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# Application of hybrid laser arc welding for the joining of large offshore steel foundations

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## Abstract

To reduce the costs of the fabrication of offshore wind turbine foundations it is necessary to investigate new fabrication technologies. Hybrid laser arc welding is a potentially well-suited process for this because it requires less groove preparation to achieve deep weld penetration and lower heat input, compared to traditional arc welding. A skirt section of a suction bucket in 16 mm steel was used as a case to investigate the hybrid laser-arc welding in order to demonstrate which types of weld and which weld positions are possible. Three types of weld joints were chosen and welded with different welding positions; a butt joint of a bended section, a butt joint of a flat section and a lap joint. Stable welds with sufficient penetration were achieved for the flat welding position of the butt joint of bended section and butt joint of flat section.

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*Keywords:* Hybrid laser welding; Weld penetration; Weld position; Offshore wind turbine foundation

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## 1. Introduction

In many cases, the production of wind energy has moved to offshore locations because larger wind turbines are produced, and suitable space on land is limited in some regions. At sea the locations with low water levels are utilized first, and new offshore wind turbine parks have to be located at deeper water levels. At the same time, the Levelized Cost of Energy (LCoE) produced from offshore wind turbines must be lowered to make production cost-effective. The cost of the offshore wind foundation, including production and installations, amounts to 20-30% of the entire cost of

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setting up an offshore wind park, Offshoreenergy (2016-2017). For this reason new foundation designs are required, see Fig. 1, which can lower the costs by reducing the material consumption and reduce costs of production, transportation and installation. The idea behind this design is the bucket which is sucked into the seabed for the purpose of serving as a foundation for the entire structure, including the tower and wind turbine. The skirt consists of modular segments of steel plates which must be joined by lap joints to form the circular skirt.

One of the promising methods for reducing the production costs of such large steel structures is the use of hybrid laser arc welding (HLAW). Owing to the high intensity laser energy in HLAW, this makes it possible to reduce the number of passes and minimize the heat distortion compared with that seen in conventional arc welding techniques. This drives the trends found in heavy industries, where they are looking for new opportunities for substituting their conventional welding methods with hybrid laser welding, Nielsen (2015). The shipbuilding industry was a pioneer in using hybrid laser welding for thick-section steels. Almost two decades ago hybrid laser welding was taken into use for the manufacturing of several-meter-long ship panels. The plate thicknesses are usually between 3 to 12 mm, and in some cases up to 30 mm, Kristensen (2009). Other potential applications of hybrid laser welding which are of high economic interest are the longitudinal and orbital weldings of pipelines, Bachmann et al. (2016). Thanks to the wavelength of solid-state lasers, which allows beam delivery via fiber optics, positional welding and the welding of complex geometries are possible, using robotized processes. This becomes especially advantageous in the case of pipeline assembling or the thick-section welding of large and heavy structures, in which the manipulation of the workpiece is almost impossible. Studies of orbital welding of thick-section steel pipes in Rethmeier et al. (2009), Gebhardt et al. (2009), and Gook et al. (2010) show that single-pass welding of pipes of up to 16 mm in thickness is possible when using appropriate process parameters. The authors also suggested using either a beveled groove (Y-groove) or preheating in order to obtain sound joints.

As mentioned above, large and heavy structures such as offshore steel foundations demand positional welding processes, as the manipulation of such parts is unpractical. Owing to the flexibility in the beam delivery of high power solid-state lasers, robotized hybrid laser welding processes can potentially be a promising cost-efficient solution to this challenge. However, positional welding seems to be challenging, especially with thicknesses of 16 mm and above, and therefore, further practice is required on this subject.

a b

Fig. 1. Offshore wind foundations. (a) Suction bucket jacket. Photo: Courtesy of DONG Energy. (b) Two mono buckets on a jack up wessel for installation. Photo: Courtesy of Universal Foundation Norway.

The component investigated in this paper was the skirt section of the suction bucket, see Fig. 2, which can be mounted on for instance a mono bucket or a suction bucket jacket, see Fig. 1. This paper presents a number of preliminary positional welding experiments using robotized hybrid laser welding. Different sections of two skirt segments with a plate thickness of 16 mm were used for the investigation, see Fig 2. Three different types of joints on the part were welded by hybrid laser welding; the butt joint of the bended section, the butt joint of the plane section and the lap joint. Welding of the joints should serve as the basis for answering the following questions in our hypothesis:

- Can an acceptable weld quality be achieved with hybrid laser welding for the three joint types?
- To what degree are the weld performance and quality reduced for different welding positions?

It should be noted that this paper focuses solely on certain fundamental quality aspects, such as weld penetration depth and melt pool stability during positional welding. However, the authors have investigated other important quality factors of hybrid laser welding of thick-section steels, such as solidification cracking, in Farrokhi et al. (2017).

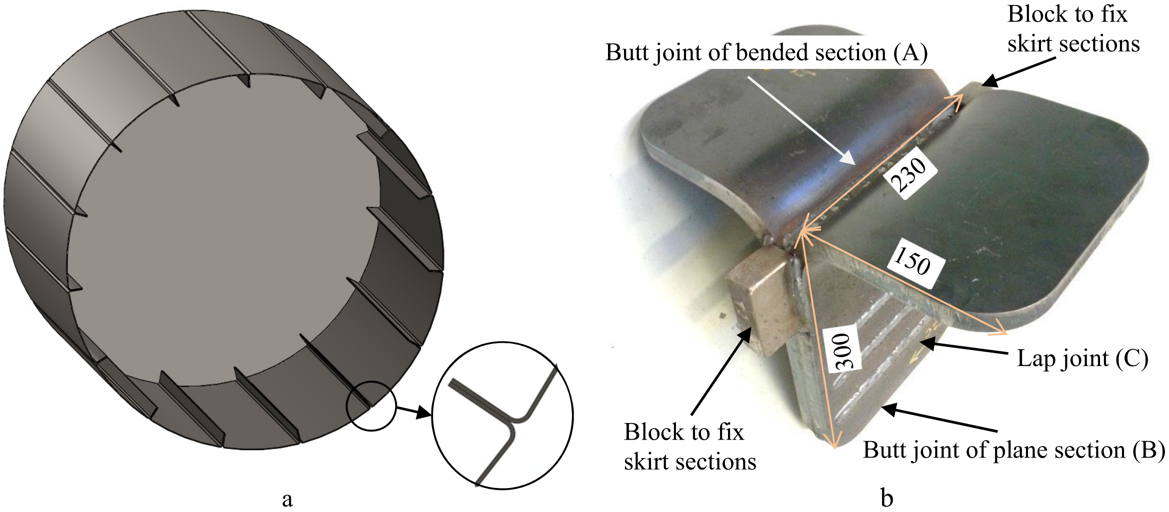


Fig. 2. (a) Several skirt sections are bended and joined to form a bucket skirt. The joint between two skirt sections is magnified. (b) Skirt section, made of 16 mm thick plates with a bending radius of 40 mm, used for the experiments with the different welding possibilities.

## 2. Industrial case

The purpose of the weld case design was to test the performance and quality of different joint types and welding positions which could possibly be used for the production of the bucket skirt. The following experiments were performed with the corresponding experimental ID's in parenthesizes:

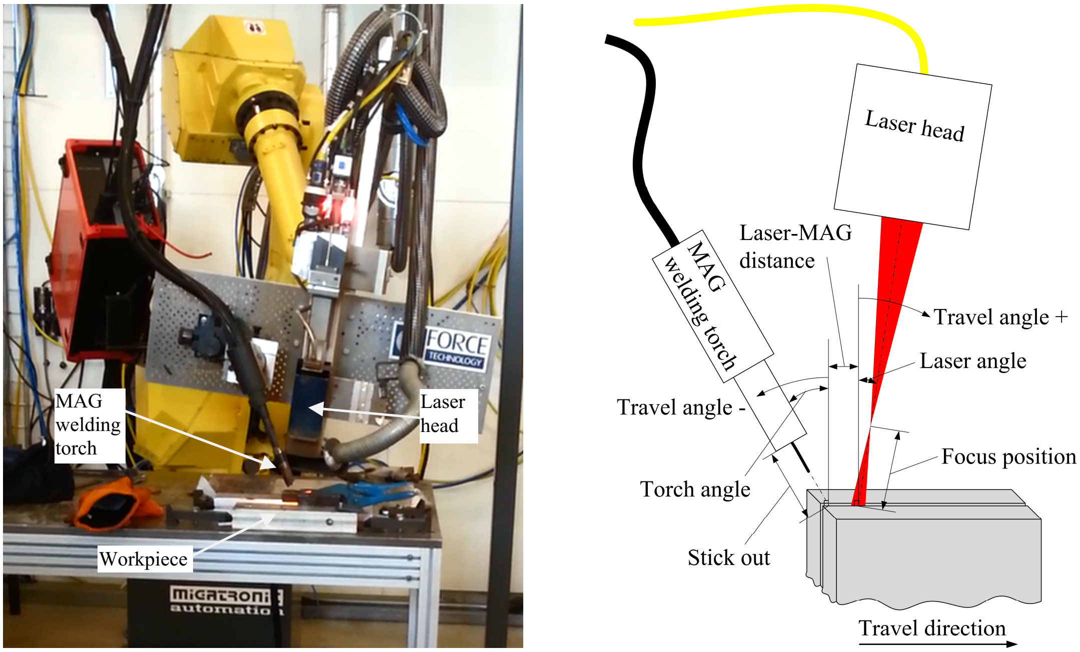
- Butt joint of bended section
  - Flat position (A1, A2)
  - Vertical down (A3, A4)
- Butt joint of plane section
  - Flat orientation (B1, B2)
  - Vertical up (B3)
  - Vertical down (B4)

- Lap joint

- Flat position (C1, C2, C3, C4, C5, C6)
- Vertical up (C7)
- Vertical down (C8)

## 3. Experimental setup

The experimental welding setup was established at Lindoe Welding Technology. This is shown in Fig. 3, and the equipment is presented in Table 1.



a b

Fig. 3. (a) Physical setup. (b) Schematic preview of setup.

Table 1. Equipment and process parameter settings used for all experiments. The focus position can be seen in Fig. 3b.

| Equipment | Type and manufacturer | Process parameters | Value |
|---|---|---|---|
| Laser | 16kW Trumpf TruDisk 16002 | Focal length ($f_{foc}$) | 600 mm |
| Processing head | Trumpf RFO Reflecting Focus Optics | Wavelength | 1030 nm |
| Arc welding machine | Fronius Trans Plus Synergic 5000 CMT | Shielding gas | 92%Ar 8%$CO_2$ |
| Manipulator | Fanuc Robot M-710i C170 | Shielding gas flow | 25 litre/minute |
| | | Filler wire | ESAB OK 12.51 |
| | | Filler wire diameter | 1.2 mm |
| | | Focus position | 25 mm |

The material used for all experiments was S355MC steel. It should be noted that no joint preparation was applied before welding, except that the surfaces were cleaned to remove any oxide layer. Two blocks of the same material were tack welded to both sides of the samples, see Fig. 2b. This prevented the melt pool from dropping off at the start and stop points of the bended sections and also limited the gap variation during the welding process. Using such fixturing, zero pre-set gap was provided at the joints. Following the welding process, macro-section samples were cut out randomly from each weld and etched for the subsequent quality evaluation. Macro-section images were made, using an automatic multiple image stitching program in a microscope.

The process variables were determined for each experiment in order to investigate the influence of travel speed and process leading order in flat and vertical welding positions. In some cases, a second filling pass of MAG was added; however, the majority of the experiments were single-pass. Moreover, to allow comparison, a few autogenous laser welding experiments were performed on lap joints. Tables 2, 3, and 4 show the process variables of the experiments.

Table 2. Settings used for the butt joint of bended sections (A).

| Experiment ID | Position | Pass number | Process | Leading | Laser angle (°) | Laser-MAG distance (mm) | Travel speed (mm/min) | Laser power (kW) | Stick out (mm) | Torch angle (°) | Wire feed speed (m/min) | Current (A) | Voltage (V) | Line energy (kJ/mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | Laser | Arc |
| A1 | Flat | 1 | HLAW | Laser | 7 | 25 | 200 | 16 | 15 | -20 | 22 | 500 | 32 | 4.8 | 4.8 |
| | | 2 | MAG | | | | 400 | | 20 | 20 | 22 | 500 | 43 | 0 | 3.2 |
| A2 | Flat | 1 | HLAW | Laser | 7 | 25 | 400 | 16 | 15 | -20 | 22 | 500 | 32 | 2.4 | 2.4 |
| | | 2 | MAG | | | | 300 | | 20 | 20 | 22 | 500 | 36 | 0 | 3.6 |
| A3 | Vertical down | 1 | HLAW | Arc | -7 | 15 | 800 | 8 | 15 | 20 | 10 | 325 | 30 | 0.6 | 0.7 |
| | | 2 | MAG | | | | 600 | | 15 | 20 | 10 | 325 | 30 | 0 | 1.0 |
| A4 | Vertical down | 1 | HLAW | Arc | -7 | 15 | 800 | 8 | 15 | 20 | 5 | 190 | 15 | 0.6 | 0.2 |
| | | 2 | MAG | | | | 800 | | 15 | 20 | 10 | 325 | 27 | 0 | 0.7 |

Table 3. Settings used for the butt joint of plane sections (B).

| Experiment ID | Position | Pass number | Process | Leading | Laser angle (°) | Laser-MAG distance (mm) | Travel speed (mm/min) | Laser power (kW) | Stick out (mm) | Torch angle (°) | Wire feed speed (m/min) | Current (A) | Voltage (V) | Line energy (kJ/mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | Laser | Arc |
| B1 | Flat | 1 | HLAW | Laser | 7 | 5 | 500 | 16 | 15 | -20 | 5 | 190 | 21 | 1.9 | 0.5 |
| B2 | Flat | 1 | HLAW | Arc | -7 | 5 | 500 | 16 | 15 | 20 | 5 | 190 | 21 | 1.9 | 0.5 |
| B3 | Vertical up | 1 | HLAW | Laser | 7 | 5 | 1000 | 8 | 15 | -20 | 2.5 | 109 | 16 | 0.5 | 0.1 |
| B4 | Vertical down | 1 | HLAW | Arc | -7 | 5 | 1000 | 8 | 15 | 20 | 2.5 | 109 | 16 | 0.5 | 0.1 |

Table 4. Settings used for the lap joints (C).

| Experiment ID | Position | Pass number | Process | Leading | Laser angle (°) | Laser-MAG distance (mm) | Travel speed (mm/min) | Laser power (kW) | Stick out (mm) | Torch angle (°) | Wire feed speed (m/min) | Current (A) | Voltage (V) | Line energy (kJ/mm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | Laser | Arc |
| C1 | Flat | 1 | Laser | | 7 | | 300 | 16 | | | | | | 3.2 | 0 |
| C2 | Flat | 1 | Laser | | 7 | | 500 | 16 | | | | | | 1.9 | 0 |
| C3 | Flat | 1 | Laser | | 7 | | 700 | 16 | | | | | | 1.4 | 0 |
| C4 | Flat | 1 | HLAW | Laser | 7 | 5 | 300 | 16 | 15 | -20 | 5 | 190 | 19 | 3.2 | 0.7 |
| C5 | Flat | 1 | HLAW | Laser | 7 | 5 | 500 | 16 | 15 | -20 | 6 | 190 | 20 | 1.9 | 0.5 |
| C6 | Flat | 1 | HLAW | Laser | 7 | 5 | 700 | 16 | 15 | -20 | 7 | 190 | 20 | 1.4 | 0.3 |
| C7 | Vertical up | 1 | HLAW | Laser | 7 | 5 | 2000 | 16 | 15 | -20 | 5 | 190 | 19 | 0.5 | 0.1 |
| C8 | Vertical down | 1 | HLAW | Arc | -7 | 5 | 2000 | 16 | 15 | 20 | 5 | 190 | 19 | 0.5 | 0.1 |

### *3.1. Quality assessment criteria*

The quality was determined by assessing macro sections of the welds, in which the penetration depth and width were measured. The required throat thickness of the weld for the skirt section is 1-2 times the plate thickness because the weld only has one load cycle during installation. For the butt joints, the minimum penetration requirement was 16 mm. For the lap joints, the weld width was measured at the joint interface, and the minimum penetration requirement was above 16 mm. The width of the welds gives an indication of the number of welds required for achieving sufficient strength at the joints. For all welds, the stability during welding was observed, and humping effects were noted down.

## 4. Experimental results

In this section the results are presented and discussed.

### *4.1. Butt joint of bended section*

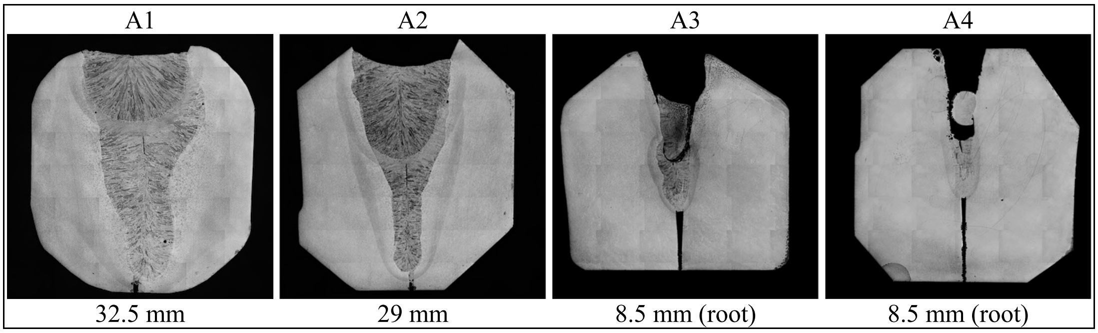


Fig. 4. Weld macro-sections of the butt joint bended sections and their corresponding penetration depths with respect to the weld surface. For the flat position welds A1 and A2 deep penetrations were obtainable whereas the vertical down welds A3 and A4 could not hold on to the filler material.

Welding of the butt joint of bended sections in the flat position (A1, and A2) resulted in penetration depths satisfying the requirement. As can be seen in Fig. 4, the root pass was first performed via hybrid laser welding, followed by a second pass that used only MAG. The total weld depth of the two passes reached up to 32 mm. The semi-Y-shape groove of the bended sections allowed a high amount of filler material to be deposited inside the joint, which resulted in about 23 mm penetration of the root weld that used 16 kW laser power, which can be seen in Fig.4 A1. The shallower penetration of the A2 root weld could almost be compensated by a slower filling pass by MAG. When comparing A1 and A2, it was seen that the lower travel speed in A1 led to a wider joint, even at the lower part of the weld, which leads to the assumption that more filler material could be inserted in the joint. However, centerline cracks appeared in the upper side of the root welds, regardless of the welding heat input or the travel speed. The vertical welding position was much less stable, and therefore a heat input which was at least 4 times lower was used in order to keep the melt pool from falling off. This resulted in a considerable drop in the penetration depth. The process parameters of the filling passes in this experiment did not result in a sufficient quality and severe lack of fusion occurred during the MAG welding, see A3 and A4.

### *4.2. Butt joint of plane section*

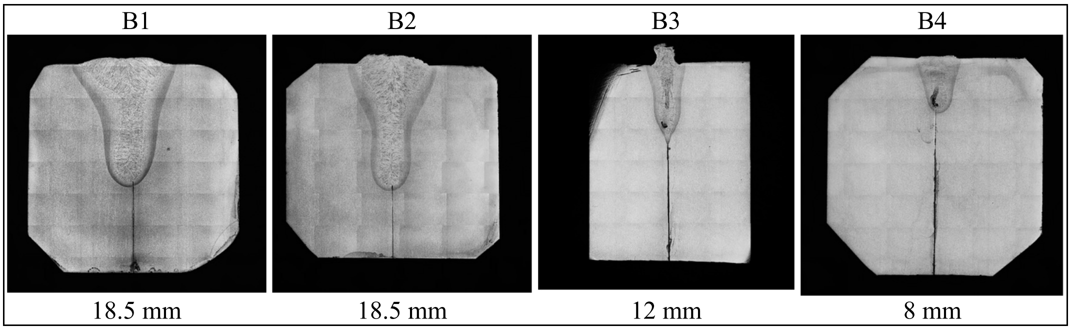


Fig. 5. Weld macro-sections of butt joint plane sections and their corresponding penetration depths. For the flat position welds B1 and B2 deep penetrations were obtainable whereas the vertical welds B3 and B4 had insufficient penetration and welding defects.

Fig. 5 shows the results of the welding of plane sections in the butt joint configuration. According to B1 and B2, almost no significant difference, in terms of penetration depth, could be detected between laser leading and arc leading processes. However, the weld bead appearance was smoother and more stable in the laser leading configuration (B1), which could be attributed to the pushing arc orientation. Experiments B3 and B4 were performed in the vertical position using one fourth of the heat input compared with that used in the flat position welding. According to the results, welding in the vertical down orientation and arc leading configuration (B4) was more stable than in the reverse situation. Welding in the vertical up orientation and laser leading configuration resulted in severe humping of the melt pool at the surface (B3).

### 4.3. Lap joint

Lap joint welding in the flat position compares autogenous laser welding (C1, C2, C3) and hybrid laser welding (C4, C5, C6) at three different travel speeds. According to the results seen in Fig. 6, the minimum travel speed was 300 mm/min for obtaining full penetration joints. However, no significant difference was seen in penetration depth between hybrid laser welding and autogenous laser welding. Moreover, comparing the weld penetration depth of lap joint and butt joint welding (e.g. C5 and B1) where the same welding parameters were applied, one can conclude that hybrid laser welding can be more efficient in butt joint welding, even with a zero pre-set gap.

For the lap-joint welds a sufficient penetration depth were only achieved for welding C1 and C4. The achieved weld width at the joint interface was just above 4 mm which entails that at least 4 welds has to be carried out to achieve a sufficient strength at the joint. The travel speed for the welds was 300 mm/min which was in the low end compared to all the presented experiments. This concludes that welding the skirt sections with lap-joints is not interesting productivity wise compared to utilizing the other joint types.

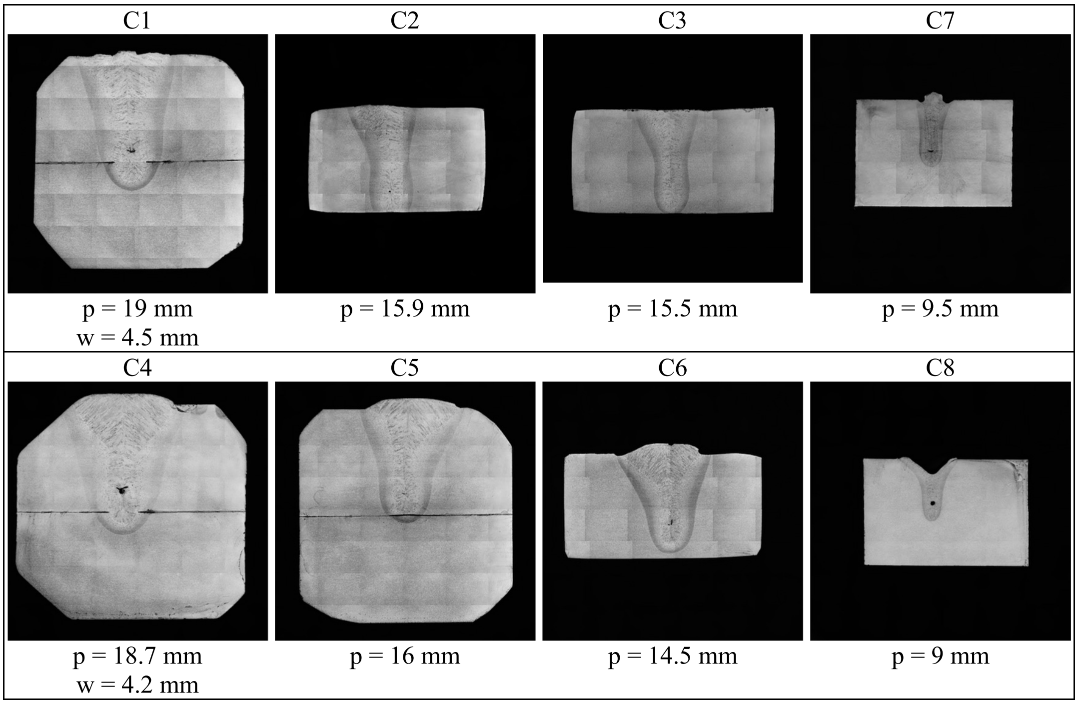


Fig. 6. Weld macro-sections of the lap joints and their corresponding penetration depths (p). The weld width (w) was measured at the joint interface for the penetration depths above 16 mm.

The lap joint welding in the vertical position was much less stable compared with the flat position. Lower power or travel speed was required to prevent the melt pool from collapsing. This led to the reduced penetration depths at the joints. Hybrid laser welding in the vertical up orientation and laser leading configuration resulted in the collapse of the melt pool, even at the double travel speed (1000 mm/min). Even when only one fourth of the heat input was used by increasing the travel speed to up to 2000 mm/min, the melt pool partly fell off, which caused poor surface quality and humping (C7). Similar to the B section experiments, when the welding position was changed to vertical down with an arc leading process, stability of the process increased for the same set of parameters (C8). However, both vertical up and down welding positions resulted in severe concavity on the surface.

## 5. Conclusion and future work

Hybrid laser welding can be applied to the skirt sections of off-shore buckets and it is suitable directly without any groove beveling to achieve the sufficient penetration depth. It can be seen that the welding position is very important and in this study sufficient welds could be achieved in the flat position. However, further studies are required to investigate other quality factors such as cracking, which occurred during some of the experiments. From the experimental study, the following conclusions can be drawn:

- The semi-Y-shape flat positioned groove of the bended section allowed a high amount of filler material to be deposited inside the joint. It resulted in about 23 mm penetration of the root weld with 16 kW laser power.
- Almost no significant difference, in terms of penetration depth, could be seen between laser leading and arc leading processes when welding plane sections in a butt joint configuration and flat position.
- The vertical welding position was significantly less stable compared with the flat welding position for the same process parameters. A lower power input and a higher travel speed were required in order to avoid the melt pool from collapsing when welding in the vertical position.
- For the process parameters used in this study, welding with the vertical down orientation and the arc leading process turned out to be more stable than with the vertical up orientation and the laser leading process.
- According to the quality assessment criteria, the flat welding showed a sufficient penetration for the butt joints. For the lap joints, the penetration depth and width of the weld at the intersection between the plates to a very limited extent resulted in acceptable welds. This can be explained by the fact that the available laser power could not provide a sufficient penetration depth.

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