

DOI: <https://doi.org/10.37434/tpwj2026.03.01>

EFFICIENT WELDING OF 80 mm S355ML PLATES USING A HYBRID LASER-ARC AND NARROW-GAP SAW PROCESS

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ABSTRACT

A new welding approach combining hybrid laser-arc welding (HLAW) and narrow-gap submerged arc welding (SAW) was investigated for joining 80 mm thick S355ML steel plates used in offshore wind turbine structures. The U-shaped joint preparation consisted of a 40 mm root face welded by HLAW, followed by a 23 mm narrow-gap section completed with multi-layer SAW passes. Process efficiency and mechanical performance were evaluated in comparison with conventional multi-pass SAW. The results showed that the combined process significantly reduces weld volume, filler metal consumption and heat input while maintaining the strength and toughness required for offshore applications. Mechanical testing confirmed a sound joint with a favorable and uniform hardness profile and adequate low-temperature performance. Charpy V-notch tests at -40 °C yielded average absorbed energies of $138\pm 45\text{ J}$ in the arc-dominated region and $65\pm 12\text{ J}$ in the laser-dominated region of the hybrid weld. The proposed approach provides an efficient and technically feasible solution for the fabrication of thick-walled offshore structures.

KEYWORDS: hybrid laser-arc welding, submerged arc welding, S355ML, thick-section steel, microstructure, mechanical properties, impact toughness

INTRODUCTION

The global transition towards sustainable energy generation has accelerated the deployment of wind energy systems. In line with the objectives of the Paris Agreement and international net-zero strategies, offshore wind power has emerged as a key technology for reducing greenhouse gas emissions while ensuring long-term energy security [1]. The continuous increase in turbine size, installation depths, and overall capacity demands has intensified the need for efficient fabrication technologies for large offshore structures.

Offshore wind turbines are predominantly constructed from thick-walled steel components such as towers, monopiles, and transition pieces. These cylindrical sections are manufactured from heavy plates that are rolled, tack-welded, and joined by longitudinal and circumferential welds. Thermomechanically rolled or normalized fine-grain structural steels including S355NL, S355ML, S420ML, and S460ML are commonly used according to EN 10025-3 and EN 10025-4. The indexes “N” and “M” denote normalized/normalized-rolled and thermomechanically rolled delivery conditions, respectively, while “L” indicates guaranteed low-temperature toughness. Typical impact energy verification temperatures are -20 °C

for N-grades, -50 °C for NL-grades, and -40 °C for ML-grades, reflecting the harsh environmental conditions offshore. These steels exhibit yield strengths between 355 MPa and 460 MPa and are commonly used for plate thicknesses ranging from 30 mm to 100 mm in tower and transition-piece fabrication, and up to 150 mm in monopile structures [2–4].

Welding such heavy sections presents significant challenges. Conventional multi-pass gas metal arc welding (GMAW) or SAW procedures require high heat input, large weld volumes, and long production times. These factors increase distortion and may negatively influence heat-affected zone (HAZ) properties. In thermomechanically rolled steels, excessive heat input can lead to grain coarsening and reduced impact toughness [5–7]. Maintaining consistent weld quality is essential for offshore fabrication, and welding procedure specifications (WPS) must be followed rigorously. According to DNVGL-OS-C401 and DIN EN 10225, the allowable heat input for fine-grain structural steels typically ranges between 3.5 ± 0.2 and $5\pm 0.2\text{ kJ/mm}$, depending on grade and toughness requirements.

Although SAW remains the industrial standard for joining thick plates, either in single-, tandem-, or multi-wire configurations, it still involves large groove volumes and high filler metal

consumption. Modern high-productivity concepts such as narrow-gap SAW (NG-SAW) and narrow-gap GMAW (NG-GMAW) processes aim to address these limitations. Narrow-gap techniques significantly reduce weld volume, while still enabling reliable fusion even in sections exceeding 200 mm [8–10].

Laser beam welding (LBW) is another high productivity joining method offering excellent penetration capability and very high travel speeds. However, the extremely rapid cooling associated with LBW can lead to increased hardness and reduced toughness in both the weld metal (WM) and the HAZ, primarily due to martensitic transformation at high cooling rates [11, 12]. The analyzed literature shows that in LBW of Q345 high-strength low-alloy (HSLA) steel, moderate preheating of around 100 °C only marginally reduces cooling rates and partially suppresses martensite formation. A significant effect is achieved only at elevated preheating temperatures around 200 °C, where martensitic layers disappear completely, hardness becomes more uniform, and both fatigue performance and corrosion resistance improve noticeably [13]. However, such high levels of preheating are generally not economical for large-scale offshore structures due to the high energy demand and extended preparation times involved. Furthermore, LBW has limited tolerance for variations in joint gaps. Even with beam oscillation, gaps of only about 0.5 mm can be reliably bridged [14]. This narrow tolerance range restricts the applicability of LBW to components with larger dimensional deviations or heavy-wall sections.

Hybrid laser-arc welding (HLAW) combines the advantages of laser welding and arc welding within a common molten pool, thereby improving gap tolerance and weld pool stability while enabling deep penetration [15]. Studies on plate thicknesses up to 20–30 mm have demonstrated high process efficiency and sound mechanical performance [16–18].

Attempts to extend laser-based welding methods to thicker plate sections, such as welding under reduced pressure [19, 20], the use of electromagnetic weld pool support [21, 22], or the application of multi-layer LBW techniques [23, 24], have demonstrated that these approaches are technically feasible. However, despite ongoing technological progress and the availability of pilot systems [25, 26], their industrial applicability remains limited because of the high complexity of the equipment and the strong sensitivity to joint preparation.

For plate thicknesses up to 35 mm, combined LBW and SAW processes have been successfully implemented [27]. This method combines two welding techniques within a shared molten pool, enabling thick plates to be joined using double-sided welding.

A practical and industrially feasible alternative is the sequential application of HLAW for the root region followed by SAW filling passes. The HLAW parameters are intentionally selected to avoid full penetration, eliminating the need for root backing or root face formation and thereby increasing the robustness and ease of implementation of the process. The subsequent SAW layers are applied from the opposite side and overlap the hybrid weld root, thereby completing the joint cross-section. Previous work on 30 mm EH36 plates [28] demonstrated that such process combinations ensure complete fusion, stable overlap between weld regions, and adequate mechanical performance even when the joint edges are non-ideal or produced by plasma cutting. Scaling this approach to significantly thicker materials requires an adapted groove geometry and a carefully selected set of welding parameters to ensure reliable metallurgical intersection between the hybrid root pass and the subsequent SAW weld layers.

The present work investigates a combined HLAW and SAW welding approach for 80 mm thick S355ML plates. The study focuses on evaluating process efficiency, weld integrity, microstructural evolution, hardness distribution, and low-temperature toughness to assess the suitability of this hybrid technique for offshore wind turbine fabrication. The specific objectives are to:

- establish a stable HLAW parameter window for deep but partial penetration;
- ensure complete metallurgical overlap between HLAW and NG-SAW;
- characterize the hardness profile across the weld and HAZ;
- evaluate the low-temperature toughness relative to offshore requirements.

MATERIALS AND METHODS

Plates made of S355ML were used for the welding trials. This thermomechanically rolled, fine-grain structural steel is defined in EN 10025-4 and offers a combination of high strength, good weldability and reliable low-temperature toughness. This makes it a suitable choice for welded, load-bearing structures in offshore environments. Its low carbon equivalent (CEV), calculated in accordance with EN 1011-2, contributes to the favorable weldability of the material and minimizes the risk of hydrogen-assisted cold cracking. The chemical composition and mechanical properties of the steel are listed in Tables 1 and 2, respectively.

In the GMAW component of the HLAW process, a 1.2 mm solid wire of type Union K 52 Ni (EN ISO 14341-A: G 50 6 M21 Z3Ni1) was used, together with an argon–carbon dioxide shielding gas contain-

Table 1. Chemical composition of S355ML steel plates according to the manufacturer's material certificate.

Element, wt.%										CEV, %
C	Si	Mn	P	S	Ni	Cr	Mo	V	Fe	
0.046	0.056	1.42	0.009	0.0015	0.067	0.036	0.008	0.001	Bal.	0.31

ing 18 % CO₂ at a flow rate of 25 L/min. For the SAW process, a 4 mm solid wire electrode of grade BA S2 in accordance with EN ISO 14171-A was selected, used in combination with the agglomerated aluminate-basic flux BF3.5. To ensure adequate toughness, the SAW consumable manufacturer recommends limiting the heat input to approximately 2 kJ/mm.

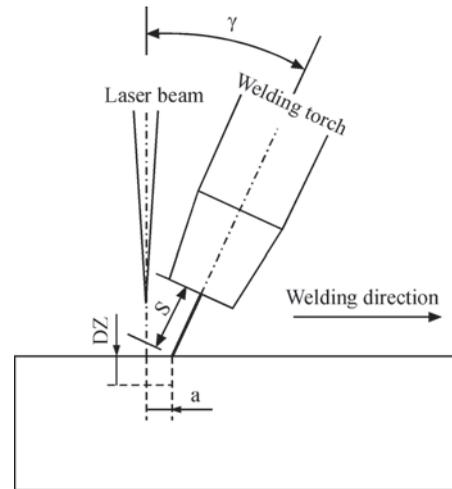
For the HLAW experiments, a 60 kW laser system from TRUMPF was employed. The system was configured by combining three 20 kW TruDisk lasers to achieve the required total power. The laser power was transmitted through the optical combination of three 100 μm fibers into a single process fiber with a core diameter of 300 μm. The TruDisk lasers operated at a wavelength of 1030 nm. A modular laser processing head of the type MPH-EHP (PT Photonic Tools GmbH) was used as the laser optics. The optical setup had a focal length of 400 mm and a magnification ratio of 2:1, resulting in a laser spot diameter of approximately 600 μm in the focal plane.

The GMAW was operated using a QINEO power source (CLOOS GmbH) in DC+ spray arc mode. The hybrid welding head, comprising the laser optic and a fixed GMA torch, was mounted on an industrial robot that guided the process along the joint.

The experiments were performed under constant geometric conditions, with the GMA torch inclined at $\gamma = 25^\circ$ to the laser axis, a laser focus position of $\Delta z = -7$ mm, a wire stick-out of 18 mm. The parameters such as laser power (P_l), arc power (P_{arc}), and welding speed (v_w) were varied to obtain optimal welds with maximum penetration depth and high external as well as internal weld quality. The HLAW process configuration is presented in Figure 1.

Table 2. Mechanical properties of S355ML steel plates according to the manufacturer's material certificate.

R_e , MPa	R_m , MPa	A_5 , %	KV, J	Hardness, HV10
401	484	29	360 (-40 °C)	160


Figure 1. HLAW process configuration

The SAW experiments were performed on an industrial longitudinal welding system capable of operating with up to five wires, each powered by a PERFECTarc® 1500 AC/DC current source from SMS group GmbH. Although the facility allows multi-wire operation with a combined current of up to 7500 A, only a single wire was used in this study to keep the heat input within the required limits.

For the welding trials, S355ML plates with dimensions of 500×200×80 mm³ were prepared. The specimen size was selected considering the available handling and positioning capabilities in the laboratory.


Figure 2. HLAW system: a — experimental setup; b — 80 mm thick specimen prepared for HLAW root pass

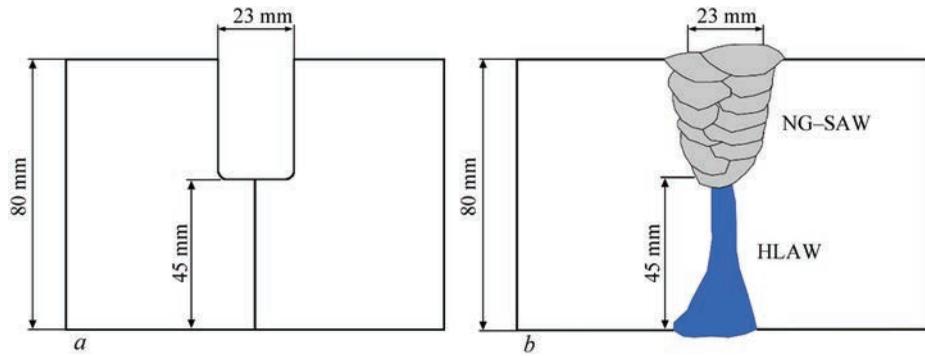


Figure 3. Schematic illustration of the weld joint in an 80 mm thick plate: *a* — joint preparation with U-groove and root face; *b* — weld produced by the combined HLAW and NG-SAW process

The experimental setup for the HLAW trials and the prepared welding specimen are shown in Figure 2, *a* and *b*, respectively.

After the HLAW root pass was applied to the butt joint, a U-shaped groove with a width of 23 mm was machined from the opposite side. The HLAW parameters were selected to achieve approximately half of the 80 mm plate thickness, producing a hybrid weld depth of about 40 mm and defining the remaining depth of the U-groove. This groove was subsequently filled by applying NG-SAW layers. A schematic illustration of the U-shaped groove and resulting weld is shown in Figure 3, *a* and *b*, respectively.

After welding, the specimens were subjected to mechanical and metallurgical testing. The testing program included Charpy impact tests in accordance with EN ISO 9016, light-microscopic examination of metallographic cross-sections in accordance with EN ISO 17639, and Vickers hardness measurements in accordance with EN ISO 9015-1.

RESULTS

WELDING EXPERIMENTS

To produce the 80 mm thick weld, the HLAW process was first applied to the butt joint. The welding parameters were selected to achieve a penetration depth of approximately 40 mm. These parameters were determined in preliminary HLAW trials, which were conducted to establish the laser power required to reach this depth. A target penetration depth of 40 mm was achieved at a laser power of 45 kW, while even at the maximum available power of 60 kW the penetration increased only slightly to approximately 42 mm. The

welding speed was kept constant at 0.6 m/min. This saturation trend indicates that further increasing the penetration depth under the given conditions is not technologically justified, as it would require a disproportionate rise in laser power.

Based on these findings, the following parameters were selected for welding the 80 mm plates: $P_l = 45$ kW, $v_w = 0.6$ m/min, and $v_f = 12$ m/min. At this wire feed speed, the GMAW operated at an arc voltage of $U_{arc} = 32$ V and a current of $I_{arc} = 300$ A. The HLAW process power was therefore approximately 54.6 kW, corresponding to a heat input (E_{HLAW}) of about 4.4 kJ/mm, assuming an overall process efficiency factor of 0.8 for both heat sources.

In the second step, welding was carried out from the opposite side using the NG-SAW process. To prevent the torch from jamming in the narrow groove, a width of 23 mm was selected. To achieve proper remelting of the hybrid root and a sound overlap between the HLAW and SAW weld regions, the first SAW pass was welded using direct current DC+, which provides deeper penetration. The subsequent filling passes were deposited with alternating current (AC) to increase deposition efficiency. Process control was further optimized through digital adjustment of the power source, with the I-balance set to 30 % positive and 70 % negative, enabling higher deposition rates without increasing heat input. The welding parameters and number of passes for the NG-SAW process are summarized in Table 3.

The interpass temperature during the SAW fill passes was monitored using a Type K thermocouple connected to a temperature data logger Lascar EasyLog EL-USB-

Table 3. Parameters of the NG-SAW process

Weld passes	Number of passes	Current type and waveform	I_{arc} , A	U_{arc} , V	v_w , m/min	E_{SAW} per pass, kJ/mm
Root pass	1	DC+	600	33	0.6	1.8
Fill passes	9	AC, I-balance 30/70	600	35	0.6	1.9
Cap passes	2					



Figure 4. Welding of an 80 mm S355ML plate: *a* — HLAW root pass; *b* — NG-SAW filler layers, and *c* — fully welded joint

TC-LCD. The interpass temperature was maintained within a range of approximately 150 to 180 °C.

A representation of the individual welding steps, namely the execution of the HLAW root pass, the deposition of the SAW filling layers, and the fully welded joint, is shown in Figure 4, *a–c*, respectively.

Full cross-sectional macrographs in Figure 5, *a–c* confirmed that the combined HLAW–NG-SAW joint was free of cracks, lack-of-fusion defects, and macroscopic inclusions. Figure 5, *a* shows the HLAW weld produced in the first step, Figure 5, *b* illustrates the deposition of the NG-SAW fill passes, and Figure 5, *c* displays the completely welded 80 mm thick joint with the marked positions of the Charpy V-notches.

The transition between the hybrid and SAW regions was smooth, with no evidence of an unmelted interface or metallurgical discontinuities. The fusion boundaries along the U-groove walls were distinct and uniform, and the bead geometry exhibited a consistent convex profile without undercut.

HARDNESS MEASUREMENTS

The Vickers microhardness ($HV1$) results for the combined HLAW–NG-SAW weld are shown in Figure 6, *a* and *b*. Measurements were taken along three lines located in the SAW fill region, the mid-thickness of the HLAW weld, and the HLAW region approximately 5 mm below the plate surface (Figure 6, *a*). The corresponding hardness profiles for the three regions are shown in Figure 6, *b*.

The hardness profiles are uniform across all regions. The base material exhibits an average hardness of $164 \pm 6 HV1$, while the weld and HAZ regions show mean values of $172 \pm 10 HV1$ (Row 1), $176 \pm 12 HV1$ (Row 2) and $171 \pm 15 HV1$ (Row 3). No significant softening or hardness drops were observed, and all values fall within the typical range for thermome-

chanically rolled S355ML steel ($160–190 HV1$). A slight hardness peak of about $205 HV1$ appears in the mid-thickness of the HLAW fusion zone, likely caused by locally increased cooling rates and the resulting finer solidification structure. This variation remains moderate and does not indicate brittle microstructural regions, confirming that the combined HLAW–NG-SAW process provides controlled thermal conditions and a stable hardness distribution across the weld.

CHARPY TOUGHNESS TESTS

Charpy impact tests were carried out at -40 °C to evaluate the toughness of the hybrid weld. Since the NG-SAW parameters correspond to standard conditions for S355ML steel, Charpy testing focused exclusively on the HLAW region, where varying thermal cycles may influence toughness. The Charpy impact tests were carried out on standard $10 \text{ mm} \times 10 \text{ mm}$ specimens prepared in accordance with ISO

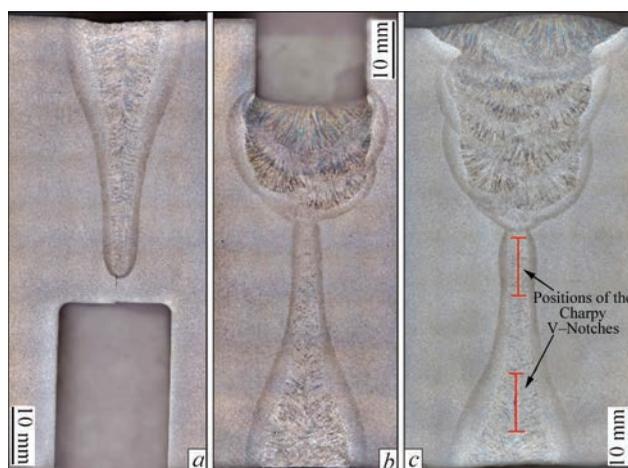


Figure 5. Macro sections of the 80 mm thick weld produced using the combined HLAW and NG-SAW process: *a* — HLAW weld from the first step; *b* — deposition of the NG-SAW fill passes in the U-groove; *c* — completed joint with indicated positions of the Charpy V-notch specimens

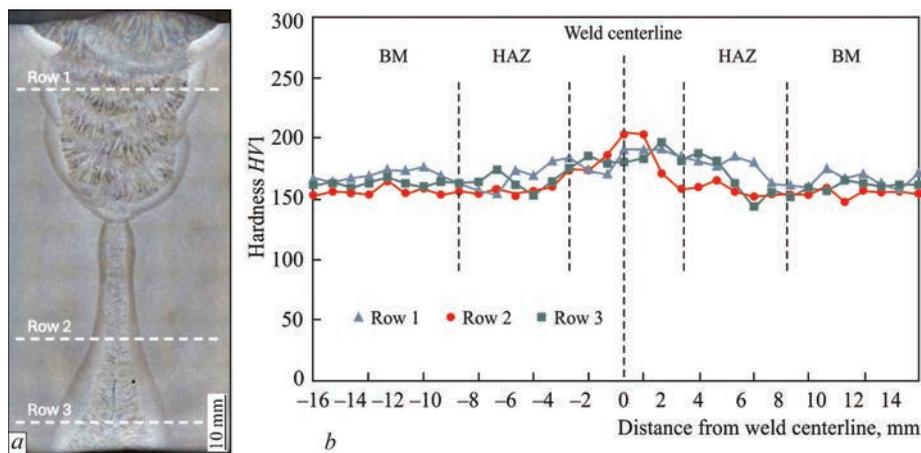


Figure 6. Results of Vickers microhardness ($HV1$) testing across the combined HLAW-NG-SAW welded joint in S355ML: *a* — schematic representation of the measurement lines; *b* — corresponding hardness profiles

148-1. Specimens were taken from two characteristic locations: the laser-dominated root region and the arc-dominated upper region of the HLAW weld, as it shown in Figure 5, *c*. Five specimens were tested in each case, with the V-notch positioned in the center of the WM. The results, presented in Figure 7, show a clear difference between the two weld regions.

The arc-dominated zone reached absorbed energies in the range between 90 and 188 J, with an average of 138 ± 43 J. The relatively large scatter reflects local microstructural variations of the arc-dominated part of hybrid weld, where the weld pool solidifies more slowly, leading to slight differences in grain size and toughness across the section. Nevertheless, all values are well above the minimum toughness levels generally required for structural steels in offshore applications at subzero temperatures.

The laser-dominated zone achieved lower values, between 52 and 80 J, with an average of 65 ± 12 J. This reduction is consistent with higher cooling rates and the formation of finer, harder microstructures. Despite the lower values, the toughness remains adequate for service conditions.

DISCUSSION

The combination of HLAW and NG-SAW proved to be a promising approach for joining 80 mm thick

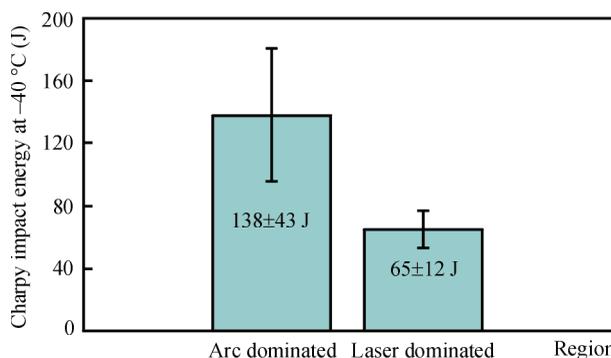


Figure 7. Results of the Charpy impact tests at -40 °C for two different regions of the HLAW weld

S355ML plates. Compared with conventional multi-pass arc welding, the hybrid concept significantly reduces weld volume, filler metal consumption and overall production time, while maintaining the mechanical performance required for offshore applications. These results are consistent with previous investigations on HLAW of fine-grain steels of up to 20 mm thickness [17, 18, 30, 31], which reported high process efficiency and sound weld quality. The present study extends this concept to 80 mm plate thickness and demonstrates that a U-shaped groove with a root face of at least 40 mm enables the application of this combined process to substantially thicker sections.

In the proposed procedure, the HLAW pass is applied first, followed by NG-SAW from the opposite side using a multilayer sequence. The weld cross-section is completed by a stable overlap of the hybrid and SAW regions. A key advantage of this configuration is that no separate HLAW root formation is required, eliminating the need for mechanical or electromagnetic backing systems [26]. This underlines the robustness and practicality of the developed process. The combination of both welding techniques resulted in a substantial reduction in weld volume and heat input. As a result, the 80 mm joint could be completed in only 12 layers instead of the approximately 42 layers typically required for conventional 30° groove preparations [32].

Based on the measured weld cross sections, the material demand can be directly quantified per meter of weld length. For the combined HLAW-NG-SAW joint, the U-shaped groove with a cross-sectional area of approximately 805 mm^2 corresponds to a weld metal volume of 805 cm^3 per meter. Assuming a steel density of 7.85 g/cm^3 , this results in a deposited weld metal mass of about 6.3 kg per meter of weld. In contrast, the conventional multi-layer SAW joint with a groove cross-section of 2355 mm^2 requires a weld metal vol-

ume of 2355 cm³ per meter, which corresponds to approximately 18.5 kg of deposited weld metal per meter. Consequently, the combined HLAW–NG-SAW approach reduces the required weld metal mass by approximately 12.2 kg per meter, corresponding to a reduction factor of about 2.9.

Assuming identical welding travel speed of 0.6 m/min, the overall welding time per meter of joint scales linearly with the number of layers. For a weld length of 1 m, each pass requires approximately 1.67 min. Consequently, a conventional 42-layer SAW procedure results in an arc time of about 70 min/m, whereas the proposed 12-layer combined approach requires only about 20 min/m. This corresponds to a reduction in welding time by approximately 50 min/m, or a factor of 3.5, which represents a time saving of roughly 71 %, even before considering additional reductions in interpass and cleaning times.

The HLAW trials revealed a nonlinear penetration behavior. A penetration depth of approximately 40 mm was achieved at a laser power of 45 kW, while increasing the power to 60 kW yielded only a minor increase to about 42 mm. Similar saturation trends were reported by Kawahito et al. [33], who observed a maximum penetration of about 70 mm at 100 kW in austenitic stainless steel under comparable conditions. This suggests that the penetration limitation is caused by physical constraints, such as keyhole instability and energy losses induced by plasma. Therefore, process optimization should prioritize stabilizing the keyhole and minimizing the effects of plasma shielding rather than increasing laser power.

Heat input was a decisive factor in ensuring the required mechanical properties. According to EN 10225, an energy input of 3.5±0.2 kJ/mm is recommended for offshore steels, with a maximum of 5±0.2 kJ/mm permitted. The parameters applied in this study kept the total heat input below 5 kJ/mm, ensuring controlled thermal cycles throughout the joint.

The combined weld exhibited a uniform hardness distribution between 160 and 190 HV1. This is largely attributed to the tempering effect induced by the subsequent NG-SAW passes on the underlying HLAW weld. Comparable hardness profiles were reported for 30 mm EH36 hybrid welds, supporting the consistency and reproducibility of the process [28].

Charpy impact testing at –40 °C confirmed that the weld meets the toughness requirements for offshore steels. The arc-dominated region achieved an average absorbed energy of 138±45 J, while the laser-dominated region reached 65±12 J. The higher toughness in the arc-dominated region is attributed to the slower cooling rate and more homogeneous microstructure,

while the lower toughness in the laser-dominated zone corresponds to the increased hardness resulting from rapid solidification. Similar observations were reported by Üstündağ et al. [18] for 20 mm structural steels and by Volpp et al. [34], who linked short thermal cycles in laser-based processes to moderate reductions in toughness. Nonetheless, all measured values remain well within the limits specified by EN 10225 and DNV OS-C401, confirming the suitability of the hybrid joint for offshore applications.

Overall, the findings demonstrate that combining HLAW with NG-SAW provides a favorable balance between productivity and mechanical performance. The synergistic interaction of laser and arc enables deep penetration, efficient heat utilization and stable weld pool behavior, while the SAW passes ensure full fusion and a homogeneous microstructure. Whereas earlier studies focused on plate thicknesses up to 20–30 mm, the present work successfully applies the hybrid concept to 80 mm S355ML plates, highlighting its potential for industrial implementation in thick-walled offshore structures. The process satisfies key fabrication requirements by maintaining a controlled heat input, a uniform hardness profile and adequate impact toughness at subzero temperatures.

CONCLUSIONS

1. The combination of hybrid laser-arc welding (HLAW) and narrow-gap submerged arc welding (NG-SAW) has proven to be a reliable and efficient method for joining 80 mm thick S355ML plates. Compared with conventional multi-pass SAW using a 30° groove preparation, the combined approach reduces the weld volume by approximately 66 %, corresponding to a decrease in deposited weld metal from about 18.5 to 6.3 kg/m. In addition, the total welding time per meter of joint is reduced from approximately 70 min/m for a 42-layer SAW procedure to about 20 min/m for the 12-layer combined process, representing a time reduction of roughly 71 %.

2. The U-shaped joint design, consisting of an approximately 40 mm deep HLAW butt weld and a 40 mm NG-SAW section, enabled full joint completion without mechanical or electromagnetic backing, demonstrating the robustness and practicality of the proposed process concept.

3. Maintaining a nominal heat input below 5 kJ/mm ensured controlled thermal cycles and resulted in a uniform hardness distribution between 160 HV1 and 190 HV1 across the weld and heat-affected zone.

4. Charpy V-notch testing at –40 °C confirmed that the welded joint fulfills the toughness requirements for offshore applications, with absorbed energies of 138±45 J in the arc-dominated region and 65±12 J in

the laser-dominated region, both meeting the limits specified in EN 10225 and DNV OS-C401.

5. Overall, the developed HLAW-NG-SAW process satisfies the mechanical and technological requirements for thick-walled offshore structures, offering a favorable combination of high productivity, weld integrity and adequate low-temperature performance.

FUNDING

The research project, “Combination of Laser Hybrid Welding and Narrow Gap Submerged Arc Welding for Thick-Walled Components”, was funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK, Germany) within the Industrial Collective Research (IGF) program following a resolution of the German Bundestag. The project (IGF No. 21532 N/FOSTA Project No. 1472/34/2020) was conducted by the Fraunhofer Institute for Production Systems and Design Technology (Fraunhofer IPK) under the auspices of the Research Association for Steel Application (FOSTA), Düsseldorf.

DATA AVAILABILITY STATEMENT

The data presented in this study are available on request from the corresponding author.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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SUGGESTED CITATION

S. Gook, M. Biegler, A. Gumenyuk, M. Rethmeier (2026) Efficient welding of 80 mm S355ML plates using a hybrid laser-arc and narrow-gap SAW process. *The Paton Welding J.*, 03, 3–11.
DOI: <https://doi.org/10.37434/tpwj2026.03.01>

JOURNAL HOME PAGE

<https://patonpublishinghouse.com/eng/journals/tpwj>

Received: 11.12.2025

Received in revised form: 27.01.2026

Accepted: 02.03.2026

XXIV INTERNATIONAL INDUSTRIAL FORUM-2026

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