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Co-Processing of Hybrid Laser Arc Welding (HLAW) & Submerged Arc Welding (SAW) for Enhancing Productivity in Thick High Strength Steel Joints

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Abstract

The shipbuilding and heavy manufacturing industries are looking for a novel welding technique to weld high-strength steel alloys with thicknesses above 25 mm. Submerged arc welding (SAW) has been the "go-to" joining process for thick material from both sides. However, using SAW alone requires thick plates to be flipped over multiple times during welding to minimize the effects of distortion and uses a large volume of weld metal. This paper presents research on the feasibility of welding thick, high-strength steel plates in a combined, sequential processing approach utilizing HLAW and SAW. The development activity entails HLAW processing the weld joint's first pass to achieve an approximate 18 mm root penetration, followed by SAW to complete the joint (38 mm). Mechanical properties, impact toughness, and microhardness hardness distribution in specific zones of one side butt multiple pass welded joints are analyzed in correlation with a microstructure in specific zones of the welded joint. The paper also discusses the applicable standards and recommendations for welding those steels, from the aspect of applications in the design of steel welded constructions. Based on the carried-out analysis and results obtained in experiments, the applied welding technology minimizes the volume of weld metal needed to complete the joint. It achieves requisite performance mechanical properties while reducing material preparation costs and labor. This joining process approach is expected to increase capabilities for shipbuilding, heavy manufacturing, and oil and gas industries.

Keywords: Hybrid laser arc welding (HLAW), Submerged arc welding (SAW), High-strength low-alloyed steels (HSLA), High yield steel (HY80), impact toughness

1. Introduction

High-strength steels (HY or HSLA type) can be considered conditionally weldable. This conditionality refers to applying process parameters and controls that provide for successful joining by welding. Fusion welding processes are the most common joining approach widely used in the fabrication of high-strength steel for shipbuilding and heavy manufacturing industries [1,2]. When steel is heated during the welding operation, the homogeneity of microstructures in the heat-affected zone (HAZ) drastically changes and influences the weld joint's mechanical properties (i.e., strength, ductility, and toughness). The microstructure of high-strength steel typically shows tempered martensite, bainite, ferrite, and martensite-austenite (M-A) constituents. Also, segregation of inclusions and precipitates within the steel can be found, including nitride, carbide, and composite [3]. A problem in the HAZ, adjacent to the fusion zone, is grain coarsening due to the heat from welding. Grain coarsening can degrade the properties of the weld joint. [3-5]. Increasing welding heat input results in larger austenite grain size and decreasing impact toughness. The presence of a wide coarse grain heat-affected zone (CGHAZ) can deteriorate the impact toughness due to coarsening grain size and M-A constituents [4-6].

The properties of the HAZ are influenced by microstructure, which is determined by phase transformation during welding, which is affected by the cooling rate [7]. It was reported that the HAZ impact

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toughness in the case of HY85 [4,8] increased at a lower cooling rate as a function of the formed bainitic microstructure and then decreased at a higher cooling rate due to the formation of fully martensitic microstructure. On the other hand, controlling the cooling time at low temperatures prevented cold cracking at high-strength steel weldment [9]. The welding method also influences the impact toughness of high-strength steel welded joints. The alloying elements reduction due to the shielding gas's oxidation effects can reduce weld metal's (WM) impact toughness [3]. Submerged arc welding (SAW), which could have a significant volume fraction of inclusions greater than shielded metal arc welding (SMAW) and flux-cored arc welding (FCAW), shows the lowest impact toughness in the weld metal. The impact toughness of WM at sub-zero temperatures is affected by the chemical composition of WM, grain size, acicular ferrite microstructure, and inclusions [5,10,11]. The size and volume fraction of non-metallic inclusions influences acicular ferrite formation, improving impact toughness. The chemical composition of filler metal (welding wire) influences the composition of WM. A higher nickel concentration in WM stabilizes austenite grain, improving impact toughness at sub-zero temperatures.

Hybrid laser arc welding (HLAW) is gaining greater acceptance within different industrial markets for producing joints in various metal alloy systems serving oil and gas, heavy manufacturing, and shipbuilding industries. The HLAW process combines laser welding with gas metal arc welding (GMAW) to reduce plate distortion and enable single-sided joining. While HLAW successfully joins low-strength material in thicknesses less than 25 mm, challenges arise in welding greater thicknesses in high-strength steels. With present laser capabilities, 16 mm thick may be the limit for HLAW processing of high-strength steels. Previous work on welding high-strength steels with HLAW has resulted in high hardness and low Charpy impact properties. This is not acceptable for high-performing applications.

Currently, shipbuilding and heavy manufacturing industries are in the early stages of HLAW implementation for fabrication in panel line construction with carbon steel. Since current HLAW capabilities limit single-sided use on thick materials, SAW has been the “go-to” joining process for thick material. However, using SAW alone requires thick plates to be flipped over multiple times during welding to minimize the effects of distortion and uses a large volume of weld metal. Because thickness limitations exist for using HLAW, development activities are being pursued to weld thicker, high-strength steels (HY or HSLA type) to increase productivity while meeting requisite material properties in a one-sided joining approach .

Compared to the conclusions of the presented references, this research investigates the feasibility of welding thick, high-strength steel plates in a combined, sequential processing approach utilizing HLAW and SAW. The development activity entails HLAW processing the weld joint's first pass to achieve an approximate 18 mm root penetration, followed by SAW to complete the joint. This paper analyses the effect of the newly developed welding co-process on the mechanical properties of the HY 80 high strength commonly used in shipbuilding, cranes, and other heavy manufacturing industries. The research further establishes the fundamental qualitative relations between the microstructure, relevant microhardness values, and measured values of the mechanical properties. Derived conclusions can be used for the relevant welding processes and welding parameters identification of this steel grade, as well as a basis for future detailed research related to quantifying qualitatively established qualitatively in this research.

2. Experimental Procedures

2.1 Materials

Plates with dimensions of 305x610x38 mm of HY80 steel were used as base material. Filler wire with a diameter of 1.14 mm, according to the AWS 5.28 class ER 100S-1 (NAVSEA T9074-BC-GIB-010/0200) for the HLAW process, was used as welding consumables. The SAW filler wire was the same as HLAW. The 800 series neutral flux, according to AWS A5.17, was used as a welding consumable. The chemical composition of base metal is shown in Table 1. The basic chemical compositions of the used consumables are shown in Table 2.

Table 1. Chemical composition of HY80 steel

C	Mn	Si	P	S	Mo	Cr
0.14	0.34	0.25	0.014	0.01	0.5	1.6
Ni	Cu	Fe				
3.1	0.18	Bal.				

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Table 2. Chemical compositions of used consumables

Filler Wire Chemical Composition										
	Content of Chemical Elements, %									
	C	Mn	Si	P	S	Mo	Cr	Ni	Cu	Fe
ER 100S-1	0.10	0.63	0.46	0.012	0.012	1.06	2.55	0.10	0.11	Bal.
Flux Chemical Composition										
	Content of Oxides, %									
	SiO_2	MnO	MgO	CaF_2	NaO_2	Al_2O_3	TiO_2	Metal Alloys		
800 series neutral flux	11	1	14	19	2	37	12	3 max.		

2.2 Welding

The objective of the work was to investigate the welding parameters for co-processing HLAW and SAW using joint geometry illustrated in Fig. 1, with a root opening of 0 mm, which was adopted. HLAW and SAW process parameter values are provided in Table 3 and Table 4, respectively. Each process's parameters were developed individually and evaluated through X-ray testing and metallographic examination.

Table 3. HLAW Process Parameters

Laser Power (KW)	Welding Speed (mm/s)	Wire Feed Rate (m/min)	Shielding Gas	Shielding Gas Flow Rate (L/min)	Back Shielding Gas	Back Shielding Gas Flow Rate (L/min)
18 – 20	25 – 30	10 - 15	Ar + 15% CO_2	15 – 30	Ar	25 - 70

Table 4. SAW Process Parameters

Welding Current (A)	Welding Voltage (V)	Welding Speed (mm/s)
480 - 520	29 - 31	7 - 8

HLAW process was used to weld the first pass with a thickness of up to 19 mm. The sample was cooled to room temperature and transferred to the SAW machine. Preheating using the HLAW welded joint to 250ºC followed by the SAW process was carried out.

After welding with the combined HLAW-SAW process, test coupons were non-destructively tested using radiographic inspection procedures to confirm the absence of welding defects. After testing, the coupons were extracted from the weld test plate for microstructure evaluation, hardness, tensile, and impact testing. The number of mechanical test samples and locations are shown in Table 5.

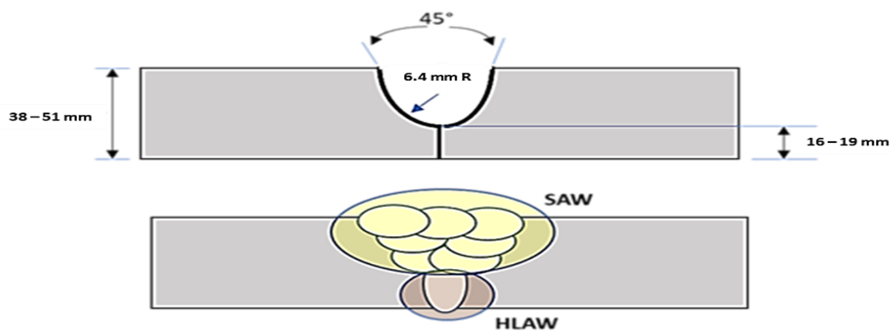


Fig. 1 Joint configuration and weld layout.

Table 5. Mechanical Test Samples.

Weld (Location)	**Tensile (Transverse)**	Impact at - 40ºC		**Bend**	**Macro**	**Hardness Map**
HLAW-SAW Full Welded Joint	2	WM	3	2	1	1
HLAW-SAW SAW Region	2	WM	3	2	1	
HLAW-SAW HLAW Region	2	WM	3	2	1	1

The transverse tensile test samples for both the SAW and HLAW regions were extracted by slicing the completed welded joint by water jet cutting processes.

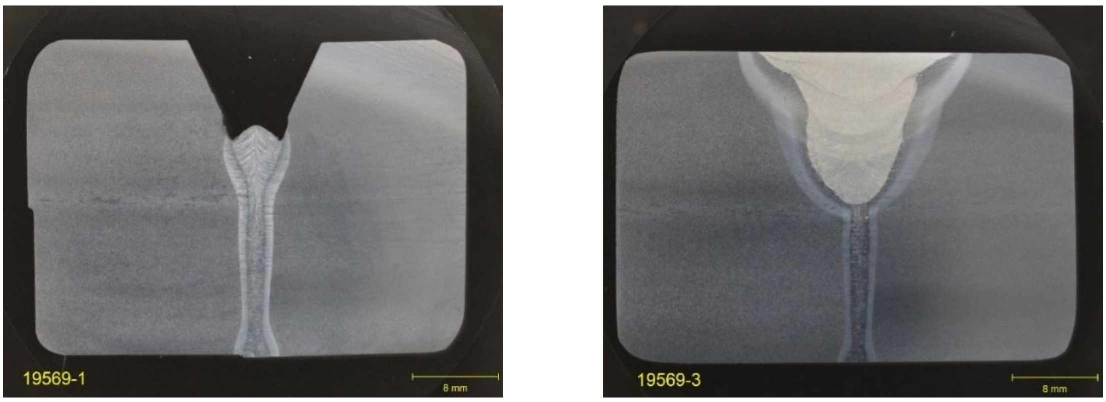
Specimens were prepared from the welded joints according to ASTM E3-17 standard for metallographic characterization by optical microscope. To determine the joint efficiency, tensile test samples were prepared per the ASTM E8-22 standard and AWS B4.0-16 specifications. Tensile tests were conducted on an Instron-8801 machine at room temperature (25°C) with a constant crosshead speed of 0.5 mm/min. The Vickers microhardness was measured using an auto hardness testing machine according to ASTM E384-17 for up to 1000 indents, including a color hardness contour map, for the weld specimen with an applied load of 500 g with a dwell time of 10 s. Impact test samples' shapes and dimensions and the testing procedure were carried out according to ASTM E23-18 standard and AWS B4.0-16 specifications. The impact samples were soaked in a liquid nitrogen container for 5 minutes, pulled out, and installed in the impact testing machine. A contact thermocouple continuously measured the temperature. When the temperature reached -40ºC, the test was carried out.

3. Results and Discussions

3.1. Microstructure Analysis

The macrographs of the HLAW butt weld, which were deposited first and co-process butt weld with SAW, are shown in Fig. 2. Both weld joints are free from macro-level defects. The width of HAZ at the HLAW weld joint is narrower than that of the SAW. That could be attributed to the lower heat input of the HLAW process due to faster traveling speed.

Fig. 3 shows the microstructure of HY80 base metal, HLAW-HAZ, and SAW-HAZ—the microstructure of BM is a mixture of granular bainite, ferrite, and martensite. The HLAW process's HAZ microstructure is a mixture of granular bainite, polygonal ferrite, and martensite. In contrast, the HAZ microstructure at SAW shows coarse grain boundary ferrite, polygonal ferrite, and bainite.



(a) HLAW- Weld Joint (b) HLAW/SAW- Weld Joint

Fig. 2 Macrographs of optical microscopy of welded joints

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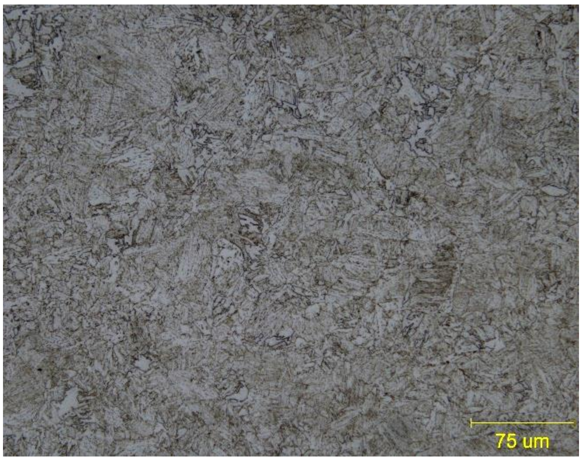

a) Base metal

b) HLAW – HAZ

c) SAW - HAZ

Fig. 3 Microstructure of HY80 base metal and HAZ of both HLAW and SAW processes

The microstructure of deposited weld metal at the overlap area between HLAW and SAW and the HAZ microstructure is shown in Fig. 4. The microstructure at the overlap weld is predominately acicular ferrite, with a mixture of granular ferrite and bainite.

The HAZ microstructure at the overlap area is a mixture of bainite, polygonal ferrite, and Widmanstatten ferrite. This result of microstructure evolution during welding could influence the mechanical properties.

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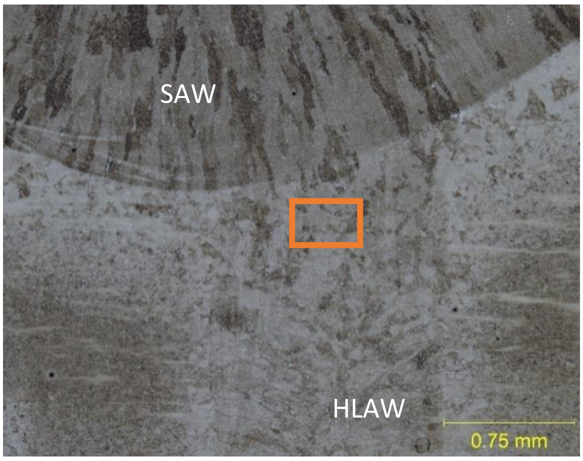
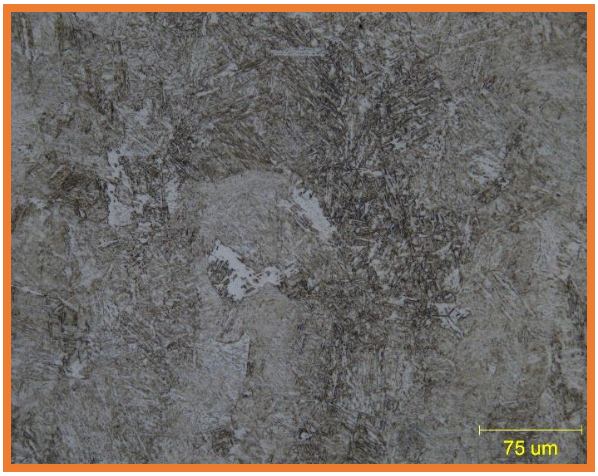


(a) Macrostructure of the overlap weld



(b) Microstructure of the overlap weld

(c) Overlap - HAZ

Fig. 4 Microstructure of weld meta and at overlap weld zone.

3.2 Hardness Measurements

The hardness mapping across the welded joint revealed a relatively higher hardness value of the metal at the HLAW weld in the 260 to 360 HV (Fig. 5). This result could be attributed to the higher cooling rate and lath martensite and bainite formation. The hardness value of the deposited metal in the SAW weld ranged from 230 to 240 HV due to the microstructure consisting of grain boundary ferrite and acicular ferrite.

The width of HAZ in the SAW region was wider and had higher areas of localized hardness values than that of the HLAW region. This variance could be attributed to the cooling rate and joint configuration differences.

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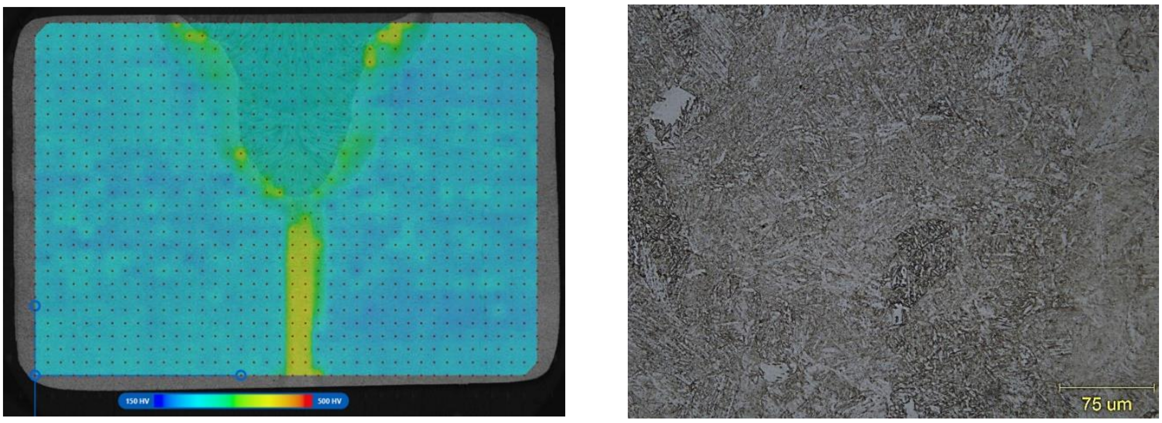

(a) Hardness map of HSLA/SAW weld joint (b) HLAW weld metal microstructure

Fig. 5 Hardness mapping across the welded joint (left); the microstructure of the HLAW weld metal.

3.3 Mechanical Testing

The transverse welded sample's ultimate tensile strength (UTS) showed higher tensile strength with failure in the base metal. Per Tech Pub 248 (Rev. 0) [12], Section 4.5.2.1- Transverse Weld Tension Tests, "If the specimen breaks in the base material outside of the weld or fusion line, the test shall be accepted as meeting the requirement, provided the strength is not more than 5% below the requirements specified value of 99.5 Ksi (5% below 99.5 ≈ 94.5 Ksi) in the case of HY80 steel," which is shown as a dotted line in Fig. 6.

Fig. 7 shows the UTS of the transverse welded joint at the SAW region (cap) and the HLAW region (root). The UTS for both transverse welds using HLAW were close to the minimum tensile strength required by Tech Pub 248 (Rev. 0) Section 4.5.2.1. The second HLAW transverse weld was below the minimum 99.5 ksi requirement but still met Tech Pub 248 (Rev. 0) requirements because it was within 5% of the base material UTS.

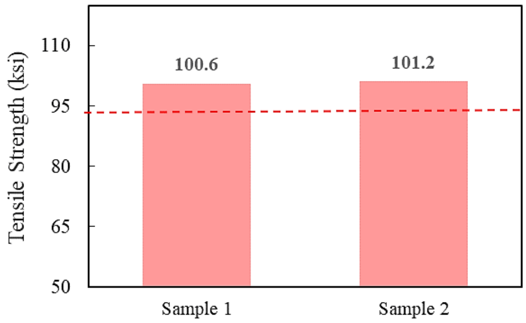

Fig. 6 UTS of co-processed, fully welded transverse joint

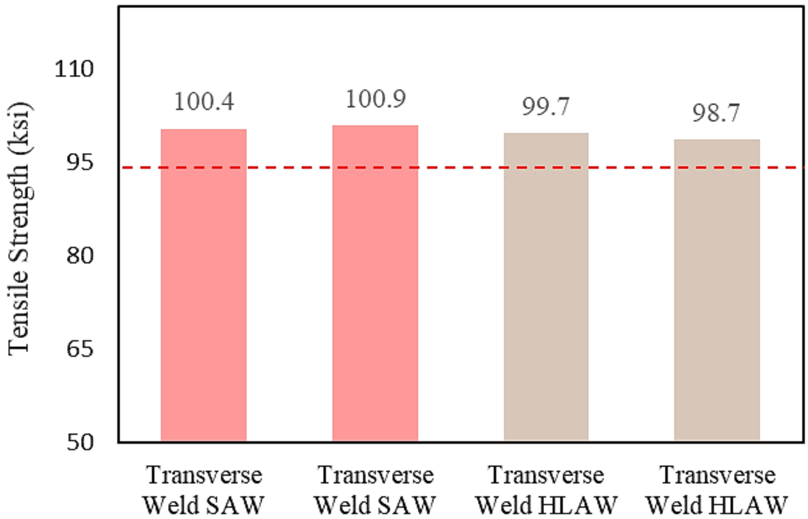

Fig. 7 UTS of transverse welded joints at both SAW and HLAW regions.

The impact test results at -40ºC are shown in Table 6. The deposited weld metal at the overlap was higher than that of the SAW deposited weld metal and lower than that of HLAW deposited weld metal. This result could be attributed to the formed microstructure evolution during welding at different regions. The microstructure evolution during co-processing positively influenced the mechanical properties, indicating the effect of developed process parameters. The obtained UTS, hardness, and impact values fell within the acceptance criteria of the applied standard, with almost zero distortion in welded test plates

Table 6. Impact Test Results

Location	**Absorbed Energy, (J) (-40°C)**			
	1	2	3	Avg
Overlap of SAW and HLAW region	127	185	126	146
SAW Region	90	98	93	94
HLAW Region	211	115	190	172

4. Conclusions

In the present investigation, 38-mm HY80 plates were joined by the HLAW and SAW to study the influence of two different welding processes on the single-side welding on the microstructure and mechanical properties of the joints. The main findings are summarized below:

- Both HLAW and SAW weld joints are free from macro-level defects. The width of HAZ at the HLAW weld joint is narrower than that of the SAW as a function of That could be attributed to the lower heat input of the HLAW process due to faster traveling speed.
- The hardness mapping across the welded joint revealed a relatively higher hardness value of the metal at the HLAW weld (260 to 360 HV) compared to the deposited metal in the SAW weld (230 to 240 HV). This variance could be attributed to the cooling rate and joint configuration differences, which affected the formed microstructure.
- The tensile properties of single-side-process welded joints conform with the “Requirement for Welding and Brazing Procedure and Performance Qualifications -S9074-AQ-GIB-010/248”. All the welded specimens get fractured at base metal in ductile mode.
- The impact values of deposited weld metal at the overlap were higher than that of the SAW deposited weld metal and lower than that of HLAW deposited weld metal. This result could be attributed to the formed microstructure evolution during welding at different regions.
- The co-process approach minimized the volume of weld metal needed to complete the joint, achieving requisite performance properties while reducing material preparation and anticipated labor costs.
- This improved joining process approach will increase shipbuilding capabilities, heavy manufacturing (construction and potentially armored vehicles), and oil and gas industries.

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