Effect of wire Preheat and Feed Rate of Pipeline Steels in Laser Beam Welding

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***Abstract*—This study investigates the effect of wire preheating and feed rate on laser beam welding of X-series pipeline steels (API 5L grades such as X52, X65, and X70). Experimental analysis revealed that these parameters significantly influence weld quality, microstructure, and mechanical strength. Preheating enhanced fusion, reduced residual stress, and promoted finer grain structure across the X-series grades. An optimal wire feed rate ensured uniform material deposition and improved joint integrity. The results demonstrate that precise control of wire preheat and feed rate is essential for achieving high-performance welds in X-series pipeline applications.**

***Index Terms*—Pipeline Steel, X-Series Grades, Microstructure, Laser Beam Welding**

I. INTRODUCTION

The global surge in energy consumption, driven by industrial growth, continues to rely heavily on fossil fuels such as petroleum and natural gas, which account for over 80% of global energy usage. Transporting these energy resources over long distances demands high-performance pipeline systems made from steels that offer superior strength and toughness. Among these, X-series pipeline steels, particularly X80, have become widely adopted due to their excellent mechanical properties, weldability, and cost-effectiveness.

Traditionally, joining of pipeline steels has relied on arc welding methods like shielded metal arc welding (SMAW), submerged arc welding (SAW), and gas metal arc welding (GMAW). However, these techniques involve high heat input, slow processing speeds, and skilled labor, which can hinder productivity and compromise weld quality. In recent years, the advancement and affordability of high-power laser systems have enabled laser beam welding (LBW) to emerge as a promising alternative. LBW offers deep penetration, high welding speeds, and a narrow heat-affected zone (HAZ), which are especially beneficial for thick-walled, high-strength steels such as X80.

Despite these advantages, autogenous laser welding has limitations in gap-bridging ability and often results in brittle microstructures like bainite due to rapid cooling. To overcome this, wire-fed laser welding and hot-wire laser welding (HWLW) techniques have been introduced, enabling modification of the weld metal chemistry and promoting the formation of more desirable microstructures like acicular ferrite. These enhancements are particularly relevant for high-strength steels in the X-series (e.g., X52, X65, X70, and X80), where weld integrity and toughness are critical.

This study focuses on the influence of wire feed rate and wire preheating during laser welding of X80 pipeline steel. It aims to evaluate how these parameters affect the microstructure and potential performance of the welds, providing insights for the broader application of LBW in high-grade pipeline steels.

II. PRINCIPLE

A. LASER BEAM WELDING(LBW) PROCESS:

Laser Beam Welding (LBW) is a fusion welding process that uses a high-energy-density laser beam as the heat source. It is well-suited for joining X-grade high-strength low-alloy (HSLA) steels, commonly used in pipelines and pressure vessels

B. Types of Lasers in (LBW):

The types of lasers commonly used to weld X-grade steels include:

1. CO_2 Lasers (Carbon Dioxide Lasers)
Wavelength: ~10.6 µm (infrared)

Features: High power, good beam quality for deep penetration
Limitations: Not easily transmitted through optical fibers; less efficient with highly reflective materials
Applications: Older setups; used for thicker sections or when beam delivery via mirrors is acceptable
2. Nd: YAG Lasers (Neodymium-doped Yttrium Aluminum Garnet)
Wavelength: 1.06 µm (near-infrared)
Features: Can be transmitted through optical fibers, better for precision welding
Limitations: Less efficient than modern fiber lasers
Applications: Suitable for medium-thickness sections and where remote welding is needed
3. Fiber Lasers
Wavelength: ~1.07 µm
Features: High beam quality, energy efficiency, compact size, excellent for deep penetration
Best for X-grade steels
Applications: Preferred for industrial LBW of pipeline steels due to high speed and quality welds
4. Disk Lasers (Thin Disk Lasers)
Wavelength: ~1.03 µm
Features: High power and beam quality, less heat input than fiber lasers at same power
Applications: Used in precision and thick-section welding of high-strength steels
C. Characteristics of X-Grade Steels:
High yield strength (e.g., X65: 65 ksi, X80: 80 ksi)
Microalloyed with elements like Nb, V, Ti. Thermo-mechanically controlled processed (TMCP) for enhanced toughness and weldability in pipeline industry. These elements which acts as strengtheners in pipeline industry to achieve mechanical properties which are tested in ASTM testing standards and applicable to welding industry.

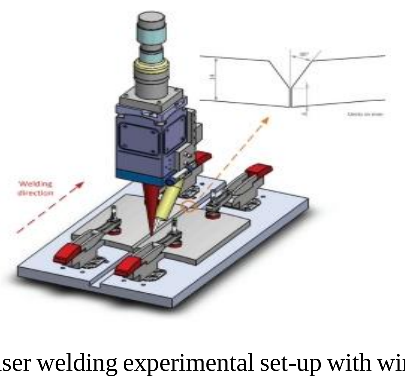

Fig. 1 Laser welding experimental set-up with wire feed.

III. LITERATURE REVIEW

Y H. YANG, et.al investigated laser welding of X80 pipeline steel, highlighting its productivity benefits and microstructural effects. Laser welding required significantly less heat input and had much faster travel speed than GMAW to achieve similar weld size. Adding ER70S-6 filler wire and preheating influenced the fusion zone (FZ) microstructure, promoting finer acicular ferrite and limiting bainite formation. Laser welding produced finer austenite grains and reduced bainite packet size in the coarse-grained heat-affected zone (CGHAZ), minimizing martensite-austenite (MA) formation compared to GMAW. This study explores the effects of filler wire volume and wire preheating on the microstructure and mechanical properties of laser-welded X80 pipeline steel. Adding ER70S-6 filler wire reduced the hardness in the upper fusion zone (FZ) due to less bainite formation, while the bottom region remained largely unaffected due to uneven filler distribute Tensile tests showed fractures in the base metal, confirming that the weld metal had higher strength, attributed to bainite and acicular ferrite formation. Charpy impact toughness increased by up to 26% at 0°C with wire addition. Acicular ferrite enhanced crack resistance, though toughness declined as the temperature dropped to –20°C and –45°C, indicating a ductile-to-brittle transition.

G.TURICHIN et.al optimized welding parameters for 14 mm thick X80 pipeline steel using hybrid laser-arc welding with MF 940M filler wire. Higher welding speeds increase cooling rates, leading to more martensite and harder microstructures; lower speeds result in softer microstructures. Preheating alters phase composition and mechanical properties oppositely to welding speed and has a stronger overall effect. Without preheating, a maximum welding speed of 2.5 m/min produces acceptable weld quality. With preheating up to 180°C, this limit increases to 3 m/min. The study is ongoing, with future work required to fully understand and optimize the welding behavior of X80 steel.

T. GARCIN et.al presented an integrated modeling approach to predict and analyze heat-affected zone (HAZ) microstructures in X80 pipeline steel under various welding conditions. The model incorporates microstructure engineering concepts and empirical formulas, especially for bainite and martensite/austenite (M/A) formation, allowing comparative analysis across welding scenarios. Transitions between ferrite, upper and lower bainite in the HAZ are gradual. Effective grain size and dislocation density—derived from EBSD studies are proposed as key indicators linked to transformation temperature and mechanical properties.

WEI GUO et.al predicted, M/A constituents must be more rigorously modeled by accounting for their size, shape, and retained austenite fraction. A shift from simplified temperature models to detailed heat transfer models is also necessary to more accurately simulate welding effects.The model currently addresses fully austenitized HAZ regions but needs to be expanded to intercritical zones like the coarse-grained HAZ (CGHAZ), where intercritical cycling and resulting martensite can negatively affect toughness and integrity.

G.A.MORAITIS et.al focused on ultra-narrow gap laser welding of S700 and S960 high-strength steels, its findings offer relevant insights for welding X80 pipeline steels, which share similar high-strength characteristics. This technique can be applied to thick high-strength steels like X80, using moderate laser power (2–3 kW) and narrow grooves, offering precise welds with minimal distortion Multi-pass laser welding in narrow gaps effectively addresses issues like melt sagging, a common concern in thick-walled X80 pipeline welding. Enhancing laser power and wire feed rate while reducing welding speed improves weld quality and efficiency guidance valuable for X80 steel welding process development. Optimized parameters were successfully applied to thicker sections, suggesting potential scalability to X80 applications with similar thicknesses. Welded joints exhibited tensile strength equivalent to the base metal, with failures occurring in the base metal—indicating weld integrity, a crucial requirement for pipeline applications.

G.CAM et.al presented a two-level, three-dimensional numerical model for simulating laser beam welding (LBW), emphasizing its efficiency in predicting distortions and residual stresses in butt-joints of materials like steel and aluminium. The model integrates non-linear thermo-mechanical analysis with temperature-dependent material properties, using a keyhole-based local model (Level-1) to accurately characterize heat input, reducing reliance on costly experimental measurements. The keyhole data is then applied in a global model (Level-2) to

IVAN BUNAZIV et.al studied on CO_2 laser welded C-Mn steels offers key insights applicable to X80 pipeline steels. Rapid cooling during welding produces hard bainite/martensite microstructures, increasing weld zone hardness — a trend expected in X80. Strength mismatch causes failure in the softer base metal, and weld/HAZ zones show higher strength but reduced ductility. Conventional CTOD testing may not reflect true toughness due to crack path deviation. Micro tensile testing is useful for assessing local properties. These findings support optimizing laser welding of X80 by managing microstructure, strength mismatch, and fracture behavior for reliable pipeline performance.

P.MAZMUDAR et.al studied on double-sided laser-arc hybrid welding of thick high-strength steels offers key insights for X80 pipelines. Y-groove beveling ensures full weld penetration, while high cooling rates produce hard bainitic-martensitic microstructures with toughness concerns. Preplaced filler wire and preheating increase acicular ferrite formation, improving toughness and reducing porosity. Combining both methods significantly boosts impact toughness (from 11.5 J to 46 J) and shifts fracture mode from brittle to ductile. These techniques are effective for enhancing weld quality in X80 pipeline applications.

R.MIRANDA et.al emphasized that laser welding parameters welding speed, heat input, and focal position are crucial for weld quality in X80 pipeline steels. Mn and Cr improve strength and corrosion resistance. Wire preheating helps control cooling rates, enhances acicular ferrite formation, and boosts toughness. Together, optimized laser settings and preheating improve weld strength, morphology, and performance in X80 applications. This study compares fiber laser and TIG welding, with findings highly relevant to X80 pipeline steel. Fiber laser welding produced sound welds with deep, narrow penetration and fine martensitic structures, resulting in higher hardness (~375 HV) and strength due to refined grains. TIG welds showed coarser bainitic microstructures and lower hardness. Laser welds also had significantly finer dendrites and better mechanical performance. These results highlight fiber laser welding as a superior method for high-strength pipeline steels like X80, offering improved microstructure, strength, and productivity.

IV. EXPERIMENTAL PROCEDURES

Welding Equipment and Materials

The experimental set-up for the wire-fed laser welding process is shown in Fig. 1. An IPG YLS-

8000 fiber laser with a maximum power output of 8 kW was used in this work, with a focal length of 300 mm, a wavelength of 1070 nm, a beam parameter product of 3.5 mm*mrad, and a focused spot size of 1.2 mm. A Lincoln Electric Power Wave L500 power supply was used to preheat and feed the wire in front of the laser. The laser welding head was equipped with a hot-wire torch and positioned by a Fanuc R-301iB Plus six-axis industrial robot system. The base metal was taken from an X80 pipeline with dimensions of 250 mm ✕ 120 mm ✕ 14 mm and an internal radius of 470 mm, with a chemical composition given in Table 1. ER70S-6 carbon steel welding wire was used with a diameter of 0.9 mm. The plate was machined with a 30-deg bevel and a 6 mm root height. Before welding, the oxides on the plate surfaces were removed by sandblasting, and the plates were tack-welded together to ensure accurate positioning and minimize distortion during welding.

Welding Test Design

This study compared autogenous, cold-wire, and hot-wire laser welding for the root pass. In hot-wire welding, preheating the filler wire (0.3–0.5 kW) raised wire temperatures to 1200–1400°C depending on wire feed rate (6–12 m/min), enhancing deposition. A 0.4 mm root opening accommodated higher filler input. The remaining groove was filled using arc welding with higher heat input (1.30 KJ/mm) compared to cold-wire laser welding (0.48 KJ/mm). Shielding gases used were pure Ar for laser and Ar-CO_2 mix for arc welding.

Microstructure Analysis Procedure

Sample Preparation:

Cross-sectional samples were cut and polished post-welding.Etching with Nital (5% nitric acid + 95% ethanol) for 5 seconds followed ASTM E407 standards to reveal the microstructure.

Imaging Tools:

Macrographs were captured using a stereoscope to observe weld dimensions.Microstructural features were examined using:An Olympus BX51 optical microscope (OM)A Zeiss Ultra scanning electron microscope (SEM).

V. RESULTS AND DISCUSSION

Weld Morphologies

Weld Setup:1 root laser weld 5 passes of filler arc weld

Surface Appearance:The laser root weld: narrow, continuous, and crack-free.The arc weld cap: wider due to larger weld pool and lower energy density.

Cross-Sectional Morphology:Laser welds fully penetrated the base material.High depth-to-width ratios, characteristic of laser keyhole welding (due to high beam power density).

Wire Feed Rate Effect:Increased wire feed rate (0 to 12 m/min) increased weld height.

Comparison to GMAW:The 30° groove angle from CSA-Z662 was used.Needed 5 GMAW passes to match the weld height of a single laser root weld.Heat input:Each GMAW pass: ~3× more than laser root weld.Cumulative GMAW heat input: ~15× that of laser welding.

The ultimate tensile strength (UTS) of the welded joints under different welding conditions is presented in Figure X. The autogenous laser weld exhibited a UTS of 652 MPa, slightly lower than the specified UTS range for the X80 base metal, which is indicated as a reference in the figure. Among the hybrid laser-arc welds, all samples, regardless of wire feed rate (WFR) or wire heating condition (cold vs. hot), demonstrated improved tensile properties compared to the autogenous laser weld.

The UTS values for the hybrid welds ranged from 682 MPa to 698 MPa, with the highest strength observed in the WFR = 12 m/min, cold wire configuration (698 MPa). This suggests that increasing the wire feed rate enhances tensile strength, likely due to increased filler material contribution and improved joint integrity. Comparatively, the WFR = 12 m/min, hot wire condition yielded a slightly lower UTS (686 MPa), indicating that while hot wire feeding facilitates deposition, it may also slightly reduce peak strength due to additional thermal input.

The cold wire-fed joints consistently outperformed their hot wire-fed counterparts at equivalent feed rates, highlighting the benefits of reduced heat input in maintaining higher tensile strength. Despite these differences, all hybrid welds exceeded the UTS of the autogenous laser weld and remained within the specified range for X80 base metal, confirming the mechanical integrity of the joints under all tested conditions.

Overall, these results underline the effectiveness of hybrid laser-arc welding in improving the tensile performance of welded joints in high-strength pipeline steels. The data also demonstrate that optimal mechanical properties can be achieved by tuning the wire feed rate and minimizing thermal input through cold wire feeding.

VI. CONCLUSION

Wire preheating in laser welding of X80 pipeline steels significantly influences the weld's microstructure and mechanical properties.Preheating the filler wire reduces the temperature gradient between the wire and the weld pool, promoting uniform melting and solidification. This leads to a more homogeneous distribution of the filler material, resulting in a consistent microstructure across the fusion zone. Specifically, preheating encourages the formation of acicular ferrite, a microstructure known for enhancing toughness, while reducing the presence of harder, more brittle phases like bainite.The improved microstructure from wire preheating translates to better mechanical properties. Notably, the weld metal exhibits increased impact toughness at low temperatures, with studies reporting up to a 26% improvement at 0°C when wire feed is employed. Additionally, tensile tests indicate that fractures occur in the base metal rather than the weld, signifying that the weld metal's strength surpasses that of the base material.Implementing wire preheating in the laser welding of X80 pipeline steels enhances weld quality by promoting a favorable microstructure and improving mechanical properties. This practice is particularly beneficial for applications requiring high toughness and strength, such as in pipeline construction and maintenance.

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