Laser-Hybrid Welding of Thick Plates up to 32 mm Using a 20 kW Fibre Laser*

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New brilliant high-power lasers such as disc laser and fibre laser open up new fields of applications for laser-hybrid welding, e.g. power generation, shipbuilding and pipeline construction. For the use of laser-hybrid welding in pipe laying, insensibility towards tolerances and the possibility of orbital welding are very important factors in addition to the weld seam quality.

Within the scope of a basic research project, first promising results for laser-hybrid welding of thick materials could be demonstrated. As base material, the typical pipeline steel API 5L X65 was selected. With the help of a 20 kW fibre laser in combination with an arc-welding process it was possible to produce high-quality welds in plates of up to 20 mm thickness in a single pass and of up to 32 mm in three to five passes, both welded in position PA. Various joint preparations were examined to weld 20 mm thick plates in one pass. Besides different welding positions, gap bridgeability and misalignment were studied. Results for microhardness and Charpy toughness are presented to proof the applicability of laser-hybrid welding for joining in pipe laying.

Key Words: Laser Beam Welding, High Power Fibre Laser, Laser-Hybrid Welding, Thick Plates, Pipe Laying

Introduction

Today, new high-power lasers with a beam power of 20 kW and more in continuous-wave mode are available on the market. They operate at a wavelength of $1.07\mu\text{m}$, so that the laser beam can be transported by optical fibres. The brilliant beam quality can be seen by the beam parameter product of $11.2\text{ mm}\cdot\text{mrad}$ or even better. This offers new opportunities for welding of plates with thicknesses of 15 mm and greater. Further advantages are the high electrical efficiency of app. 30% compared to CO_2 -lasers(app.10%) and YAG-lasers (app.3%-12%) as well as the compact design. Both facts enable these lasers to be used in mobile applications like shipbuilding, pipe welding and even pipe laying. In recent years, some industrial applications for fibre laser welding of thick plates were reported¹⁻³⁾. First results of laser-hybrid welding with a 10 kW fibre laser were achieved for 10 mm thick steel panels in shipbuilding³⁾. It has to be emphasized that it is not possible to transfer these results directly to thicknesses of 15 mm or more. The higher the thickness, the more the resulting welds resemble those produced with an electron beam (concerning the deep penetration welding effect).

Due to the increased need for energy, several future projects are planned for the construction of new pipelines with wall thicknesses of 12 mm to 32 mm and more. Therefore, laser-hybrid welding with high power lasers could be an economic alternative compared to standard welding processes like gas-metal arc (GMA) welding. For such orbital welding applications, there

is a big need for solid knowledge of the potential of laser-hybrid welding regarding the process, especially in positional welding, and the resulting weld properties. As a first step towards fully orbital laser-hybrid welding, this paper deals with the possibilities of a 20 kW fibre laser for welding up to 32 mm thick plates, including positional welding.

Materials, Joint Preparation, Welding System Configuration and Experimental Execution

As base material, the typical pipe steel API 5L X65 with the chemical composition shown in Table 1 was used:

The main difference between both steels is the carbon content which is double the amount for the 20 mm thickness. For both materials, the percentage of phosphorus and sulphur are below the accepted level for laser beam welding⁴⁾

For the filler material, different wires of the types G3Si1 and G3Ni1 with a diameter of 1.2 mm and 1.6 mm were chosen. A butt joint preparation was provided for 16 mm and 20 mm (with preheating) and Y-joint/U-joint preparations for 20 mm, 28 mm and 32 mm.

The welding experiments were performed with a 20 kW Yb fibre laser (wave length $1.07\mu\text{m}$, beam parameter product $11.2\text{ mm}\cdot\text{mrad}$, focal length 350 mm) and a 400 A GMA welding

Tab. 1 Chemical composition of the base material API 5L X65 according to chemical analysis

t in mm	C in wt.-%	Si in wt.-%	Mn in wt.-%	P in wt.-%	S in wt.-%
16	0.04	0.34	1.48	0.006	0.001
>=20	0.08	0.28	1.67	0.012	0.001
	Cr in wt.-%	Ni in wt.-%	Cu in wt.-%	Mo in wt.-%	Fe in wt.-%
16	0.17	0.03	0.20	0.01	bal.
>=20	0.01	0.01	0.19	0.01	bal.

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power source. The experimental hybrid welding system configuration and experimental execution can be seen in Fig. 1. Welding was carried out with leading arc, backhand with a fixed angle γ of 25° and varying parameters a and S . During the welding trials it was observed that backhand torch configuration leads to better process stability. The root dropping of the molten metal could be reduced significantly, especially when thicker plates were welded. Furthermore, the penetration was deeper than with forehand torch configuration, when identical welding parameters were used.

Single-Pass Welding

In the first welding experiments, single-pass welds were produced in position PA to identify the maximum weldable plate thickness. In order to obtain full penetration welds in 20 mm plates, beam powers of up to 19 kW were used to achieve a high weld quality and an acceptable welding speed of about 2 m/min. Different joint preparations were examined. Either a joint preparation with 16 mm root face and a 30° bevelling angle or preheating (160°C) of the material was necessary to weld 20 mm plates in a single pass (see Fig. 2 and Fig. 3).

20 mm were found to be the maximum plate thickness for single-pass welding of X65 in position PA with a laser power of 20 kW. The welding speed has a major influence on the root formation. Too low welding speeds (<0.8 m/min) result in the occurrence of droplets appearing on the root side.

The lowest welding speed to avoid those droplets turned out

Fig. 1 Hybrid welding system configuration and experimental execution

Fig. 2 Macrosection single-pass welding, $t = 20 \text{ mm}$

to be 1.9 m/min for single-pass welding.

Compared to results from the literature referring to multi-kW CO_2 -laser-hybrid welds of 20 mm thick plates it could be demonstrated that the welding speed achievable with a fibre laser can be 50% to 200% higher^{5,6)}. One even bigger advantage is the possibility to weld 20 mm in position PA which is not given with the CO_2 -laser-hybrid process. The CO_2 -laser-hybrid process is limited to welding in position PC when using 20 mm plate thickness.

Misalignment and gap bridgeability

For the use of hybrid welding in field applications the insensitivity of the process towards tolerances is very important. To examine those possible tolerances during fabrication (misalignment and gap bridgeability), a plate thickness of 16 mm was chosen, because the welding parameter range for this thickness offers opportunities to react with parameter variations on the tolerances^[mb1].

The experiments for the evaluation of the misalignment were carried out with constant and varying misalignment. It could be shown that without welding parameter adaptation a vertical misalignment of 1 mm is tolerable (see Fig. 4). By varying the welding speed and the position of the hybrid head it was possible to produce sound welds with up to 2 mm misalignment (see Fig. 5):

The experiments concerning the gap bridgeability were also performed with varying gaps between 0 mm and 0.5 mm. It could be shown that with 16 mm plate thickness gaps of up to 0.3 mm could be bridged without changing the welding parameters (see Fig. 6). With growing gap width, root dropping can appear

Fig. 3 Top and root view single-pass welding, $t = 20 \text{ mm}$, $P_L = 18 \text{ kW}$, $v_w = 2.3 \text{ m/min}$

Fig. 4 Macrosection single-pass welding, $t = 16 \text{ mm}$, varying misalignment b along the specimen

Fig. 5 Macrosection and root view, single-pass welding, $t = 16$ mm, constant misalignment 2 mm

Fig. 6 Macrosection and top view, single-pass welding, $t = 16$ mm, 0.3 mm gap

Fig. 7 Experimental setup for positional welding

and undercut formation increases. This is a disadvantage compared to CO₂-laser-hybrid welds, where gaps between 0.5 mm and 0.8 mm can be bridged^{5, 6)}.

Positional welding

For the use of hybrid processes in pipe laying, one of the most important aspects is the ability to weld in a fully (semi-) orbital process. Therefore, experiments for positional welding in positions PF (up) and PG (down) at angles of 30°, 60° and 90° were performed. The experimental setup is shown in Fig. 7.

The results indicate that the laser-hybrid process can be used in PG (down) up to 90°. Welding in PG positions results in typical weld sink formation (see Fig. 8).

For PG 30°, the same welding parameters as for PA can be

Fig. 8 Positional welding PG (down), $P_L = 17$ kW, $v_w = 2$ m/min, $t = 16$ mm

Fig. 9 Positional welding PF (up) 30°, $t = 16$ mm

used. With increasing angle, the welding parameters of the GMA process have to be adapted; especially the wire feeding rate needs to be reduced because of the rising effect of the gravitation force towards the weld pool. The welding process in PG (down) proved to be more stable on the root side than in PA position, which can be explained by the change of forces in the weld pool (hydrostatic pressure). That leads in the end to less root dropping and fewer need of filler material.

Welding in position PF (up) leads to a stable process up to an angle of 30°. Instead of an undercut, significant weld reinforcement is observed (see Fig. 9).

With a further increase of the angle (60°, 90°), the process becomes instable and droplet-like bead formation occurs. For the position PG 60° (up), a solution was found through a cooling treatment of the weld pool. This was realized by an additional argon shielding gas which was blown to the back part of the weld pool (see Fig. 10). Position PG 90° (up) was not suitable for welding with the laser-hybrid process. Good results were achieved with laser beam welding (see Fig. 11). Additional use of a cold wire led to better results with a tendency towards a weld reinforcement instead of a weld sink (see Fig. 11 right).

Multi-Pass Welding

In order to assess the weldability of plate thicknesses greater than 20 mm, multi-pass welding experiments were conducted with 28 mm and 32 mm thick plates of X65.

Fig. 10 Positional welding PF (up) 60°, t = 16 mm

Fig. 11 Positional welding PF (up) 90°, t = 16 mm

The 28 mm plates were welded with a Y-joint preparation and a root face depth of 16 mm. The opening angle was 45°. With this geometry it was possible to weld the root pass with 19 kW laser power at a welding speed of 1.7 m/min. The most promising results for the root pass were obtained by using the spray-transfer mode in the GMA process instead of a pulse process. The remaining joint could be welded by one GMA layer. It was thus possible to weld 28 mm in 2 passes (see Fig. 12 left).

For 32 mm thick plates, a U-groove with a root face depth of 18 mm turned out to be best suitable because of its smallest burn out effect and smooth upper bead appearance, with few or no side undercuts. For the first layer, a laser power of 19 kW and a welding speed of 1.5 m/min were used. In this case it was not possible to fill the remaining joint by one or two layers without weld cracking caused by the bead geometry. For this reason, four filler layers were mainly arc welded in short-circuit mode with reduced arc current, supported by a defocused laser beam (15 mm below the work piece surface) at a low beam power of 2 kW (see Fig. 12 right). The filler wire feeding rate was varied between 12 m/min and 15 m/min and the welding speed was chosen to be in

Fig. 12 28 mm 2 layers (left) and 32 mm 5 layers (right) Multi-pass welds

Fig. 13 Microhardness curves, X65 0.04% C, t = 16 mm

the range between 0.5 m/min (last pass) and 1 m/min. The produced welds were crack free according to x-ray analyses.

Overall, it can be concluded that laser-hybrid welding is a very efficient process for the (root) first layer, because it is possible to weld high root face depths (16 mm to 18 mm) at high welding speeds (1.5 m/min to 1.7 m/min). For the following layers, standard GMA / SAW processes eventually supported by lower laser powers seem to be the best choice.

Microhardness and Charpy Toughness

The laser-hybrid process led to very thin weld seams. In combination with the high welding speeds of up to 2.5 m/min, this process resulted in very short $t_{8/5}$ cooling times, for example 0.95 s at the root of the 16 mm welds. Nevertheless, the hardness was still acceptable.

The results of microhardness measurements are presented in the following figures. In Fig. 13 a 16 mm thick weld of API 5L X65 with 0.04% C led to 280 HV0.5, which is 40% higher than the respective value of the base material but is still below 350 HV0.5 [mb2].

Further welding experiments using API 5L X65 with 0.08% C in a thickness of 20 mm were evaluated. The base material hardness (~200 HV) is comparable to that of the 16 mm steel. In

Fig. 14 Microhardness, curves X65 0.08% C, 20 mm

Fig. 15 Microhardness curves, X65 0.08% C, 20 mm, preheating 160°C

the welds, the maximum hardness amounted to 410 HV0.5 which is too high (see Fig. 14). The main difference between these two welds has to be seen in the higher carbon content of the base material; and not in the higher thickness.

In order to reduce the maximum hardness, experiments with a preheating of up to 160°C were performed. The results can be seen in Fig. 15. It was possible to lower the maximum hardness to 330 HV0.5, which is still 60% higher than the base material hardness.

For the use of the laser-hybrid welding process in pipe laying one very important aspect can be seen in the resulting weld toughness. Therefore, Charpy tests were performed at different temperatures (six specimens per temperature). The notch was placed in the middle of the weld (see Fig. 16).

The results recorded at the different temperatures are depicted in Fig. 17. Down to a temperature of -40°C, all specimens showed the maximum testing value of 450 J (upper shelf). At temperatures of -80°C or below, the lower shelf is reached. The transition temperature can be estimated to be -50°C. At that temperature, the first specimen did not reach the maximum testing value, but in three cases less than 50 J.

Conclusion

From the results presented in this paper the following

Fig. 16 Charpy test specimen notch position overview (left), detail (right), $t = 16$ mm

Fig. 17 Charpy test results at different temperatures, $t = 16$ mm

conclusions can be drawn:

- (1) 20 mm X65 welded with a laser-hybrid process require 18 kW laser power at 2.3 m/min welding speed and a joint preparation. As an alternative, butt joint welding is possible when using preheating of 160°C, which also reduces the microhardness.
- (2) Edge misalignment of up to 2 mm and gaps of up to 0.3 mm can be bridged when joining 16 mm plates by single-pass laser-hybrid welding.
- (3) Positional welding is possible for PA, PF, PG with adaptation of the welding parameters.
- (4) Multi-pass welding of 32 mm thick plates yields sound welds with five layers.
- (5) Laser-hybrid welding is a very efficient process for the (root) first layer in multi-pass welding
- (6) The microhardness analyses and Charpy toughness tests show acceptable results for industrial application.

References

- 1) A. Sumpf, M. Anders, U. Jasna: Erweiterung der Prozessgrenzen beim Laser-MSG-Hybridschweißen durch Anwendung einer Pulverbadstütze und/oder Lichtbogen-pendelung. DVS Bericht 244, 2007, pp.28-34.
- 2) U. Dilthey, U. Reisgen, S. Olschok.: Robot application for laser GMA hybrid welding in shipbuilding. ICALEO 2007. Congress Proceedings 2007, Orlando, FL, USA

- 3) P. Seyffarth, R. Gaede,: Fully Automated Panel Line with Highest Accuracy Minimizes Reworking and Assemblying. 3rd European Conference on Production Technologies in Shipbuilding, Stralsund, October 23-24, 2008, to be published.
 - 4) N. N.: Guidelines for Approval of CO₂-Laser Welding in Ship Hull Construction. Classification Societies unified, 1996
 - 5) J. K. Kristensen: Thick Plate CO₂-Laser/MAG Hybrid Welding of Steels. IIW doc. IV-932-07. IIW Annual meeting 2007, Dubrovnik, Croatia.
 - 6) H. Keller CO₂-Laserstrahl-MSG-Hybridschweißen von Baustählen im Blechdickenbereich von 12 bis 25 mm: PhD-Thesis, RWTH-Aachen, 2003.
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