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Laser Submerged Arc Welding (LUPuS) with Solid State Lasers

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Abstract

The laser beam-submerged arc hybrid welding method originates from the knowledge that, with increasing penetration depth, the laser beam process has a tendency to pore formation in the lower weld regions. The coupling with the energy-efficient submerged-arc process improves degassing and reduces the tendency to pore formation. The newly developed hybrid welding process allows the welding of plates with a thickness larger than 20° mm in a single pass and the welding of thicker plates with the double-sided single pass technique.

In this special hybrid process, the use of CO_2-lasers causes problems when forward sliding flux of slag meets the laser beam path and forms an uncontrollable plasma plume in the beam path. This plasma then shields the work piece from the laser power and thus provokes the collapse of the laser keyhole and leads to process instability. The substitution of the CO_2-laser with a modern solid-state laser significantly improves the performance and the stability of the hybrid process. This contribution will demonstrate the latest results and improvements by means of welding results gained with steel plates with a thickness of up to 40 mm.

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Keywords: Laser; Solid State; Submerged Arc; Hybrid Welding

1. Motivation

The joining of thick walled structural steel components with wall thicknesses up to and over 100 mm is a typical application in the pipeline industry and the wind energy sector (grounding and tower structures). Main joining process is submerged arc welding (SAW), both in conventional and narrow gap bevel preparations. These bevel preparations are to be machined and filled in numerous weld layers. This process consumes time, filler wire and flux.

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The inevitable heat input leads to thermal distortion that requires additional time and work either due to repeated turn-over during the welding process and/or straightening after welding.

The use of beam welding processes with high weld-in depths and concentrated heat input promises cost reduction due to the saving of welding time and of filler material and it is, at the same time, generating less thermal distortion.

For most applications with thick walled structures, the use of electron beam welding (EBW) in vacuum chambers is not economical. The laser beam welding (LBW) process has, on the other hand, shortcomings such as lower gap bridge-ability and, due to concentrated heat input and high cooling rates, the tendency to hardening of the weld metal. These negative aspects have been alleviated by the process combination of laser beam and gas metal arc (GMA) welding.

The benefit of substituting the submerged arc welding process with a hybrid process consisting of a laser beam and an arc welding process can be easily understood by comparing a typical bevel preparation and weld sequence on a plate with a wall thickness of merely 35 mm, Fig. 1.

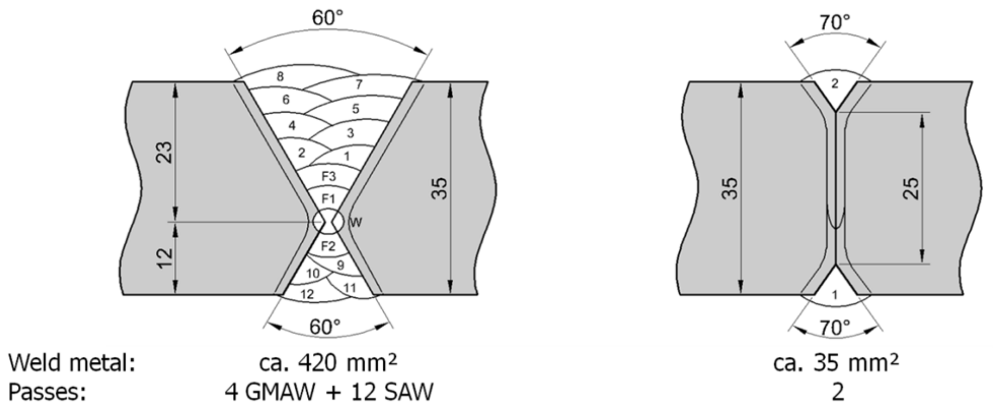

Fig. 1. Comparison of SAW and LB-GMA hybrid welding of plates with a wall thickness of 35 mm.

The advantages of using a laser beam arc hybrid welding process are clearly visible. Taking into account that the average welding speed achievable with a laser beam arc hybrid welding process is at least two times the speed of a single-wire submerged arc welding process, the saving of total welding time is also even more appealing. The use of the double-sided, single pass technique with the hybrid process minimizes thermal distortion and, at the same time, weld seam backing is no longer necessary.

As promising as the use of a laser beam gas metal arc hybrid welding process may seem for thick plate applications, there are some problems which hinder a wider use so far. The laser beam GMA hybrid process tends to form a more or less pronounced porosity with increasing weld-in depth. [1] This tendency increases, especially with a lack of full penetration, for example when the double-sided, single-pass technique is applied.

2. State of the Art

In order to overcome the limitations of the laser beam gas metal arc hybrid welding process in terms of porosity in deep weld regions, the Welding and Joining Institute developed the laser beam submerged arc hybrid welding process (LB-SAW or LUPuS). The substitution of the gas metal arc welding process with the submerged arc welding process increases the degassing ability due to the higher heat input and the good thermal insulation of the slack and the flux. The submerged arc process generates long and deep molten pools with increased solidifying times. Porosity formed by the metal vapor capillary of the laser beam process part has now the ability to degas through the molten pool of the following submerged arc welding dominated molten pool.

The hybrid process has been initially developed using a 20 kW CO_2-Laser. Since the laser radiation of this laser type with a wavelength of 10600 µm already has a tendency to form a plasma plume above the keyhole, several measures had to be taken to stabilize the hybrid process. As a primary measure, the flux of the submerged arc welding process had to be separated from the laser beam path. In order to achieve this, a separating plate was inserted between the two process parts. As a second measure, the total amount of flux was reduced by scaling down the flux hopper. Finally the anyway necessary helium gas flow to prevent formation of plasma above the keyhole was increased and directed towards the separating plate. In this configuration, the helium not only prevents plasma formation but also removes flux and holds back the slag from the laser foot point, Fig. 2

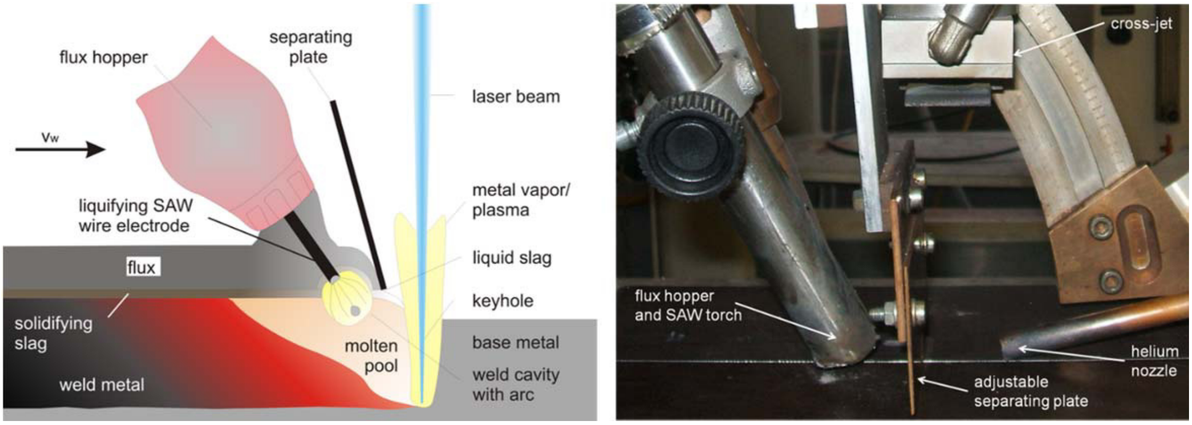

Fig. 2. Laser beam submerged arc hybrid welding setup, schematic (left) and implemented setup (right).

With this setup successful double-sided, single-pass connection welds on unalloyed construction steel (S355, S460) and pipeline steel (X65 – L460MB) with wall thicknesses of 35 mm have been performed, Fig. 3. The typical bevel preparation used is a DY-preparation with a 70° total opening angle and a root face height of 25 mm.

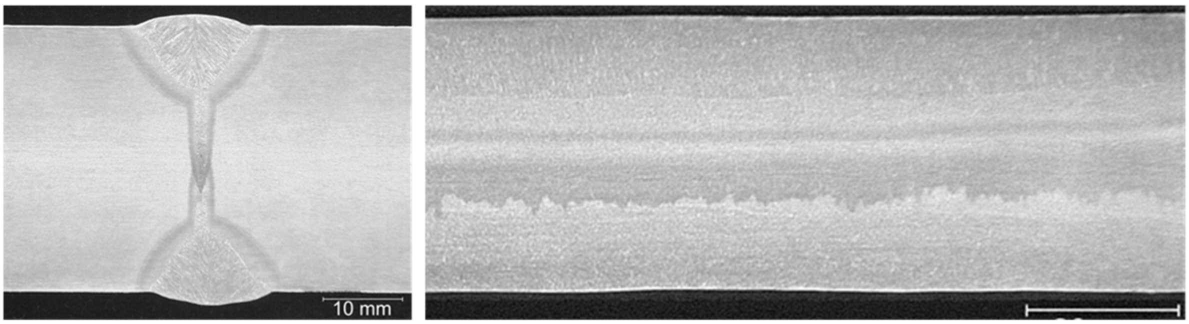

Fig. 3. X65 pipeline steel, 35 mm wall thickness, milled bevel preparation, zero gap, P_L=20 kW, v_W=1 m/min.

The weld metal is virtually free of pores and with wall thicknesses of 35 mm a safe connection weld with adequate overlap of pass and counter-pass was reproducibly achievable. Hardness measurements, tensile and Charpy tests showed acceptable results. [2] As a by-product, the connection welds made with double-sided, single-pass technique showed little to none remaining thermal distortion regardless whether the parts were preheated or not, Fig. 4.

Fig. 4. X65 pipeline steel, 35 mm wall thickness – remaining thermal distortion after double-sided, single pass connection weld.

3. Transition to Solid-State Laser

The laser beam submerged arc hybrid welding process with CO_2-laser is able to deliver more than acceptable connection welds on steel plates with wall thicknesses of up to 35 mm. Nevertheless, the problem of process reliability and reproducibility remains. Even though much effort was invested in the setting of geometrical parameters of the separating plate and gas nozzle, the occasional plasma plume formation due to minimal amounts of flux reaching the laser beam path was not entirely preventable.

The impact of minimal amounts of flux in the CO_2 laser beam submerged arc process leads to at least a formation of a partial laser plume, which leads to a significant decrease of weld-in depth. A full-developed plasma plume absorbs the laser power above the keyhole and virtually shields the work piece, Fig. 5 (left).

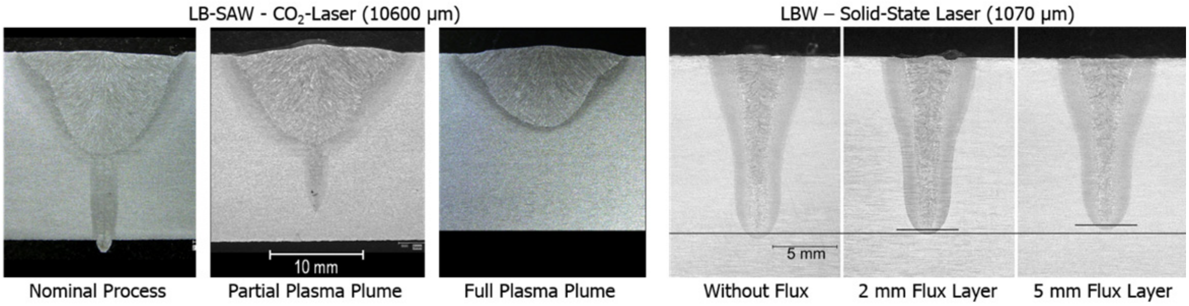

Fig. 5. Impact on flux on CO_2-laser (left) – Solid-State Laser (right).

Trials with flux layers on plates during laser beam welding with solid-state laser showed very little influence on achievable weld-in depths, Fig. 5 (right). Even dense flux layers of 5 mm thickness resulted in insignificant loss of penetration depth. The laser radiation with much shorter wavelength of 1070 µm is, in the first place, less prone to plasma formation. Flux or slag in the laser beam path are vaporized instantly and the resulting vapor and fumes are not turned into plasma due to low absorption of laser power. To prevent an adverse effect of the fumes, a simple air-knife above the process cleans the laser beam path, Fig. 6.

The use of solid-state lasers for the application of laser beam submerged arc hybrid welding also inherits the immanent advantages of this laser type. Modern solid-state lasers like fiber or disk lasers deliver high power outputs while maintaining a comparatively high beam quality with an increased efficiency of 30-35 % (CO_2-Laser: 10-15 %). This leads to smaller focal diameters and hence higher laser intensities which can be transformed into weld-in depth or welding speed at lower operating costs.

Additionally the laser radiation can be guided by fibers instead of metal mirrors. This increases the flexibility of the welding setups and opens possibilities for additional parameters (e.g. laser inclination angle) and spatial separation of laser beam generation and welding station. Moreover, this simplifies the realization of welding machines that are able to perform long linear welds, e.g. for longitudinal welded pipelines.

Finally, with solid-state lasers the shielding gas type was changed from high priced helium with high gas flows (up to 50 l/min) to control the laser plasma to more affordable argon or argon mix gases with lower gas flows (20-25 l/min).

The newly designed laser beam submerged arc hybrid welding head allows smaller process distances and provides more and easier possibilities to alter the geometrical parameters of the single process parts. Besides the process distance, these parameters include the inclination angle of both SAW torch and laser beam, as well as the position and the angle of the separating plate, Fig. 6.

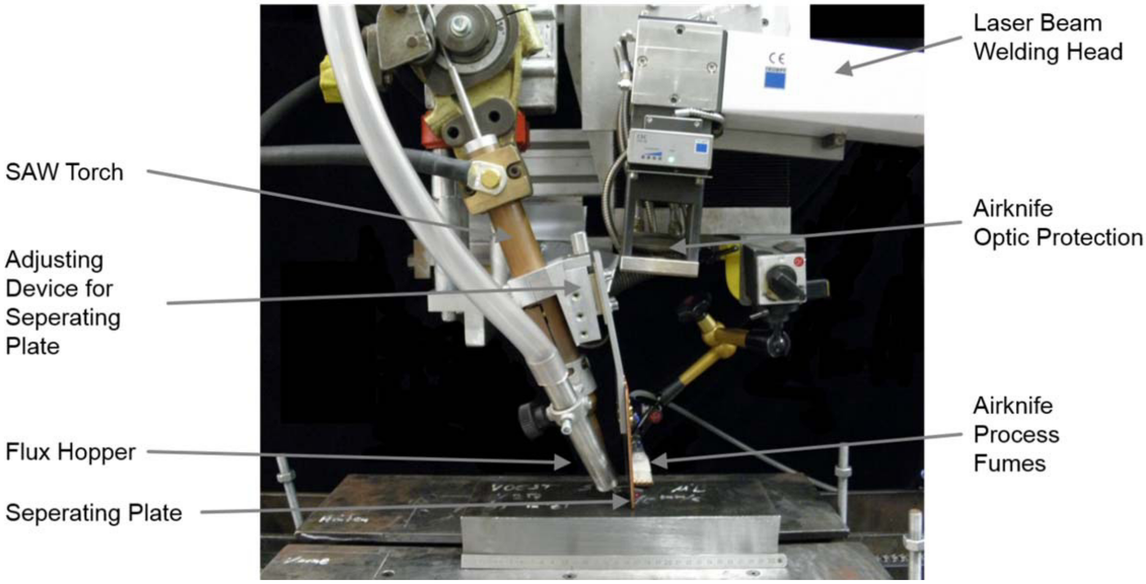

Fig. 6. Laser Beam Submerged Arc hybrid Welding (LB-SAW) setup with solid-state laser.

The wire feed unit and the SAW torch are sized to use commonly available wires for submerged arc welding with diameters of 3 mm and 4 mm.

The hybrid welding setup is driven by a 16 kW Trumpf TruDisk laser and an ESAB LAE 1250 submerged arc power source. All process parameters are controlled by a combination of measurement and control hardware and a software frontend. Beside the control of the process parameters as well as the start and stop of the process, the system also measures the welding voltage and current, the laser power and up to four thermocouples.

Since the initial research work with laser beam submerged arc hybrid welding was conducted with a 20 kW CO_2-laser, the change to a 16 kW solid-state laser seems, at first sight, to be a step back. Nevertheless, the significantly higher beam quality and hence higher laser intensity at the work piece as well as the virtually non-existing plasma formation of the laser lead to increased process performance in terms of wall thickness and reproducibility. The rate of usable weld seams due to plasma formation was below 70 % with the CO2-laser. Since the change-over to the solid state laser source, more than 50 connection welds in double-sided, single layer technique (i.e. more than 100 individual welds) have been performed without a single process disturbance due to flux or slag in the beam path. The range of wall thicknesses that can be welded increased from 35 mm to 40 mm and beyond.

4. Welding results

Welding trials have been performed within a large range of process parameters. In the following, some relevant welding results will be given. The bevel preparation was DY with a total opening angle of 60° and a root face height of 25 mm (35 mm wall thickness) or 30 mm (40 mm wall thickness).

4.1. Welding Trials 35 mm X65 (L450MB), 3 mm Wire, positive polarity

Based on the research work done with CO_2-lasers, a basic parameter set for laser beam submerged arc hybrid welding with the disk laser has been developed for 3 mm wire (S3) with positive polarity, Table 1.

Table 1. Basic Parameters - X65, 3 mm positive wire.

Parameter	Unit	Value
Laser Power	[kW]	16
Voltage (Set Point)	[V]	36
Wire Feed	[m/min]	2,4
Welding Speed	[m/min]	1,0

The hybrid welding process generates even weld seams with smooth transitions from weld metal to work piece surface. The cross-section shows virtually pore-free weld metal and a sufficient overlap between pass and counter-pass to ensure flawless connections, Fig. 7.

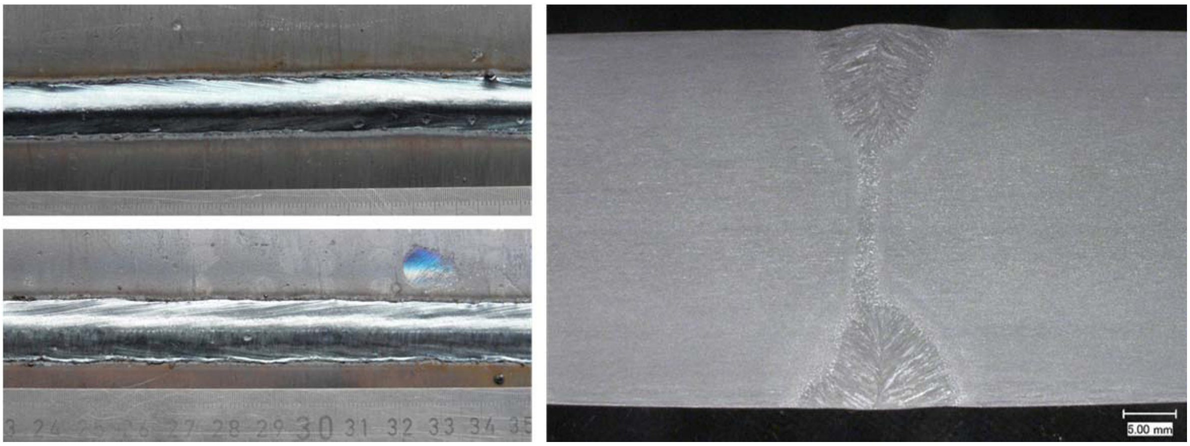

Fig. 7. X65, 35 mm, 3 mm positive wire – Weld Seam Appearance (left) – Cross-Section (right).

The outer submerged arc welding dominated areas show a large weld penetration. The measured process data shows an average welding current of 615 A, Table 2.

Table 2. Measured Process Data - X65, 3 mm positive wire.

Parameter	Unit	Value
Voltage	[V]	30
Current	[A]	615
Deposition Rate	[kg/h]	8
Energy Unit per Length	[kJ/mm]	2,067

This value exceeds the maximum current specified for the used flux. This resulted in overheated slag which was periodically running into the laser beam path. The solid state laser tolerated the slag without leading to process instability. Nevertheless, the process has been altered to reduce the welding current and stabilize the slag.

4.2. Welding Trials 35 mm X65 (L450MB), 3 mm Wire, negative polarity

Based on the knowledge that in submerged arc welding with reversed polarity (negative wire), both, welding current and penetration depth will decrease at constant deposition rate, a basic parameter set has been developed. [3] In order to further decrease the welding current, also the deposition rate, i.e. the wire feed and welding speed have been reduced slightly, Table 3.

Table 3. Basic parameters - X65, 3 mm negative wire.

Parameter	Unit	Value
Laser Power	[kW]	16
Voltage (Set Point)	[V]	36
Wire Feed	[m/min]	2,4
Welding Speed	[m/min]	0,8

Also with negative wire polarity, the hybrid process generates even weld seams. The main difference is noticeable in the cross-section. Beside the absence of pores and other flaws, the much smaller penetration depth of the submerged arc is evident. Nevertheless the weld seam geometry is more suitable for the hybrid process. Since the penetration depth is dominated by the laser, the smaller penetration of the arc blends to a smooth transition between the characteristic areas of the weld seam, Fig. 8.

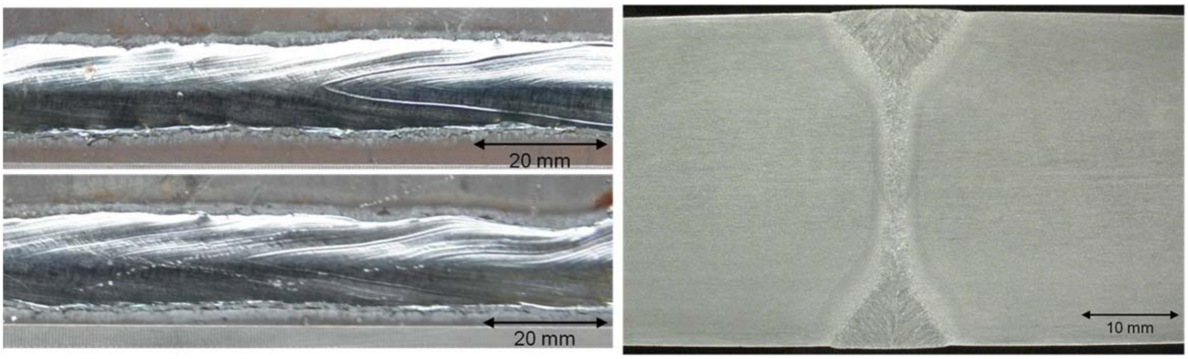

Fig. 8. X65, 35 mm, 3 mm negative wire – Weld Seam Appearance (left) – Cross-Section (right).

The measured process data show the success of the measures which were taken to decrease the current, Table 4.

Table 4. Measured Process Data – X65, 3 mm negative wire.

Parameter	Unit	Value
Voltage	[V]	30
Current	[A]	380
Deposition Rate	[kg/h]	6,33
Energy Unit per Length	[kJ/mm]	2,055

The measured average current of merely 380 A is way below the maximum advised for the flux and hence with this parameter set neither flux nor slag reached the laser beam path. Due to the reduced welding speed while keeping the laser power at 16 kW, the total energy per unit length is about the same as in the trials made with with positive wire, Table 2.

4.3. Welding Trials 40 mm P265GH, 3 mm Wire, positive polarity

Based on the promising results at X65 with 35 mm wall thickness, welding trials on P265GH with plate thicknesses of 40 mm were conducted. To ensure a sufficient overlap between the pass and counter-pass the welding speed has been decreased to 0,75 m/min, Table 5. By keeping the same basic DY bevel preparation, the wire feed rate had to be adjusted to achieve an even filling degree. To prevent possible lack of fusion in the outer, SAW-dominated areas a positive wire polarity was chosen again.

Table 5. Basic Parameters – P265GH, 3 mm positive wire.

Parameter	Unit	Value
Laser Power	[kW]	16
Voltage (Setpoint)	[V]	36
Wire Feed	[m/min]	1,9
Welding Speed	[m/min]	0,75

Also with this parameter set the weld seam surfaces show an even appearance and a smooth transition to the base material. The cross-sections show an adequate overlap between pass and counter-pass and no sign of porosity or other flaws, Fig. 9.

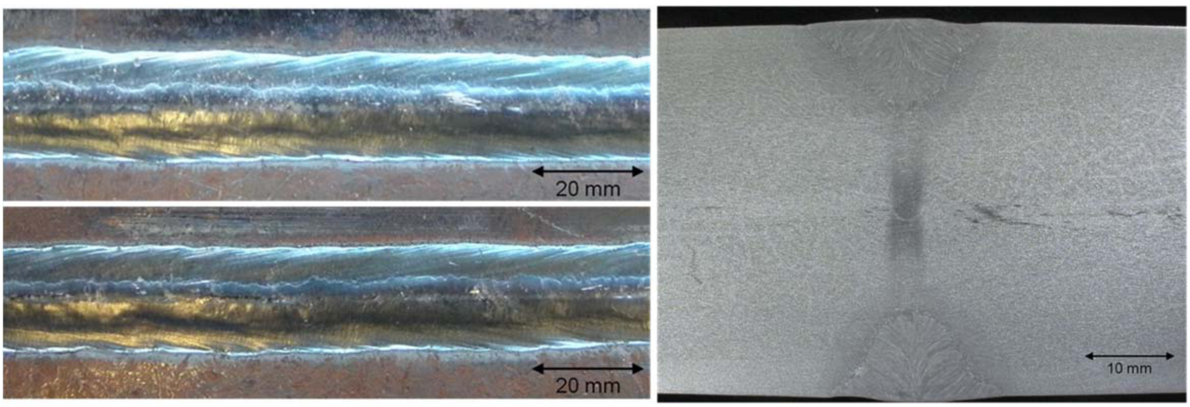

Fig. 9. P265GH, 40 mm – Weld Seam Appearance (left) – Cross-Section (right).

Despite the reduction of the deposition rate, the process data lead to the highest energy per unit length of the three presented parameters, Table 6

Table 6. Measured Process Data – P265GH, 3 mm positive wire.

Parameter	Unit	Value
Voltage	[V]	30
Current	[A]	560
Deposition Rate	[kg/h]	6,33
Energy Unit per Length	[kJ/mm]	2,624

This is established by the fact that the laser power remained at 16 kW while the weld speed was reduced to 0.75 m/min. In addition, the positive polarity of the wire leads to an average welding current of 560 A, quite on the border of the suggested maximum value of 600 A for the used flux. However, even when this parameter set was used there was no problem with slag reaching the laser beam foot point.

5. Summary and Planned Development

The laser beam submerged arc hybrid welding process with CO2-laser already showed that steel plates with up to 35 mm wall thickness can be welded successfully in double-sided, single layer technique. However the process showed problems in terms of process safety and reproducibility. The sensitivity of the laser beam radiation to form uncontrollable plasma plumes when even small amounts of flux or slag reach the laser beam is the Achilles' heel of this process variant.

With the substitution of the CO_2-laser with a modern disk laser this problem was solved. The laser radiation with shorter wavelength is far less prone to plasma formation. Even large amounts of slag/flux reaching the laser foot point do not influence process stability and penetration depth. In fact, while the rate of successful welding trials was limited to about 70 % with the CO_2-laser, during the numerous trials not a single trial using the solid-state laser was unsuccessful due to flux or slag in the laser beam path.

Despite the formal lower available laser power, the weldable wall thickness was increased to 40 mm and beyond.

The next planned steps include further research about homogenization of the mechanical properties across the wall thickness. During this course, tests with different wire/flux combinations and adapted parameter sets are planned.

There are several possible ways to further increase the performance of the laser beam submerged arc hybrid welding process. Recently, first trials with optimized laser beam forming units (smaller transport fiber, aspect ratio) have been conducted and first successful connection welds on S460 plates with up to 51 mm wall thickness have been performed, Fig. 10.

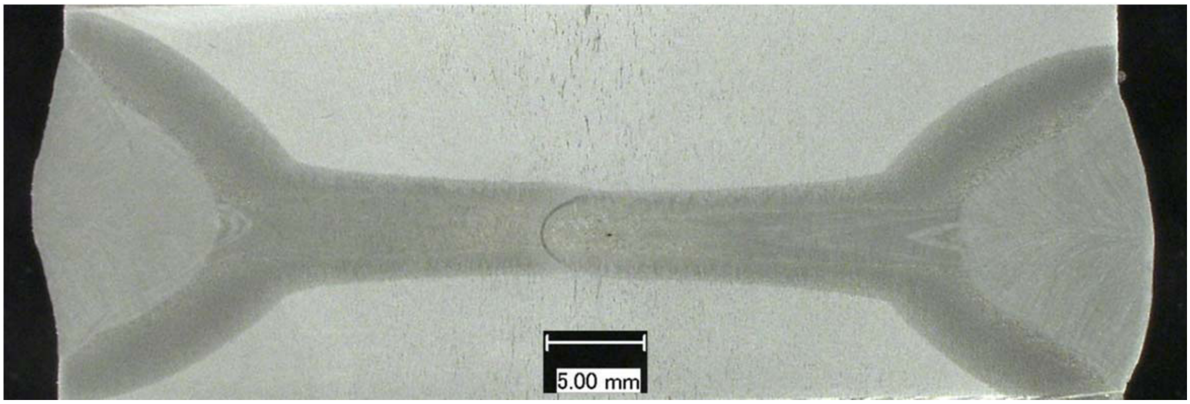

Fig. 10. Sample of laser beam submerged arc hybrid connection weld at S460 with 51 mm wall thickness.

Another option is the use of a multi wire submerged arc process. With this variant, larger plate thicknesses could be welded by increasing the bevel preparation depth while keeping the root face height at a level that ensures a sufficient overlap of the laser dominated penetration depths.

Acknowledgements

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References

[1] Dilthey, Uwe, Woeste, Klaus, Olschok, Simon: Modern beam-welding technologies in advanced pipe manufacturing, Conference report: Eurosteel, 2005.
[2] Reisgen, Uwe, Olschok, Simon, Jakobs, Stefan: Laser Beam Submerged Arc Hybrid Welding, Physics Procedia 39 (2012), pp. 75-83. LANE 2012, Elsevier B.V.
[3] Müller, P.; Wolff, L., Handbuch des Unterpulver-Schweißens, DVS Fachbuchreihe, DVS-Verlag, Düsseldorf, 1983, Nr. 63 I+II, ISBN 3-871-55066-3