Evaluation of High Penetration Hybrid Laser-GMAW Welding Process Productivity Applied in the Joining of Thick Plates and Pipelines

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Abstract

Welding processes are present in all sectors of the industry, highlighting the manufacturing industry of thick plates and pipelines. In these applications, welding processes have a major influence on costs, schedules, risk analysis and project feasibility. Conventional arc welding processes, such as the gas metal arc welding (GMAW) process, have limitations when applied to high thickness joints due to their maximum achievable penetration depth. On the other hand, the laser beam welding (LBW) welding process, despite reaching high penetration depths, has several limitations mainly regarding the geometric tolerance of the joint. In this regard, the hybrid laser-arc welding (HLAW) process emerges as a promising bonding process, combining the advantages of the GMAW and LBW processes into a single melting pool. Despite the many operational and metallurgical advantages, the HLAW process presents a high complexity due to the high number of parameters involved and the interaction between the laser beam and the electric arc. The present work discusses the challenges involved in the parametrization of the HLAW process applied to the joining of thick plates and pipes, and empirically evaluated a comparison between the HLAW and GMAW processes, showing a reduction of operating time of approximately 40 times, and a reduction of consumption of shielding gas and filler material of approximately 20 times, evidencing the technical and financial contribution of the hybrid process.

1. Introduction

Welding processes are present in all industry sectors. In the construction, repair and maintenance activities of thick structures, welding is the main manufacturing process used, with the purpose of granting structural integrity of the joints. In addition, more productive welding processes directly influence costs, schedules, risk analysis and project feasibility [1].

In thick plate and pipe joining applications, conventional arc welding processes are commonly employed, such as GTAW (Gas Tungsten Arc Welding), GMAW (Gas Metal Arc Welding), SMAW (Shielded Metal Arc Welding) and SAW (Submerged Arc Welding). Depending on the thickness of the joint to be welded, its grooving prior to welding is required, followed by several filling passes, thus ensuring metallurgical joining in all its thickness. The bevel machining operation, added to the required number of weld beads required, directly implies longer manufacturing time as well as higher material consumption [2-5].

Pipe welding is a challenging process. The lack of qualified professionals and the difficulties in performing this activity, especially in the root pass, is evident. Typically, pipe welding is performed with GTAW process in the root pass and SMAW in the filling passes, both manually. In some cases, depending on the availability and qualification of welders, the root is also performed with SMAW process, usually cellulosic electrode. However, the worldwide trend in the pipeline sector is the use of GMAW welding process, and mainly applied with mechanized systems [6].

Another alternative is the Laser Beam Welding (LBW) process, which allows to weld large thicknesses in a single pass with high welding speeds when compared to arc welding processes. [7].

When performed autogenously, i.e. without the use of filler material, the LBW process demands for a minimum geometric tolerance of the joint, both in its gap and high-low, characterizing a low process robustness. This high requirement for joint preparation is difficult to achieve in thick sheets and pipelines [8].

Given the advantages and limitations of GMAW and LBW welding processes, HLAW (Hybrid Laser Arc Welding) processes emerge, where the action of the two heat sources in the same melting pool allows high welding characteristic in speed and penetration depth of LBW process and high geometric tolerance of the GMAW process, making it a highly productive and reproductive process [9-11]. In the same way, the interaction of the arc and the laser plume in a common welding pool also enables several metallurgical advantages, as formation of microstructures with less fragility due the thermal aid of the heat source generated by the electric arc acting as a cooling retarder in the fusion zone [12]. The HLAW process is already present in several industry sectors, such as automotive, rail, aerospace, naval, oil and gas extraction, among others [13].

Despite the potential advantages of the process, the interaction between the laser beam and the electric arc represents a high complexity to its application, due the large number of parameters already involved in the individual processes [14, 15]. Previous work carried out by the research group found the complexity of the interaction between the laser beam and electric arc, realizing the need to expand knowledge in this area [16]. Several authors report in their works the financial advantages of using the HLAW process when compared to arc welding processes, such as GMAW alone [17].

Thus, the present work proposes an empirical evaluation of the complexity in the parametrization of the HLAW process to be applied in joining of thick plates and tubes. The tests on thick plates will allow, besides the points highlighted above, a productivity comparison in the joining application between the GMAW and HLAW processes, contributing their advantages aspects to the different industrial applications.

2. Materials And Experimental Procedure

HLAW welding tests were performed on ASTM A516 GR 70 steel sheets. Initially, in order to evaluate the maximum penetration depth achieved with the available processing system, tests were performed on 25.2 mm thick sheet metal. The use of thicker than necessary sheets was intended to prevent the penetration depth from being limited by any characteristics external to the welding parameters. The choice of this substrate was due to its high use in welded pressure vessels, where it is sought to increase the ductility of the substrate. AWS ER 70S-6 1.2 mm diameter wire was used as filler material on HLAW processes. Fiback® fiberglass backing manufactured by Aquasol Corporation was used for HLAW joint welding testing.

Table 1 shows the chemical composition of the substrate and the filler material used.

Table 1 - Chemical composition of substrate and filler material used in HLAW processes.

ASTM A516 GR70	
Element	Composition (% wt)
Carbon (C)	0.27 (max)
Manganese (Mn)	0.85 - 1.20
Phosphor (P)	0.035 (max)
Sulfur (S)	0.035 (max)
Silicon (Si)	0.15 - 0.40

AWS ER 70S-6	
Element	Composition (% wt)
Carbon (C)	0.06 - 0.15
Manganese (Mn)	1.40 - 1.85
Phosphor (P)	0.035 (max)
Sulfur (S)	0.035 (max)
Silicon (Si)	0.80 - 1.15
Copper (Cu)	0.50 (max)

A fiber LASER source (Yb-Ytterbium) from manufacturer IPG PHOTONICS® with a maximum power of 10 kW, wavelength (λ) between 1070,0 nm and 1080,0 nm, theoretical focus beam diameter ($Øff$) of 0.8 mm, BPP of 8.0 mm*rad and focal length of 300 mm was used in the laser process. The DIGIPLUS A7 multiprocess welding source manufactured by the company *IMC Soldagem* was used for the GMAW process, as well as the STA20-2 wire feeder. Welding speed was controlled by a CNC system based on a Siemens 840D controller. Figure 1 shows the sketch of the equipment setup for HLAW welding tests.

After the welding tests were performed, the samples were analyzed visually and cross sectioned. Metallographic cross sections were prepared and etched with a 2% Nital (98% alcohol 2% nitric acid) reagent for 6 seconds, allowing the geometric observation and analysis of the fusion zone and the presence of internal discontinuities.

As the objective of this work is the parameterization of the HLAW welding process applied in a typical joint, these parameters were adjusted as needed, and each change was demonstrated during the observed results, which led to the performing of several welding tests, presented with details in the next section.

Due to the characteristics of the available HLAW system, the present work focused in the joining of 10 mm root face and 15 mm thick plates, being this length shorter than the highest penetration achieved during the analysis tests applied on plate. The set of parameters selected for the tests, under their specific conditions, aimed to reach a penetration close to that sought in joint application. Therefore, the initial parameters were those listed in Table 2.

Table 2 - Initial parameters used for HLAW joint welding.

ASTM A516 GR70	
Element	Composition (% wt)
Carbon (C)	0.27 (max)
Manganese (Mn)	0.85 - 1.20
Phosphor (P)	0.035 (max)
Sulfur (S)	0.035 (max)
Silicon (Si)	0.15 - 0.40

AWS ER 70S-6	
Element	Composition (% wt)
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Silicon (Si)	0.80 - 1.15
Copper (Cu)	0.50 (max)

Among the parameters above mentioned, the pulse current, pulse current time, background current, background current time, wire feeding speed and laser power were changed during the experiments. Besides that, this work focused on the correct setup of the groove in order to optimize the joining application of the HLAW process in thick plates and pipes.

Several authors [18-23] highlight the influence of geometric parameters between the laser beam and the electric arc on HLAW processes, as illustrated in Figure 2, highlighting the LASER focal point distance (Fy), the distance between the laser and the arc (DLA) and the angle of the GMAW welding torch (α), and indicating the chosen values used for the performed tests.

From the set of selected input parameters, it was necessary to evaluate the bevel angle consistent with the proposed process, which was done based on a GMAW weld bead made on plate. According to fixed geometric criteria of the desired groove, an area was proposed that would accommodate the reinforcement obtained, even though a distinct behavior in its application on groove was expected, as shown in Figure 3. Following the above procedure, a 30° bevel opening angle was chosen for HLAW preparation joint procedures.

Finally, once the HLAW was optimized with satisfactory results, it was performed welding tests using the GMAW process alone in two variants, with and without weaving and both manually carried out. Since the penetration of the GMAW heat source is not comparable with the HLAW process, it was necessary to adapt the groove to enable the joining of the full thickness of the plate. The adopted geometric setup will be shown together with the experiments and parameters. These experiments were used to compare the HLAW and GMAW processes based on operating time, consumption of shielding gas and filler material, evidencing the technical and financial contribution of the hybrid process.

3. Results And Discussion

HLAW process presents a complex analysis due to the high number of parameters existing from the two individual processes, besides the complex resulting interaction between the laser beam and the electric arc. Thus, initially, several tests were performed in order to evaluate the influence of each parameter on the geometry resulting from the weld bead, such as the laser power, shielding gas, configuration of wire feeding, interdistance between electric arc and laser beam and distance between the laser beam focal point and the sample surface. The results showed a high repeatability and provide the optimized parameters to be used.

Assuming a fixed welding speed for all plate tests of 1 m/min, a maximum penetration depth of 14.8 mm (Figure 4) was achieved. These procedures corroborate the high penetration efficiency of the HLAW process and its importance in thick pipe and sheet welding procedures

During the welding procedure on joint using the same process parameters, unlike that observed in the welding test on plate, a sensitive behavior was observed as to the ability to reach full penetration and to maintain the root without dropping out of the groove, illustrated in the macrograph obtained through the cross section of the weld bead (Figure 5). This behavior is explained by the different thermal management from different thicknesses. A thicker plate will remove more heat from the joint region in comparison with a thinner one. Figure 5 indicates an excess of heat for this welded joint.

This behavior was also observed by some authors [24, 25], who suggests that high penetration arc welding processes require the use of backings, also known in the literature as support. Backing is the name given to the material or device placed at the back of the joint to be welded adjacent to the joint root. The material may be partially fused or remain unfused during welding and may be metallic or non-metallic. Among the most commonly used are ceramic, copper, and fiberglass backing, each containing its specific advantages and limitations for use.

While copper backing has as its main feature the high value of thermal conductivity, which helps in solidification and consequent mechanical support of the weld root. Ceramic backing has a high melting point, making it difficult to fuse to the weld and substrate. Finally, fiberglass backing, in addition to its flexibility and ease of application, has as its main advantage to allow to some extent a gas flow inside the bevel.

Due to the above-mentioned characteristics, it was opted to use Fiback® fiberglass backing manufactured by Aquasol Corporation.

With the use of fiberglass backing, the observed behavior of gas and thermal flow in the molten pool was abruptly changed, modifying the geometric penetration and width results achieved (Figure 6). This difference in penetration observed is probably since the backing provides a mechanical shield to the passage of heat, plasma, and molten metal.

As the preliminary parameters did not reach full penetration for these joint, further tests were made with the maximum available laser power, with 9 and 10 kW. Still, full penetration was not observed (Figure 7).

The next step was to analyze the groove opening, called in the work as gap. To determine the optimized gap, welding tests were performed, where an optimized gap of 0.6 mm with 8 kW laser power was achieved (Figure 8).

Even achieving a satisfactory root result, the bead reinforcement had a defect by undercut that should be optimized and avoided. Thus, after several parameter optimization tests, the average GMAW process current was changed to 170 A and the wire speed to 9 m/min. With the changes described, the optimized HLAW welding result was achieved (Figure 9).

Also, in order to determine an operating window with the parameters for the joint HLAW process, tests with a gap variation of 0 to 1 mm were performed in steps of 0.1 mm, where unsatisfactory results with a gap less than 0.3 mm and greater than 0.8 mm (Figure 10).

As mentioned, the choice of opening angle was made after the previous study of the reinforcement area reached by the process in sheet metal testing. In this context, tests with bevel openings of 20° and 40° were also performed using a gap of 0.6 mm, which presented unsatisfactory results (Figure 11).

Finally, joint welding tests were performed with the individual LBW and GMAW processes. The LBW process, for the plate thickness used and maximum available power of 10 kW, did not achieve full penetration. Moreover, the unfeasibility of using gapped joints in the LBW process is notorious (Figure 12). In addition, porosity formation can be observed within the weld bead.

For the application of the GMAW process, as it has a certain limitation as to the maximum penetration attainable, it is necessary to use a shorter root face, allowing a metallurgical joining in the whole length of the joint. In Figure 13, one can see a comparison between the geometric profiles of joints used in the HLAW and GMAW processes.

As for the GMAW process applied in joint, two scenarios were used, with fillet weld bead and weld bead with weaving. Both processes used 120 A current, 20 V voltage and 3.5 m/min wire speed. However, the welding speed varied according to the torch movement technique employed. The choice of use of movement modes was due to the greater coherence for comparative analysis with other processes when applied in joint filling (Figure 14).

Common to all sectors of the manufacturing industry, the constant search for more productive and safe processes represents one of the main guidelines to pursue. Productivity, even though it cannot be translated exclusively by the speed of the welding process, is highly influenced by it, thus being valid an analysis of necessary process time and input consumption.

Thus, input values were used for input consumption calculations listed in Table 3.

Table 3 - Input values for shielding gas and wire consumption calculation in HLAW and GMAW welding processes for joining

Cost/Meter AWS ER 70S-6 1.2 mm Diameter (U$)	71.43
Shielding Gas - HLAW	92% Ar + 8% CO_2
Shielding Gas - GMAW	75% Ar + 25% CO_2
Cost/Liter 92% + Ar 8% CO_2 (U$)	0.007
Cost/Liter 75% + Ar 25% CO_2 (U$)	0.005

From the calculation for 1-meter of joint welding, a comparative financial and process time analysis between HLAW and GMAW processes was performed, illustrated in Figure 15 and Table 4.

Table 4 - Comparison of required time and shielding gas and wire consumption for 1-meter welding joint with HLAW and GMAW welding processes.

	HLAW	GMAW Fillet Weld Beads	GMAW Weld Beads with Weaving
Welding Time - 1 m (min)	1.00	37.04	45.19
Wire Consumption - 1 m (U$)	0.33	5.28	6.44
Shielding Gas Consumption - 1 m (U$)	0.11	2.91	3.55
Total Material Consumption - 1 m (U$)	0.43	8.19	9.99

It is noteworthy that this comparative analysis should not be treated absolutely, so that only the necessary welding time and the consumption of filler wire and shielding gas were considered in their calculations. Costs involving pre-welding processes such as joint preparation, initial cost of laser and arc welding equipment, as well as the actual working hours of operators of both processes were not considered.

Still, it is important to point out that the two processes are not being used at their optimized levels and can therefore be considered with an analysis of the usual behavior of both.

From the analysis of Figure 14, it is clear the difference in productivity and materials consumption between the two evaluated processes, making the time required to manufacture the joint in the order of 40 times less by the HLAW process. As well as a financial reduction of input use by 20 times.

4. Conclusion

From the analyzes and discussions present in the work, it was possible to obtain the following conclusions:

- The application of the HLAW process in a joint was only possible through the use of backing, where the fiberglass backing presented high fit for the purpose, due to its flexibility and relative passivity of gas flow transport. This represents a limitation in controlling the heat input and therefore the penetration in the HLAW processes when comparing with the GMAW process alone, which is capable to be applied without backing.
- By adjusting the welding parameters, it was possible to achieve a satisfactory 15 mm thick HLAW joint welding procedure in one pass. In other hand, using two different GMAW variants, with and without weaving, it was necessary to use multiple welds passes and deep grooves to enable a full joining among the thickness of the plates.
- When compared to the GMAW process it represented approximately 40 times less time required and shielding gas and wire consumption approximately 20 times less for joining 1-meter joint.

The results obtained clearly indicate the operational and productivity advantages of the HLAW process applied to joining of thick sheets and pipelines. These results corroborate the importance of studying and developing hybrid welding processes for application in the industry.

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References

1. SATORI F., SILVA R. H. G., DUTRA C. D., PAES L. E. S., SCHWEDERSKY M. B., MARQUES C., A Comparative Analysis of Different Versions of the MIG/MAG Process Modern Variants for the Root Pass in Orbital Welding. **Soldagem & Inspeção**, v. 22, 2017. DOI: https://doi.org/10.1590/0104-9224/si2204.04
2. BUNAZIV I, FROSTEVARG J, AKSELSEN OM, KAPLAN AFH (2018). DOI: The penetration efficiency of thick plate laser-arc hybrid welding. **The International Journal of Advanced Manufacturing Technology**, v. 97, n. 5-8., p. 2907–2919. 10.1007/s00170-018-2103-x
3. DAL CASALINOG, ANGELASTRO MANOU (2010). DOI: DOI: Hybrid Laser Welding: A Review. Int Sci Book https://doi.org/10. 2507/daaam.scibook.2010.38
4. NIELSEN S. E., High power laser hybrid welding—challenges and perspectives. **Pysics Procedia**, v. 78, p.24–34,
5. FARROKHI F, ENDELT B, KRISTIANSEN M (2019) A numerical model for full and partial penetration hybrid laser welding of thick-section steels. **Optics** & **Laser Technology**, v. 111, p. 671-686, DOI: 10.1016/j.optlastec.2018.08.059
6. PUNALES EMM, Alfaro SCA (2021) Stability of the GMAW Process. Welding - Modern Topics IntechOpen. DOI: 10.5772/intechopen.90386
7. FETZER F, HAGENLOCHER C, WEBER et al (2021) Geometry and stability of the capillary during deep-penetration laser welding of AlMgSi at high feed rates. **Optics** & **Laser Technology**. DOI: https://doi.org/10.1016/j.optlastec.2020.106562
8. LI R, WANG T, YAN F et al (2014). DOI: A study of narrow gap laser welding for thick plates using the multi-layer and multi-pass method. **Optics & Laser Technology**. v. 64.. p. 172–183. https://doi.org/10.1016/j.optlastec.2014.04.015
9. SHI J., Z. Y., LIU L., Application of Pulsed Laser-TIG Hybrid Heat Source in Root Welding of Thick Plates Titanium Alloys.**Applied Sciences**, v.7, DOI: https://doi.org/10.3390/app7050527
10. KLIMOVA-KORSMIK O. TURICHINGKM (2018) SKLYAR M., ZHITENEV A., KURAKIN A., POZDNYAKOV A., Laser-Arc Hybrid Welding Perspective Ultra-High Strength Steels: Infleunce of the Chemical Composition of Weld Metal on Microstruture and Mechanical Properties. **Procedia CIRP**, v. 74, p. 752-756,
11. GÓRKA J., STANO S., Microsctruture and Properties of Hybrid Laser Arc Welded Joints (Laser Beam-MAG) in Thermo-Mechanical Control Processed S700MC Steel. **Metals**, v. 8, 2018. DOI: https://doi.org/10.3390/met8020132
12. SILVA RGN, PAÇO CMM, RODRIGUES MB et al (2020) A comparison between LBW and hybrid laser-GMAW processes based on microstructure and weld geometry for hardenable steels. **The International Journal of Advanced Manufacturing Technology**, v. 110, p. 2801-2814, DOI: https://doi.org/10.1007/s00170-020-06076-1
13. KAH P., SALMINEN., MARTIKAINEN J., The effect of the relative location of LASER beam with arc in different hybrid welding processes. **International Congress on Applications of Lasers and Electro-Optics (ICALEO)**. DOI: https://doi.org/10.2351/1.5061539

14. ACHERJEE B. Hybrid laser arc welding: State-of-art review. **Optics** & **Laser Technology**. V. 99, p. 60-71 (2018) DOI: https://doi.org/10.1016/j.optlastec.2017.09.038
15. BIDI L, LE MASSON P, CICALA E et al (2017). DOI: Experimental design method to the weld bead geometry optimization for hybrid laser-MAG welding in a narrow chamfer configuration. **Optics & Laser Technology**. v. 89.. p. 114–125. https://doi.org/10.1016/j.optlastec.2016.09.046
16. SILVA R. G. N., PEREIRA M., RODRIGUES M. B., PEREIRA A. S. P., SCHWEDERSKY M. B., Electric evaluation of hybrid laser-TIG welding: Interaction between arc and laser plume.**Journal of Laser Application**, v.32, DOI: https://doi.org/10.2351/7.0000088
17. YAPP D., BLACKMAN A., Recent developments in high productivity pipeline welding. **Journal of the Brazilian Society of Mechanical Sciences and Engineering**, v. Vol. 26, DOI: https://doi.org/10.1590/S1678-58782004000100015
18. FELLMAN A., J. P., KUJANPÄÄ V. CO2-GMA hybrid welding of carbon steel – the effect of shielding gas composition. **International Congress on Applications of Lasers and Electro-Optics** (**ICALEO**). DOI: https://doi.org/10.2351/1.5060046
19. BUNAZIV I., AKSELSEN O. M., SALMINEN A., The Fiber Laser-MIG Hybrid Welding of 5mm 5083 Aluminum Alloy. **Mater**. **Process**. **Tecnhol**., v. 233, p. 107-114,
20. HAYASHI T., KATAYAMA S., ABE N., OMORI A. High-power CO2 laser-MIG hybrid welding for increased gap tolerance. Hybrid weldability of thick steel plates with a square groove. **Welding International**, v. 18, p. 692-701,
21. BUNAZIV I, AKSELSEN OM, REN X, SALMINEN A (2015). DOI: Hybrid Welding Possibilities of Thick Sections for Arctic Applications. **Physics Procedia**, v. 78., p. 74–83. 10.1016/j.phpro.2015.11.019
22. LIU L., XU R., Investigation of Corrosion Behavior of Mg-Steel Laser-TIG Hybrid Lap Joints. **Corrosion Science**, v. 54, p.212–218,
23. MAGEE KH (1990) MERCHANT V. E., HYATT C. V., Laser assisted gas metal arc weld characteristics. **International Congress on Applications of Lasers and Electro-Optics** (**ICALEO**). DOI: https://doi.org/10.2351/1.5058381
24. REISGEN U, OLSHOCK S, ENGELS O (2018) Laser beam submerged arc hybrid welding: A novel hybrid welding process. Journal of Laser Applications v 30. DOI: https://doi.org/10.2351/1.5037269
25. WAHBA W, MIZUTANI M, KATAYAMA S (2016) ; Single pass hybrid laser-arc welding of 25 mm thick square groove butt joints. **Materials** & **Design**. v. 97. DOI: https://doi.org/10.1016/j.matdes.2016.02.041

Figures

Figure 1

Sketch of workbench for HLAW joining procedure.

Figure 2

Geometric parameters between laser beam and GMAW welding torch.

Figure 3

Proposed method for calculating bevel angle corresponding to the resulting bevel area.

Figure 4

Cross section of the HLAW welding bead with 10 kW of laser power, reaching 14.8 mm penetration.

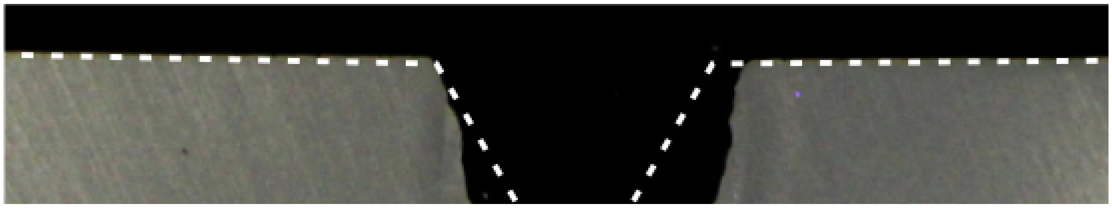

Figure 5

Weld macrograph performed by HLAW process applied in joint with excess heat and without backing.

Figure 6

Weld macrograph performed by the HLAW process applied in joint using fiberglass backing.

Figure 7

Weld macrograph performed by the HLAW process applied in joint using backing and laser power of 10 kW.

Figure 8

Weld macrograph performed by HLAW process applied in joint using backing and laser power of 8 kW and 0.6 mm gap.

Figure 9

Weld macrograph (a), surface aspects (b), and root aspect (c) of the weld beam performed by HLAW process applied in joint using backing and laser power of 8 kW, 0.6 mm gap, and adjustment of the average GMAW process current to 170 A and wire speed to 9m/min.

Figure 10

Weld macrograph performed by HLAW process applied in joint using backing with joint opening of a) 0mm and b) 1mm.

Figure 11

Weld macrograph by HLAW process applied in joint using bevel angle backing of a) 20 ° and b) 40 °.

Figure 12

Weld macrograph performed by the LBW process applied in joint with backing, with laser power of 10 kW.

Figure 13

Geometric profiles of joints used for process application a) HLAW and b) GMAW.

Figure 14

Weld macrograph performed by the GMAW process applied in conjunction with a) fillet weld beads and b) weld beads with weaving.

Figure 15

Comparison of required time and shielding gas and wire consumption for 1-meter welding joint with HLAW and GMAW welding processes.