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# A comparative study of laser-arc hybrid welding with arc welding for fabrication of offshore substructures

**I Bunaziv**[1], **X Ren**[2] **and V Olden**[1]

[1] Materials and Nanotechnology, SINTEF Industry, P.O. Box 4760 Torgarden, NO-7465 Trondheim, Norway

[2] Metal Production and Processing, SINTEF Industry, NO-0314 Oslo, Norway

E-mail: ivan.bunaziv@sintef.no

**Abstract.** Laser-arc hybrid welding (LAHW) is an efficient and promising joining method for offshore structures made from metallic alloys. Under a high-power laser output, a keyhole is formed that efficiently melts a metal and provides high penetration depths compared to shallow and wide welds made by conventional arc welding, thus it requires much less time for production. A significant reduction in welding time leads to a substantial reduction of welding consumables and electricity use. Higher gap bridging ability can be achieved and tolerances for plate preparation is reduced when an arc is added to a laser beam. This work explicitly presents and compares different welding methods and their efficiency in application for offshore windmill substructures. According to a preliminary calculation, LAHW may reduce welding time by 10–20 times depending on process parameters and up to 15 times lower consumables usage. It was identified that the highest costs in welding is the filler wire followed by a shielding gas and electricity. This leads to high efficiency of LAHW in term of sustainability and reduction of $CO_2$ emissions in general compared to well-established arc welding. However, the narrow and deep welds made by LAHW may suffer from high hardness in the root area, inhomogeneous filler metal mixing, which may lead to poor microstructure, cracking and porosity. This requires an extensive research work on the process optimization and understanding the underlying physics to provide sound welds which must comply with the international standards.

## 1. Introduction

Welding technology is widely used for joining large steel structures. One of the most promising applications is for windmill structures and sub-structures as well. Recently, renewable energy harvesting industry becoming more important to achieve CO2 neutrality and seek higher independency. Up to now, the most dominating welding process is arc welding due to affordability, flexibility, and reliability. Laser beam welding (LBW) is highly attractive joining process compared to conventional arc welding due to highly concentrated energy providing high penetration depths. At sufficiently high-power densities the metal starts to melt and during its evaporation a vapour filler capillary or keyhole is formed which efficiently utilize the energy of incident laser beam **[1-3]**. Therefore, fewer passes are required to join thick sections. LBW may penetrate almost 25–30 mm in a single pass which is much higher than arc welding depending on the process parameters **[4-6]** and utilizes faster welding speeds > 1.0 m/min, thus may offer a substantial increase in productivity.

A more advanced process is laser-arc hybrid welding (LAHW) which usually combines laser welding with gas metal arc welding (GMAW) to provide filler metal for improved microstructure which is more important in thick steel welding **[7-10]**. It can achieve even higher productivity than LBW due to synergistic effect between two heat sources. However, by combining two different heat sources, the complexity of the process is increasing and requires more time for optimization due to much larger number of process parameters.

High penetration depth and welding speeds lead to a significant reduction in welding time and use of welding consumables. Conventional arc welding is a well-developed process, and its electrical efficiency may reach 85–90% for GMA and almost 95% for submerged arc welding (SAW). GMA welding is more attractive due to lower heat inputs and flexibility compared to SAW. Laser beam has lower efficiency since energy must be converted by optics with losses and conventional fiber lasers have wall-plug efficiency (totally converted energy after focusing a laser beam used for melting) of 30%. Modern solid-state fiber laser systems offer a high wall-plug efficiency and may reach 54% according to IPG Photonics **[11]**, which is electrical to optical heat transformation for melting, thus it can even save energy use during production and can be termed as *green* lasers. These saving comes from higher productivity and shorter time used for welding. This offers a high potential for reducing operating costs. Welding consumables is another important factor to consider due to their high costs. LAHW due to higher penetration and fast welding speeds may utilize much fewer welding consumables.

The direct comparison between LAHW and GMAW in term of costs and efficiency is presented in this work. Such comparisons have not been published yet according to authors' knowledge. As a user case, 40 mm thick conventional low carbon S355ML grade steel is selected and welded with two welding methods using standard procedures and double-sided welding technique. Double-sided technique was chosen since a full single-pass penetration of 40 mm thick steel requires much more than 16 kW fiber laser power output which is the limit of the laser station used in this study.

In most of the published research works, researchers showed that LBW and LAHW is more efficient than arc welding in term of productivity and may reach an increase in welding speed by 10–20 times **[4, 12-19]**. However, an explicit study case on the performance is not available according to the authors' knowledge. Moreover, the difference in consumption of welding consumables is not provided. In this work, a concrete case study was used with direct comparisons. According to the preliminary calculations, LAHW may reduce welding time by 10–20 times which depends on the process parameters and up to 15 times lower consumables usage. It was identified that the highest cost as a consumable in welding is the filler wire followed by the shielding gas and the electricity. The difference in electricity use is rather low between two processes but may increase further in near future having more impactful decision. This leads to high efficiency of LAHW in term of sustainability and reduction of $CO_2$ emissions compared to conventional GMAW. LBW showed high hardness, whilst added arc, forming LAHW, provided a significant increase in penetration depths and 40 mm thick steels can be welded with two passes. Measured hardness in the root area of fusion zone was similar to the GMA welds and lower hardness was achieved than is required by the standard DNVGL-OS-C401 where indicated maximum hardness for the tested steel should be < 350 HV. X-ray µCT revealed some cracking in deep LAHW and pores which requires a further attention in the future for improvement of the weld quality. Impact toughness results showed similar and acceptable toughness in welds made by both LAHW and conventional arc welding.

## 2. Methodology

### 2.1. Materials

The used steel plates were 40 mm in thickness and cut to dimensions of 500 mm in length and 150 mm in width. The base metal (BM) is thermomechanically rolled steel (TMCP) with a microstructure consisting of banded ferrite-pearlite providing min. 340 J impact toughness at −60 °C. A commercial 1.2 mm in diameter metal-cored wire was selected. The steel and filler wire chemical compositions are shown in Table 1. The BM has a carbon equivalent value of CET = 0.23 and CEV = 0.34 representing good weldability. The yield strength ($R_{p0.2}$) of BM is 460 MPa and ultimate tensile strength ($R_m$) is 517 MPa. The filler wire provides yield and tensile strength of ≥ 500 MPa and 570–690 MPa respectively. Impact toughness of the filler wire is min. ≥ 47 J at −60 °C as welded.

For both processes double-sided Y-bevelling geometry was used with different parameters since arc welding requires much higher material removal to get access in the root area, it is shown in Figure 1. Machined surfaces had fine surface quality ($R_a$ = 0.8 µm).

**Table 1.** Chemical composition (wt.%) of base metal S355ML (mill certificate values, with small amounts of Nb, V and Ti < 0.05 wt.%) and wire (nominal values in manufacturer's datasheet).

| Material | C | Si | Mn | P | S | Ni | Cr | B | Fe |
|---|---|---|---|---|---|---|---|---|---|
| Base metal | 0.07 | 0.28 | 1.52 | 0.010 | 0.001 | 0.08 | 0.05 | 0.0002 | balance |
| Filler wire | 0.09 | 0.48 | 1.30 | 0.009 | 0.011 | 0.92 | 0.02 | - | balance |

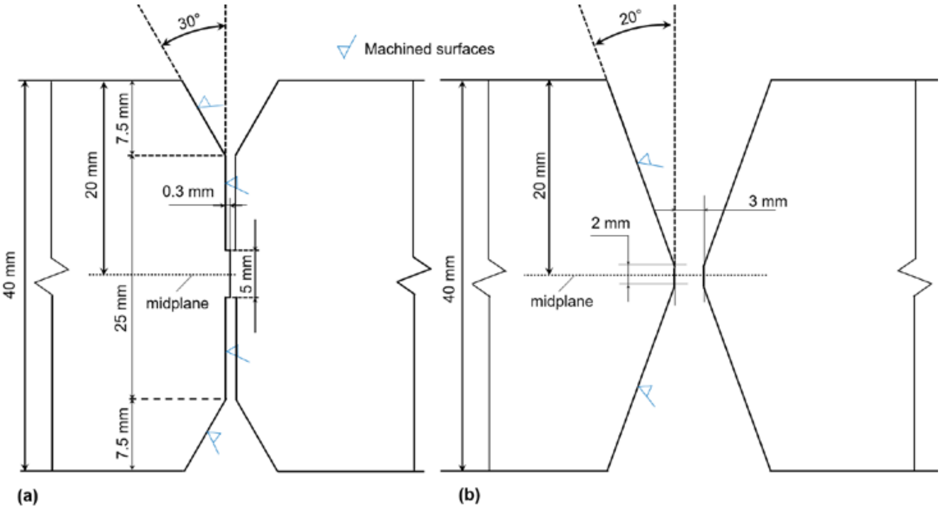

**Figure 1.** Groove preparation geometries for (a) laser-arc hybrid welding and (b) gas metal arc welding.

### 2.2. Equipment and setup parameters

A continuous wave multi-mode 16 kW Yb:fiber laser (IPG Photonics YLS-16000-S2 type model) was used in the experiments which has fiber core diameter 300 µm, beam parameter product 12 mm·mrad, and 1070 nm wavelength. The laser beam had the Gaussian-like heat distribution with the following optical parameters: 300 mm focal length, smallest focused spot size on the surface is 512 µm in diameter (as measured), and the Rayleigh length of 5.6 mm (as measured). The laser beam was inclined by 8° from normal towards the welding surface to eliminate back reflections. GMAW (TPS 400i type machine from Fronius GmbH) torch had 55° inclination angle. Welds were made with an articulated robot. The setup used with nomenclature of LAHW can be retrieved from **[8]**. Constant welding parameters within this work are 15.0±2.5 mm filler wire stick-out, trailing arc position (laser is leading with a dragging angle), and laser-arc interdistance ($D_{LA}$) was 4.0±0.5 mm. A shielding gas mixture consisting of 82% Ar + 18% $CO_2$ was used with 25 l/min flow rate. The focal point position (*FPP*) was located at −4 mm down into steel plates. Ultra-high power laser beam welding form up to 15 cm plasma plume above the keyhole. Therefore, a two air-knife system was used to mitigate plasma plume above the keyhole and eliminate spatter impingement from protection glass above the keyhole. The first air-knife was located just above the arc torch (compressed air up to 8 bar) and secondary air-knife (compressed air up to 5 bar) was located at 10 cm above the process or welded plate surface. The arc welds were made using a similar arc welding machine with a more perpendicular angle of 85° from the welding surfaces and pushing wire position.

### 2.3. Process variables

To compare LAHW with GMAW directly, adequate selection of process parameters should be considered. The average welding speed for GMAW is in the range of 0.2–0.4 m/min (corresponds to 3.33–6.66 mm/s) and for LAHW it has much wider range. For this work two different welding speeds were selected based on our previous experience 0.4 and 0.8 m/min corresponding to low and high speed respectively. Process parameters are listed in Table 2. Note, arc current and voltage are regulated based on the wire feed rate (*WFR*) which is adjusted by a synergy line (not provided in this work). For the second pass, the laser beam power was slightly increased to ensure a full penetration depth.

**Table 2.** Process parameters used for the welding experiments. *WFR* is wire feed rate. $P_L$ is laser power. For GMAW average values are indicated in parenthesis. Designations $Q_L$, $Q_A$, and $Q_H$ are heat input for laser beam, arc, and total hybrid respectively. Note, the average welding speed for arc welding was 0.26 m/min.

| Welding type and notation | Welding speed *m/min* | No. of total passes | *WFR* *m/min* | $P_L$ for 1st pass, *kW* | $P_L$ for 2nd *pass, kW* | $Q_L$, kJ/mm | $Q_A$, kJ/mm | $Q_H$, kJ/mm |
|---|---|---|---|---|---|---|---|---|
| Autogenous LBW | 0.40 | 2 | - | 8 | 10 | 0.84–1.05 | - | - |
| LAHW-low-speed-5WFR | 0.40 | 2 | 5 | 8 | 10 | 0.84–1.05 | 0.48 | 1.32–1.53 |
| LAHW-low-speed-10WFR | 0.40 | 2 | 10 | 8 | 10 | 0.84–1.05 | 1.08 | 2.13–2.32 |
| LAHW-low-speed-14WFR | 0.40 | 2 | 14 | 8 | 10 | 0.84–1.05 | 1.36 | 2.20–2.42 |
| LAHW-high-speed-10WFR | 0.80 | 2 | 10 | 12 | 15 | 0.63–0.79 | 0.54 | 1.18–1.32 |
| GMAW | 0.10–0.36 (avg. 0.26) | 14 | 4.4–7.8 (7.4) | - | - | - | 0.83–1.50 (1.14) | - |

### 2.4. *Characterization and impact testing of welds*

Metallographic studies were performed according to the ISO 17639 **[20]** standard. Etching was carried out in a 2% Nital solution for 5.0 s. Macrographs were examined with optical microscope for microstructure characterization. Measurements of Vickers microhardness ($HV_{0.5}$) were conducted with a 500 gf load according to the ISO 22826 **[21]** standard.

The Charpy V-notch (CVN) impact toughness test was performed according to ISO 9016 **[22]** with standard specimen dimensions of $55\times10\times10$ mm$^3$. The samples were machined out so that the centerline of the CVN specimen is located at fusion line (FL) and weld metal centreline for both methods. The fracture path propagated parallel the welding direction. Five parallels were used for each indicated weld locations. The samples were tested at −30 °C.

## 3. Results and discussion

### 3.1. *Initial welding trials and optimization*

The transversal macrographs of the welds are shown in Figure 2. Autogenous LBW using welding speed of 0.4 m/min with 8–10 kW laser beam power provided relatively low penetration depth. Therefore, to reach a full penetration, 10 kW or 12 kW is required as minimum. Added low power arc forming LAHW, 5.0 m/min *WFR*, increases the depth of the fusion zone with full penetration weld. Added higher power arc with 10 m/min, the penetration depth is increases further. Such overpenetration may decrease process efficiency since more laser beam energy was used. However, it is advantageous to avoid lack of fusion since penetration depth in high power laser slightly varies. Moreover, higher heat input may provide lower hardness in the root because it is directly correlated with the cooling rate **[8]**. According to Bunaziv et al. **[8]**, deep and narrow welds with 0.8 m/min welding speeds and 15 kW laser power, provided cooling time from 800°C to 500°C of 0.5–1.0 sec, thus brittle microstructures were formed. The next experiment with increased *WFR* from 10 to 14 m/min, provided no increase in penetration depths but underfill was reduced. It is often the case that using fast welding speeds and low *WFR*, the underfills and even undercuts may form **[23]**. A good example is the weld with 0.8 m/min and 10 *WFR* having a significant underfill. A further increase in *WFR* may reduce underfill. However, too high *WFR* may lead to significant keyhole collapses since substantial amount of extra metal is added to the weld pool. Moreover, the process becomes difficult to observe even with filters and diode illumination laser. Therefore, extra arc welds for capping are required to form a weld reinforcement. To make full penetration welds with no underfills/undercuts using 0.8 m/min welding speed is nearly impossible with 15 kW laser power output with used optical parameters. It requires higher optical power density, by increasing laser power to e.g. 20–25 kW and/or reducing spot diameter to 200–300 µm (not performed in this scope). Such welds will have even higher depth-to-width ratio which provide excessive hardness and brittle microstructure in the root. Such welds were presented in our previous works **[8, 24]** but they had much cracking in the root area and are not acceptable based on international standards yet. Therefore, extensive research is required to achieve such goals.

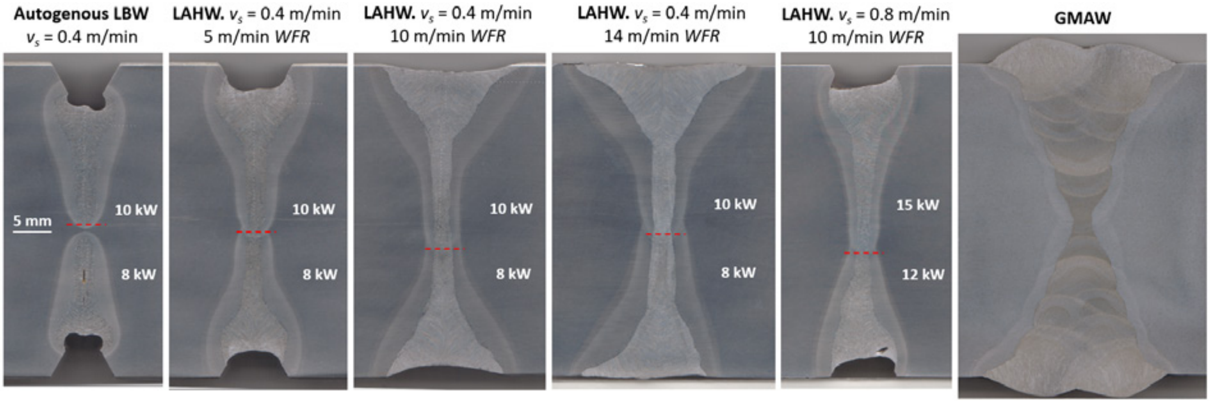

**Figure 2.** Transversal macrographs of deposited welds showing penetration depth, difference in fusion zone geometry, and heat-affected zones.

### 3.2. *Energy efficiency and welding consumables*

Based on the performed experiments, two welds were selected for extensive calculation for efficiency: LAHW with 0.4 m/min welding speed and GMAW. The case studies were expanded by introducing and comparing with weld having 0.8 m/min welding speed and the same welds requiring extra arc deposited caps to understand their influence on productivity and costs. The results are reflected in Figure 3. To weld one meter long 40 mm thick plate, it requires one hour of the welding time using GMAW. Whereas LAHW with arc cap deposition have a significant increase in productivity by almost five times due to high penetration depths due to a laser beam. Pure LAHW (without arc cap deposition) increases the productivity by 12 times which is substantial. High density LAHW further increase the productivity by 24 times compared to conventional GMAW. This a tremendous increase, however, to get high quality welds with minimum number of imperfections using such high welding speeds it is an extraordinary challenging task.

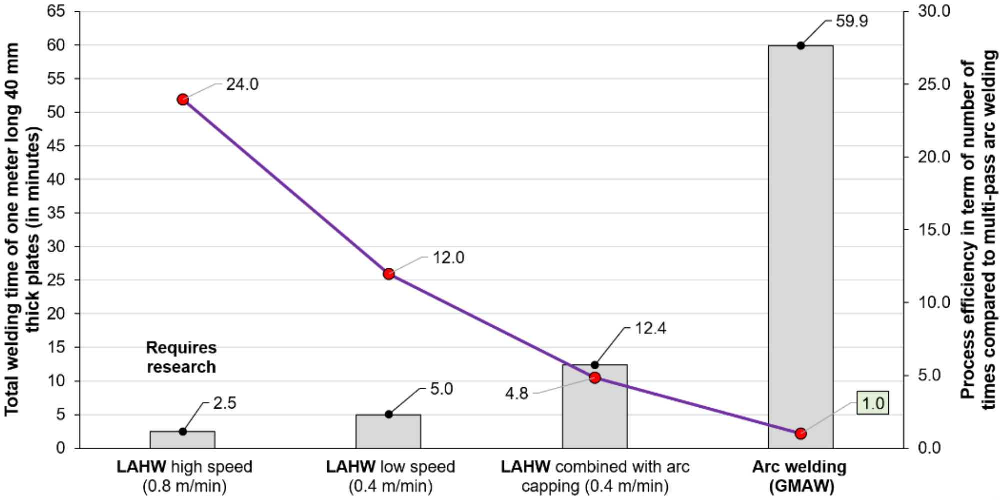

**Figure 3.** Comparison in productivity of different welding techniques and processes.

Based on welding speeds, power outputs, and electrical efficiencies of processes, the energy consumption of the selected and extrapolated cases is shown in Figure 4. Although GMAW has much higher wall-plug efficiency, it consumes the highest amount of electricity since 14 passes are required to make the welded joint. Therefore, almost two times higher consumption of electricity for GMAW is expected compared to LAHW with arc capping. The most efficient is LAHW (pure without arc deposited caps) at high welding speeds. The difference in filler wire consumption is calculated to be much more significant in pricing between the processes (see Figure 5a), and pure LAHW consumed 9 times less of filler wire than GMAW. Taking the approximate price of 250 EUR per one spool (18 kg is a typical weight), the price of consumed filler wire is 10 times higher than electricity. Considering that to produce a filler wire, a high energy is required, LAHW provides significantly lower $CO_2$ footprint. The second largest expense is shielding gas, see Figure 5b, and the difference is even higher between the processes. Shielding gas is often overlooked in pricing but the prices are increasing and tend to increase even higher in upcoming years. Moreover, if helium is used, then this difference becomes even higher. Important to note that the prices of consumables may be different since it depends on many factors, also affected by a purchasable amount. Based on the calculations, LAHW expenditures on electricity is slightly lower than GMAW but based on welding consumables considering that they price is enormous as reflected in Figure 6.

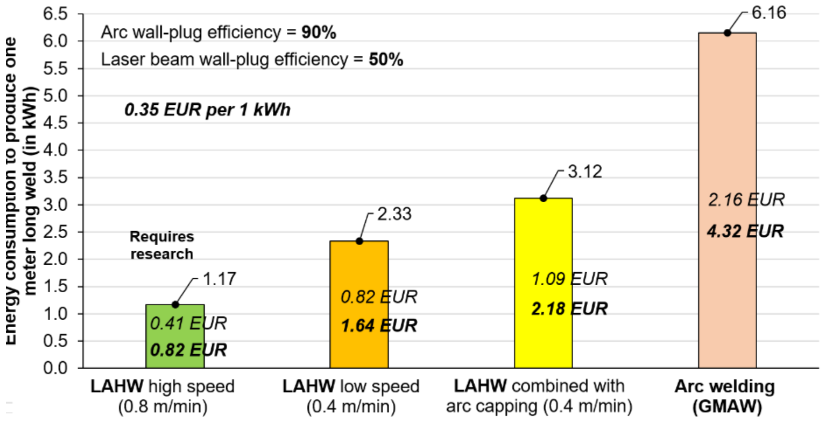

**Figure 4.** Energy consumption of different welding techniques and processes. Note, the energy consumption for only heat source operation is indicated by lower price.

The expenses on additional costs and operations must be considered as well. For example, reduction machining costs of bevelling. Assessment on the effect of flip-over/changing positions of plates during production should be also considered. These all includes in the total operation and labour costs based on the productivity. Naturally, the capital costs investments for LAHW are much higher than for GMAW. Moreover, it requires assessment of safety due to dangerous laser emission since class IV lasers are used. In addition, it requires more skilful personnel to operate. In this work, the break point of investments for LBW/LAHW is not provided. However, it is expected that LAHW may reach the break point within the first few years depending on production volume.

### *3.3. Hardness and internal defects of welds*

The measured hardness in the root area in LAHW with low welding speeds (0.4 m/min) was in the range of 270–280 HV. For faster welding speeds (0.8 m/min) the hardness was 315–320 HV which is expected due to faster cooling rate and more brittle microstructures observed in these areas. For arc welds, the hardness was also the highest in the middle of the plate (275–290 HV) due to faster cooling conditions, which is almost the same as LAHW with 0.4 m/min welding speeds. This shows very promising results for LAHW process considering its significantly enhanced productivity. Narrow and deep welds often possess porosity and centerline cracking located primarily in the root area. The welds with a 20–25 mm in depth are much more susceptible to such defects due to a few reasons as shown and described comprehensively in **[8, 24]** and directly linked to (*i*) fast cooling rate and (*ii*) high stress field with associated solidification shrinkage. Most of these cracks are most likely solidification cracking which forms within mushy zone. Therefore, microstructural improvement has limited or no effect on the cracking suppression **[8]**. In this work, a high resolution µCT scanner revealed thin and small solidification cracks developed at weld centerline in all deposited deep LAHW joints. Therefore, a comprehensive study must be addressed in the future work and especially its effect on fatigue properties.

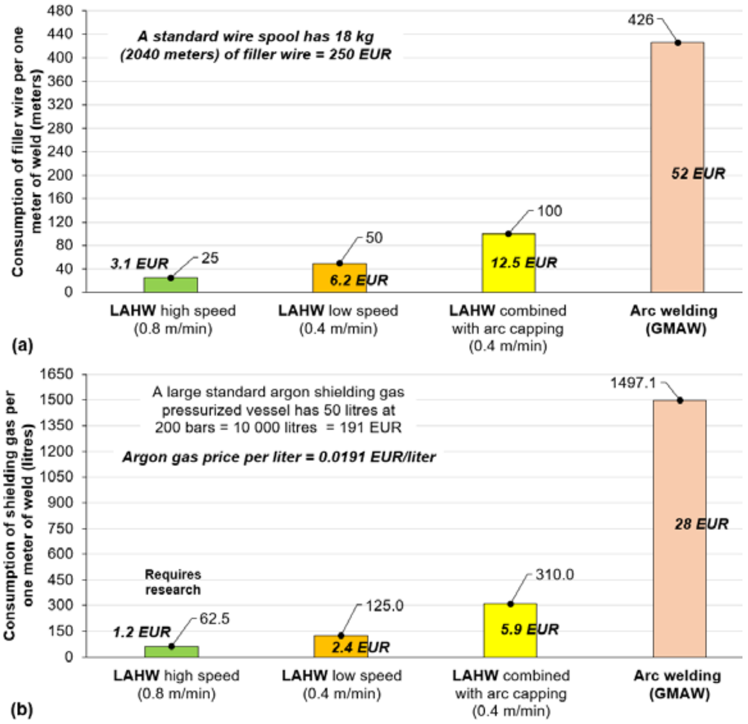

**Figure 5.** Consumption of (a) filler wire and (b) shielding gas for different welding processes.

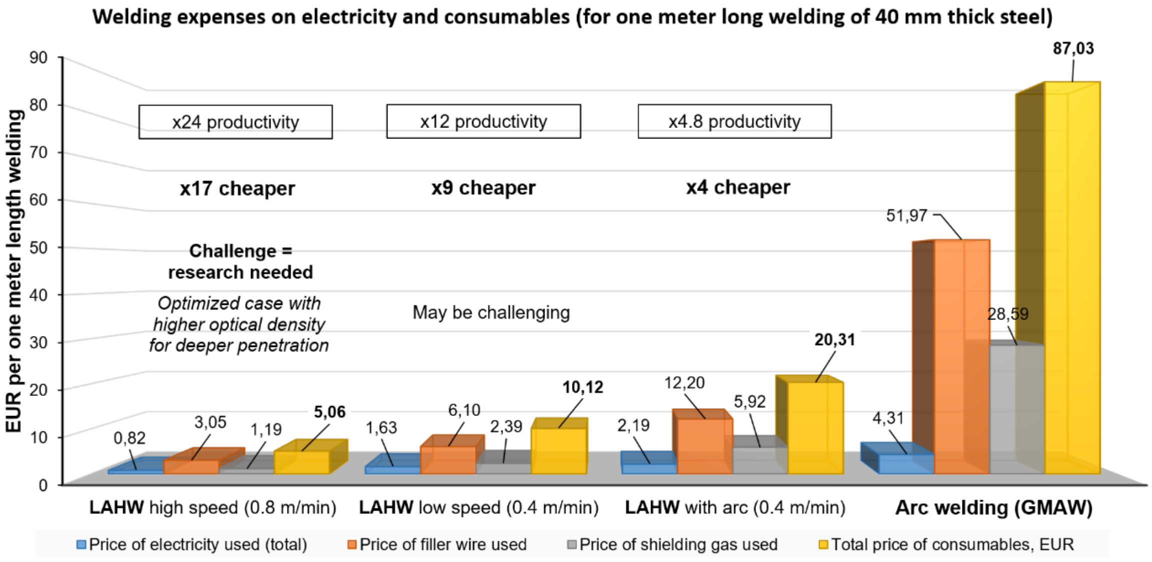

**Figure 6.** Overview of used most important consumables for different welds.

### *3.4. Impact toughness*

The standard Charpy V-notch test results conducted at −30°C temperature are presented in Figure 7. The selected welds from LAHW and GMAW had very similar impact toughness for both FL and WM with a relatively low data scattering apart from FL in GMAW case. This is expected since placing the V-notch in a X-shaped joint geometry is challenging because it inevitably covers some weld metal areas. Therefore, toughness values for fusion line often provides more scattering than for WM. LAHW provided similar toughness to GMAW since similar microstructure was obtained. Although LAHW, had slightly smaller vol.% of AF, the toughness was high since much fewer residual stresses are formed which may increase resistance to fracture. Notably, it is difficult to achieve better microstructure than one found in the produced GMAW welds using standard procedures since used metal-cored wire is well tested. The heat input per pass is similar (see Table 2) for both processes since in this case for LAHW only $Q_L$ is relevant while $Q_A$ dissipates in the upper area with low effect on the root, this is described in detail in **[25]**. Therefore, the grain size in the coarse-grained heat affected zone (CGHAZ) is also similar. This leads to a similar toughness for both joining methods used. However, LAHW is 12 times faster than GMAW which makes it an attractive alternative fusion joining method for thick-walled steel components and substructures.

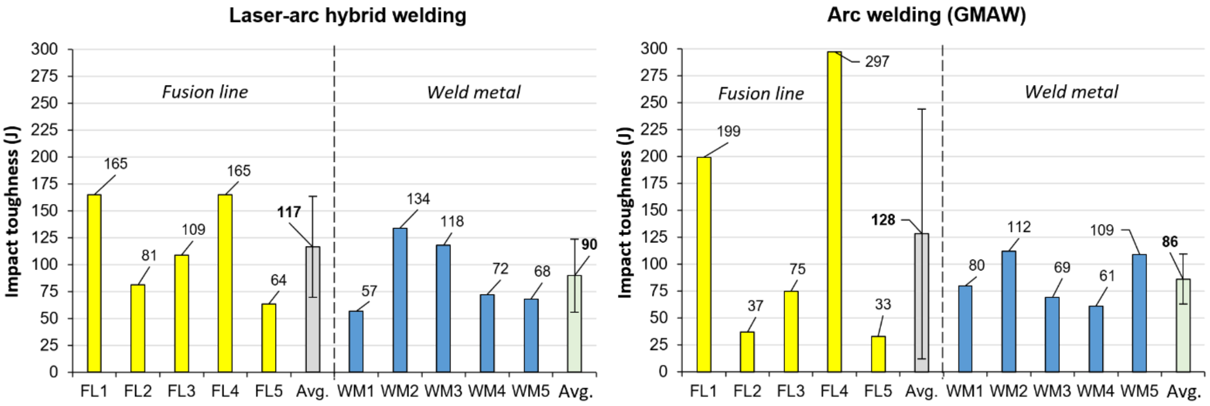

**Figure 7.** Impact toughness results tested at −30°C. FL1−FL5 and WM1−WM5 indicates numbering of samples.

## 4. Conclusions

Based on the experimental results, the following conclusions can be drawn:

- LAHW is significantly more productive than GMAW due to high penetration depth which requires much less passes.
- LAHW consumes twice less energy than GMAW due to higher penetration depths providing much less welding time.
- Welding consumable usage and financial expenses for LAHW is significantly lower than GMAW and generally are much higher than electricity usage.
- The most expensive consumable is filler wire used for filling the groove between two welded specimens. For LAHW, much less bevelling is used, thus the welding process is more efficient.
- Despite of economic advantages of LAHW, there are many challenges regarding the quality of welds and the most critical one is cracking at weld centreline.
- With well-optimized process parameters, it is possible to achieve defect-free joints using LAHW at low welding speeds of 0.4 m/min. The impact toughness results show promising results and are comparable to GMAW.

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## References

[1] Kaplan A 1994 A model of deep penetration laser welding based on calculation of the keyhole profile. *J. Phys. D: Appl. Phys.* **27**(9) 1805-14

[2] Otto A, Schmidt M 2010 Towards a universal numerical simulation model for laser material processing. *Phys. Procedia* **5** 35-46

[3] Cho J-H, Na S-J 2006 Implementation of real-time multiple reflection and Fresnel absorption of laser beam in keyhole. *J. Phys. D: Appl. Phys.* **39**(24) 5372-78

[4] Bunaziv I, Frostevarg J, Akselsen O M, Kaplan A F H 2018 The penetration efficiency of thick plate laser-arc hybrid welding. *Int. J. Adv. Manuf. Technol.* **97**(5) 2907-19

[5] Reisgen U, Olschok S, Jakobs S, Engels O 2016 Modern hybrid welding process for structural steelwork engineering—Laser submerged arc hybrid welding. *J. Laser Appl.* **28**(2) 022011

[6] Sokolov M, Salminen A, Kuznetsov M, Tsibulskiy I 2011 Laser welding and weld hardness analysis of thick section S355 structural steel. *Mater. Des.* **32**(10) 5127-31

[7] Steen W M 1980 Arc augmented laser processing of materials. *J. Appl. Phys.* **51**(11) 5636-41

[8] Bunaziv I, Langelandsvik G, Ren X, Westermann I, Rørvik G, Dørum C, Danielsen M H, Eriksson M 2022 Effect of preheating and preplaced filler wire on microstructure and toughness in laser-arc hybrid welding of thick steel. *J. Manuf. Processes* **82** 829-47

[9] Bunaziv I, Akselsen O M, Frostevarg J, Kaplan A F H 2018 Deep penetration fiber laser-arc hybrid welding of thick HSLA steel. *J. Mater. Process. Technol* **256** 216-28

[10] Meng X, Artinov A, Bachmann M, Rethmeier M 2019 Numerical and experimental investigation of thermo-fluid flow and element transport in electromagnetic stirring enhanced wire feed laser beam welding. *Int. J. Heat Mass Transfer* **144** 118663

[11] Shcherbakov E A, Fomin V V, Abramov A A, Ferin A A, Mochalov D V, Gapontsev V P 2013 Industrial grade 100 kW power CW fiber laser. In *Advanced Solid State Lasers Congress*, OSA Technical Digest (online), ATh4A.2

[12] Bunaziv I, Dørum C, Nielsen S E, Suikkanen P, Ren X, Nyhus B, Eriksson M, Akselsen O M 2020 Laser-arc hybrid welding of 12- and 15-mm thick structural steel. *Int. J. Adv. Manuf. Technol.* **107**(5) 2649-69

[13] Grupp M, Klinker K, Cattaneo S 2011 Welding of high thicknesses using a fibre optic laser up to 30 kW. *Welding International* **27**(2) 109-12

[14] Quintino L, Costa A, Miranda R, Yapp D, Kumar V, Kong C J 2007 Welding with high power fiber lasers – A preliminary study. *Mater. Des.* **28**(4) 1231-37

[15] Gook S, Gumenyuk A, Rethmeier M 2014 Hybrid laser arc welding of X80 and X120 steel grade. *Science and Technology of Welding and Joining* **19**(1) 15-24

[16] Cao X, Wanjara P, Huang J, Munro C, Nolting A 2011 Hybrid fiber laser – Arc welding of thick section high strength low alloy steel. *Mater. Des.* **32**(6) 3399-413

[17] Fukami K, Setoda K 2013 Development of high-efficiency MIG-laser hybrid welding technology. *Welding International* **27**(2) 87-92

[18] Webster S, Kristensen J K, Petring D 2008 Joining of thick section steels using hybrid laser welding. *Ironmak. Steelmak.* **35**(7) 496-504

[19] Üstündağ Ö, Gook S, Gumenyuk A, Rethmeier M 2020 Hybrid laser arc welding of thick high-strength pipeline steels of grade X120 with adapted heat input. *J. Mater. Process. Technol* **275** 116358

[20] ISO 17639 - Destructive tests on welds in metallic materials - Macroscopic and microscopic examination of welds. in, International Organization for Standardization, 2003

[21] ISO 22826 - Destructive tests on welds in metallic materials - Hardness testing of narrow joints welded by laser and electron beam (Vickers and Knoop hardness tests). in, International Organization for Standardization, 2005

[22] ISO 9016 - Destructive tests on welds in metallic materials - Impact tests - Test specimen location, notch orientation and examination. in, International Organization for Standardization, 2012.

[23] Frostevarg J, Kaplan A 2014 Undercut suppression in laser-arc hybrid welding by melt pool tailoring. *J. Laser Appl.* **26**(3)

[24] Bunaziv I, Wenner S, Ren X, Frostevarg J, Kaplan A F H, Akselsen O M 2020 Filler metal distribution and processing stability in laser-arc hybrid welding of thick HSLA steel. *J. Manuf. Processes* **54** 228-39

[25] Bunaziv I, Akselsen O M, Frostevarg J, Kaplan A F H 2019 Application of laser-arc hybrid welding of steel for low-temperature service. *Int. J. Adv. Manuf. Technol.* **102**(5) 2601-13