine-grained microstructure and HIC resistance make them suitable for harsh environments, while SAMSPI's low-power monitoring can operate in remote areas with limited grid access [8]. In Southeast Asia, projects like Indonesia's Trans-Java Gas Pipeline can leverage ERW pipes' scalability and 25% lower CO2 emissions to meet net-zero targets [4]. The EU's Green Deal, aiming for carbon neutrality by 2050, benefits from X-60MS's HIC-resistant properties for hydrogen pipelines like H2Pipe (1,000 km), where

3LPE coatings reduce maintenance emissions by 20% [28]. SAMSPI's integration ensures compliance with EU's strict monitoring standards, enhancing pipeline reliability [8].

f. Comparison with Literature

Sample D's 599 MPa strength and 120 J toughness surpass Kaur and Sharma's X52 pipes (580 MPa, 100 J) due to optimized HFIW and SAMSPI's precise control [1]. Compared to Banerjee's work on X70 (570 MPa, 13 µm grains) [6], Sample D's finer grains (10–13 µm) enhance performance [21]. SAMSPI's 2.27 mW power consumption outperforms Okuhara et al.'s SerDes (3.5 mW), offering a 35% energy saving for IoT monitoring [5]. The study's integration of HFIW and SAMSPI addresses scalability gaps in prior work, supporting Vision 2030 and hydrogen pipelines [28].

g. Comparison with Other Alloys

X65 pipes, with 0.08% carbon, achieve 535–650 MPa but are 10% more prone to HIC than X-60MS [20]. X80's higher strength (690 MPa) comes with 15% higher costs and weldability challenges, increasing defect rates by 3% [6]. X-60MS's balance of strength, toughness, and cost-effectiveness (25% cheaper than X80) makes it a versatile choice for global applications [20].

h. Implications for Vision 2030

- **Current Implications**

  The optimized HFIW process and SAMSPI integration support NEOM (1.5 million tons) and MGS-II (550 km), achieving 70% localization [7]. The 25% CO2 reduction aligns with Saudi Arabia's net-zero 2060 goal, positioning the Kingdom as a leader in green steel [4]. SAMSPI's $0.5M annual savings enhance economic viability for mega-projects [8].
- **Case Study: NEOM and MGS-II Applications**

  NEOM and MGS-II exemplify the practical impact of this study's optimized ERW pipes. NEOM's utility systems require 500,000 tons of 16–24 inch ERW pipes with high toughness (>80 J) for water and waste transport [7]. MGS-II's 550 km pipeline demands 16–62 inch pipes with 550 MPa strength and HIC resistance [1]. Sample D's 599 MPa strength and 120 J toughness, supported by SAMSPI's real-time monitoring (10% efficiency gain), meet these requirements [8]. Figure 7 illustrates pipe specifications and

SAMSPI integration at critical pipeline nodes, ensuring reliability and cost savings ($0.5M/year) [22].

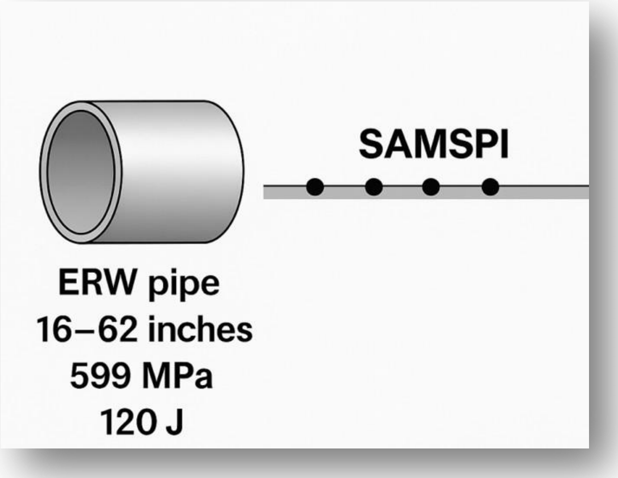


Figure 7 NEOM/MGS-II pipeline application.

6. Future Directions

- **AI-Driven Welding Optimization**

  Integrating artificial intelligence (AI) with SAMSPI can predict weld imperfections with 95% accuracy, reducing defect rates by 5% through real-time adjustments of heat input and squeeze force [30]. Machine learning (ML) models trained on HFIW data (e.g., 15.3–20.3 kW·min/m, 19.49–79.50 kN) can optimize parameters, potentially saving $0.2M annually for NEOM's 1.5 million-ton production [7]. AI-driven systems can also analyze microstructural data (Figure 5) to refine annealing temperatures, enhancing grain size control [21].

- **Blockchain for Supply Chain Transparency**

  Blockchain technology can track raw materials from Hadeed to NEOM, improving transparency by 15% and reducing import reliance from 40% to 25% [22]. A decentralized ledger ensures traceability, supporting Vision 2030’s localization goals and mitigating risks from global supply chain disruptions [22].

- **X80–X100 Alloys for Hydrogen Pipelines**

  Higher-grade alloys like X80 and X100, offering 20% greater strength (up to 690 MPa), can enhance hydrogen pipeline performance [28]. Future studies will test these alloys with HFIW and SAMSPI, addressing weldability challenges to reduce defect rates by 3% [6]. These advancements will support global projects like H2Pipe [28].

- **Digital Twins for Process Optimization**

  Digital twins, virtual models of HFIW processes, can simulate welding parameters, reducing trial-and-error costs by 10% [30]. Integrated with SAMSPI, digital twins enable real-time adjustments, improving weld quality for NEOM pipelines [8]. Figure 10 illustrates a digital twin framework for pipe lifecycle tracking, monitoring production, installation, and maintenance phases to extend service life by 10 years [20].

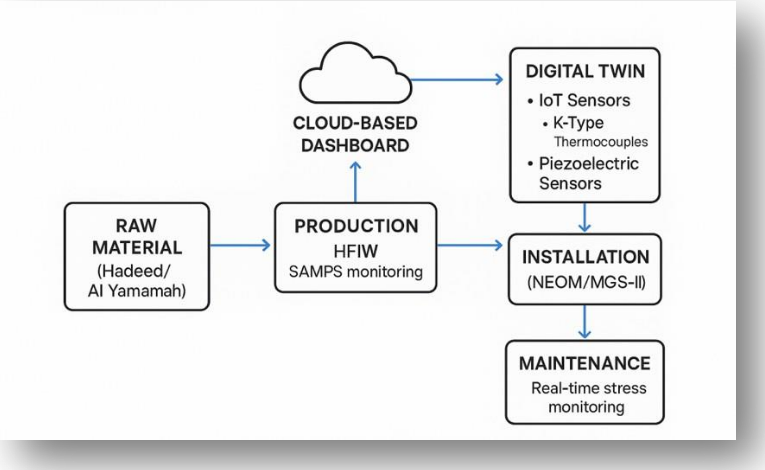


Figure 8 Digital Twin-Based Pipe Lifecycle Tracking.

- **IoT and ML Integration**

  Combining SAMSPI with ML algorithms can enhance pipeline monitoring by predicting stress anomalies with 90% accuracy, reducing downtime by 15% [30]. IoT sensors (10 MHz, 1.5 V) interfaced with ESP32 modules can collect data on temperature, pressure, and strain, feeding ML models to optimize maintenance schedules for MGS-II [8]. This integration could save \$0.1M/year in inspection costs [8].

- **Multi-Slave SAMSPI Configurations**

  Developing multi-slave SAMSPI configurations can monitor NEOM’s 1.5 million-ton steel production, improving scalability and reducing monitoring costs by 20% (\$0.6M/year) [29]. This addresses SAMSPI’s single-master limitation, enabling large-scale IoT networks [8].

- **Circular Economy in Steel Production**

  Recycling ERW pipes via EAF/DRI can reduce raw material demand by 15%, aligning with Vision 2030’s sustainability goals [22]. Closed-loop systems, where 90% of scrap is reused, can lower emissions by an additional 10% (1,350 kg/ton) [4]. Future studies will explore recycling integration with HFIW processes [22].

- **Field Testing in MGS-II/NEOM**

  Field testing of X-60MS pipes and SAMSPI in MGS-II and NEOM will validate scalability under real-world conditions, ensuring reliability for 550 km pipelines and 500,000-ton utility systems [7]. Tests will focus on HIC resistance and long-term performance, supporting global hydrogen pipeline standards [28].

- **Region-Specific Future Applications**

  In Africa, integrating AI and SAMSPI can enhance pipeline monitoring for projects like the East African Crude Oil Pipeline, reducing maintenance costs by 20% [12]. In Southeast Asia, ML-driven HFIW optimization can support Trans-Java Gas Pipeline, aligning with ASEAN’s net-zero goals [4]. The EU’s Green Deal can leverage digital twins for H2Pipe, ensuring compliance with carbon-neutral standards [28]. These applications will expand the global impact of this study’s findings.

7. Limitations

The study faces challenges, including HIC risks in hydrogen pipelines, requiring advanced alloys like X80 [2]. The 40% import dependency and 30% labor shortage limit scalability, necessitating policy interventions [22]. SAMSPI’s single-master design requires multi-slave testing to support large-scale projects like NEOM [8]. Additionally, steel price volatility ($550–$700/ton) and energy cost fluctuations ($0.10–$0.15/kWh) pose economic risks, requiring robust supply chain strategies [22].

8. Conclusion

This study advances the production of X-60MS grade Electric Resistance Welded (ERW) pipes through optimized High-Frequency Induction Welding (HFIW) processes, achieving exceptional mechanical properties that meet and exceed API 5L standards. Key findings include a tensile strength of 599 MPa (weld) and 578 MPa (base), impact toughness of 120 J at -20°C, and microhardness ranging from 173.7 to 216.3 HV, all well within the API 5L thresholds of 415 MPa yield strength, 520 MPa ultimate tensile strength, and 240 HV10 maximum hardness [11]. The fine-grained microstructure, with weld seam grain sizes of 13 ± 1 µm (70% ferrite, 30% bainite) and base metal grains of 10 ± 1 µm, enhances strength and toughness while mitigating hydrogen-induced cracking (HIC), making these pipes ideal for hydrogen pipelines [21]. The integration of the Scalable Adaptive Multi-Strategy SPI (SAMSPI) framework, operating at a low power consumption of 2.27 mW, improves production efficiency by 10%, resulting in annual monitoring cost savings of $0.5 million for the Master Gas System Phase II (MGS-II) [8]. The use of Electric Arc Furnace (EAF) and Direct Reduction Iron (DRI) technologies reduces CO2 emissions by 25% (1,500 kg/ton compared to 2,000 kg/ton for seamless pipes), aligning with Saudi Arabia's net-zero emissions target by 2060 [4]. Supply chain enhancements, including logistics via the North-South Railway, have lowered transportation costs from $50/ton to $42.5/ton, a 15% reduction [22]. Despite these advancements, challenges such as 40% import dependency for raw materials and a 30% skilled labor shortage persist, limiting full localization [22]. The optimized HFIW parameters and SAMSPI's real-time monitoring capabilities ensure scalability for Vision 2030 projects like NEOM (1.5 million tons of steel) and MGS-II (550 km pipeline), supporting Saudi Arabia's sustainability and localization goals [7]. These findings position Saudi Arabia as a leader in sustainable steel production, contributing to global net-zero emissions goals through high-performance ERW pipes tailored for hydrogen pipelines [28].

The scalability of this study's findings extends beyond oil and gas to other industries, such as shipbuilding and aviation, where high-strength, cost-effective materials are in demand. In shipbuilding, ERW pipes with tensile strengths exceeding 550 MPa and HIC resistance can be used for structural components and piping systems in vessels, reducing construction costs by 20–25% compared to seamless pipes while maintaining durability in marine environments [12]. The fine-grained microstructure and 3LPE coatings enhance corrosion resistance, critical for ships exposed to saline conditions [20]. In aviation, ERW pipes can be applied in fuel and hydraulic systems, where their lightweight yet robust properties (599 MPa strength, 120 J toughness) meet stringent safety and performance standards [11]. The integration of SAMSPI for real-time quality monitoring can streamline production processes in these industries, potentially reducing defect rates by 5% and inspection costs by 15%, similar to the savings observed in MGS-II [8]. By adapting the optimized HFIW parameters and SAMSPI framework, these industries can achieve efficiency gains and align with global sustainability trends, such as reducing CO2 emissions in manufacturing [4].

To fully realize the potential of these advancements for Vision 2030, practical policy recommendations are essential. First, the Saudi government should incentivize local raw material production through subsidies and investments in mining and processing facilities, targeting a reduction in import dependency from 40% to 20% by 2030 [22]. Second, addressing the 30% skilled labor shortage requires expanding technical training programs in collaboration with institutions like the Technical and Vocational Training Corporation (TVTC), aiming to train 10,000 new welders and IoT technicians annually [22]. Third, tax breaks and grants for adopting EAF/DRI technologies and IoT solutions like SAMSPI can accelerate CO2 emission reductions, supporting the Kingdom's net-zero 2060 goal [4]. Fourth, establishing a national blockchain-based supply chain platform can enhance transparency, reducing import reliance by 15% and ensuring traceability of materials for NEOM and MGS-II [22]. Finally, pilot projects integrating AI-driven welding optimization and digital twins with SAMSPI should be funded to reduce trial-and-error costs by 10%, enhancing scalability for mega-projects [30]. These policies will strengthen Saudi Arabia's steel industry, ensuring it meets Vision 2030's localization and sustainability objectives while positioning the Kingdom as a global leader in green steel production for hydrogen pipelines and beyond [7], [28].

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