Lasers in Manufacturing Conference 2017

Welding of high thickness steel plates using a fiber coupled diode laser with 50 kW of output power

Uwe Reisgen[a], Simon Olschok[a], Matthias Weinbach[b], Oliver Engels[a,*]

[a] Institut für Schweißtechnik und Fügetechnik, Pontstraße 49, 52062 Aachen, Germany
[b] Laserline GmbH, Fraunhofer-Straße, 56218 Mülheim-Kärlich, Germany

Abstract

Welding in the plate thickness range between 10 mm and 25 mm is increasingly gaining importance in the industry, e.g. shipbuilding and pipeline production. Modern laser beam welding methods allow for economical joining in this thickness range. Tolerances regarding the weld preparation, however, are challenging for such a welding process. Variable welding gaps are unavoidable in this plate thickness range and need to be bridged efficiently and reliably.

Thanks to the perpetual development of the diode laser technology by Laserline, fibre coupled diode laser beam sources with a continuous wave (cw) output power of 50 kW and above are available today. Diode lasers have the highest wall plug efficiency of all laser systems reaching more than 50% overall efficiency and have proven themselves even in the harshest of production environments. In combination with a large spot diameter this allows for the economical joining of steel plates with a large plate thickness and the typically occurring tolerances.

This paper presents the first welding results obtained with structural steel in the plate thickness range between 20 mm and 25 mm. Weldings in butt joint and T-joint configuration with sawed zero-gap and different pre-set joint gaps are shown and discussed. Besides weld seams with a high degree of quality also typical weld defects and other distinctive features are demonstrated.

Keywords: Diode Laser; high Power; Welding

---

* Oliver Engels Tel.: +49 241 80-97234; fax: +49 241 80-97234.
E-mail address: engels@isf.rwth-aachen.de

1. Motivation / State of the Art

Welding of thick-walled steel structures is increasingly gaining in importance in industrial production. Especially in pipe production, ship-building or also in the production of foundation structures for offshore wind energy power plants, plates with a thickness of more than 20 mm must be joined by Hoops et al., 2011 and Houldcroft, 1989. This joining task is, currently, carried out using conventional submerged arc welding by Gericke, 2013. Here, the large number of weld beads and also the accompanying high thermal load on the part in the region of the joining zone are characteristic. In order to counteract these deficits and also to obtain the increase of the welding speed, also beam welding methods, such as laser beam welding, are applied for the joining of very thick plates by Vollertsen et al., 2010. The disadvantage of minor gap bridging ability which is typical of this joining method, is counteracted by the combination of the laser beam welding process with a conventional gas-metal arc welding process towards a hybrid welding by Seffer et al., 2012. Here, it is possible to obtain a penetration depth of up to 20 mm. For a more efficient welding of thick plates (penetration depth of approximately 25 mm), further research projects are dealing with the combination of laser beam welding and submerged arc welding towards a hybrid method by Reisgen et al., 2016. The hybrid welding methods, however, have the disadvantage of increased complexity due to the more sophisticated equipment technology. The process variation of laser beam welding in vacuum allows, however, the obtainable penetration depth, but at the expense of a more complex equipment technology for generating the required vacuum by Reisgen et al., 2015.

In laser beam welding of thick plates, normally CO_2- or solid-state lasers are used since these beam sources are available in sufficient power classes and beam qualities. Up to now, diode lasers with the required power class and, at the same time, sufficiently high beam quality, have not been available on the market. But Diode Lasers have improved tremendously over the last two decades. Beam qualities and output powers of Diode Lasers today make them a powerful tool in wide varieties of industrial material processing. Many of which have formerly been the exclusive domain of solid-state technologies like deep penetration key-hole welding, see Fig. 1

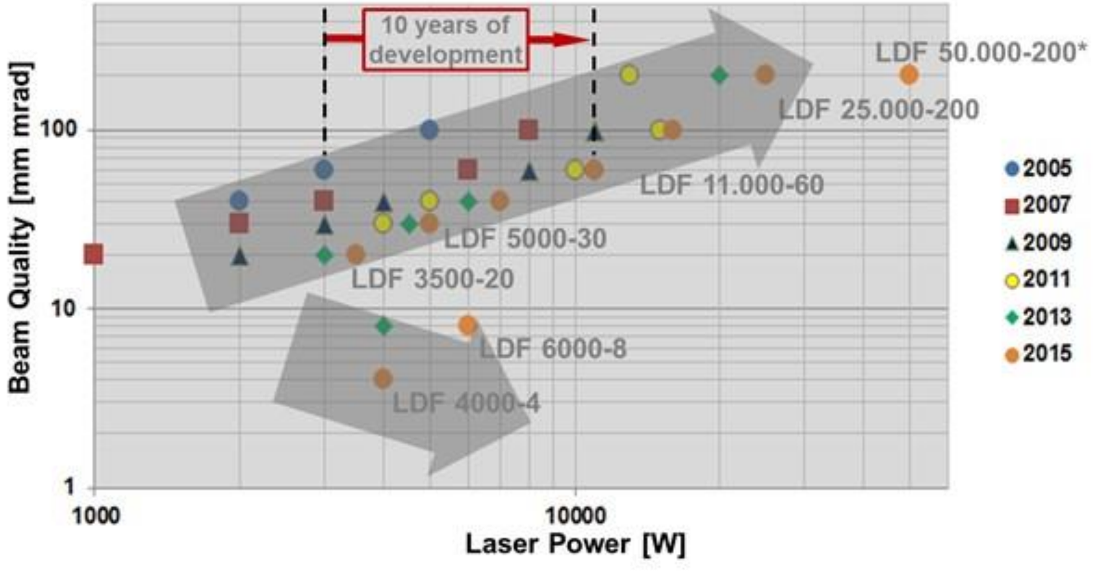
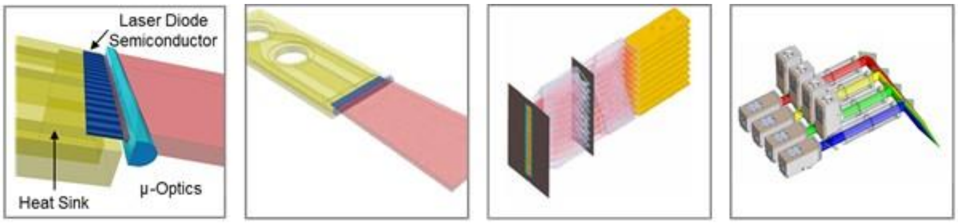


Fig. 1. Development of Diode Lasers

Due to the continuous development of the diode laser technology by Laserline, fiber-coupled diode laser beam sources with a continuous wave (cw) output power of up to 60 kW and are now available. Advantages of modern diode lasers are the high robustness and the low operating costs. Diode lasers have the highest wall plug efficiency of all Laser technologies reaching more than 50% overall efficiency and have proven themselves even in the harshest of production environments. To create output powers of 60 kW the industry proven reliable Laser head design of Laserline Diode Lasers was scaled up.

The fundamental emitter is a Laser diode bar mounted on a heat sink. These bars are combined to a stack of bars and their individual emissions are merged into a line shape. The beams of several stacks are then combined due to different polarization and wavelengths to form the complete internal Laser beam. That Laser beam is subsequently coupled into a glass fiber to transport it to the working optics, see Fig. 2.



Diode Laser Chip **Diode Laser Bar** **Diode Laser Stack** **Diode Laser Head**

Fig. 2. From semiconductor to beam source

2. Experimental set up

The experiments described in this paper were conducted at the Laserline Applications Lab. As a test bench a CNC controlled motion system was used, that allowed for precise process control and motion along XYZ-coordinates. The set up is depicted in Fig. 3.

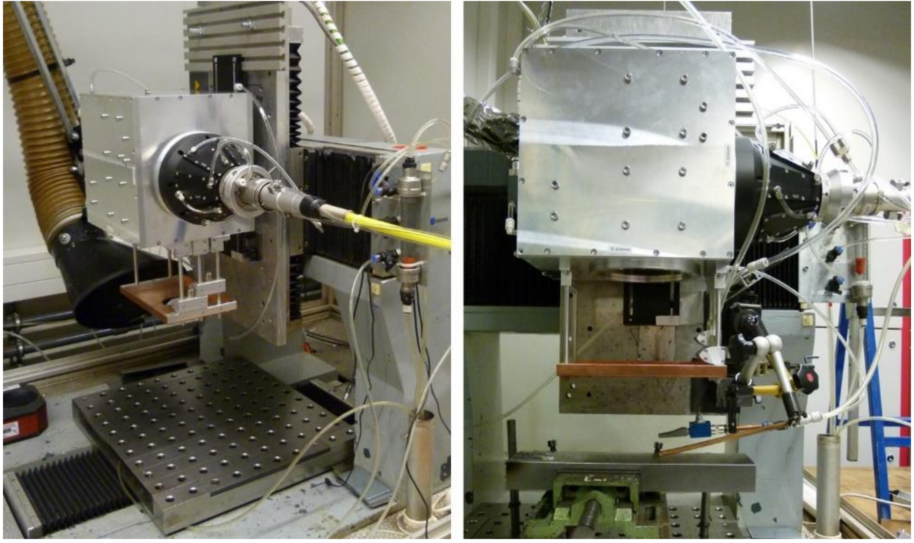


Fig. 3. Welding set up

The used fiber-coupled Diode Laser system by the company Laserline is name as LDF 50.000 – 200 and has got a maximum output power at the fiber of 50 kW. The diameter of the fiber is 2000 µm and the beam quality is 200 mm mrad. The used optical head is a prototype mirror with 150 mm diameter and a focal length of 400 mm which leads to a mathematically determined spot diameter of 2.7 mm. With this set up unalloyed construction steel with different plate thicknesses are welded.

3. Results and Discussion

3.1. Bead on plate

In a first test series, welding-in tests with different laser beam powers were carried out with constant travel speed and constant focus position. This test series serves the purpose to gain fundamental knowledge about the shaping of the welded seam in the part interior and also about the exterior weld seam appearance. The travel speed is a constant 1 m/min and the focus is positioned at 1 mm below the part surface. The process zone was, moreover, shielded with argon as shielding gas. The laser beam power was varied between 30 kW and 50 kW. Fig. 4 depicts the outer weld appearance.

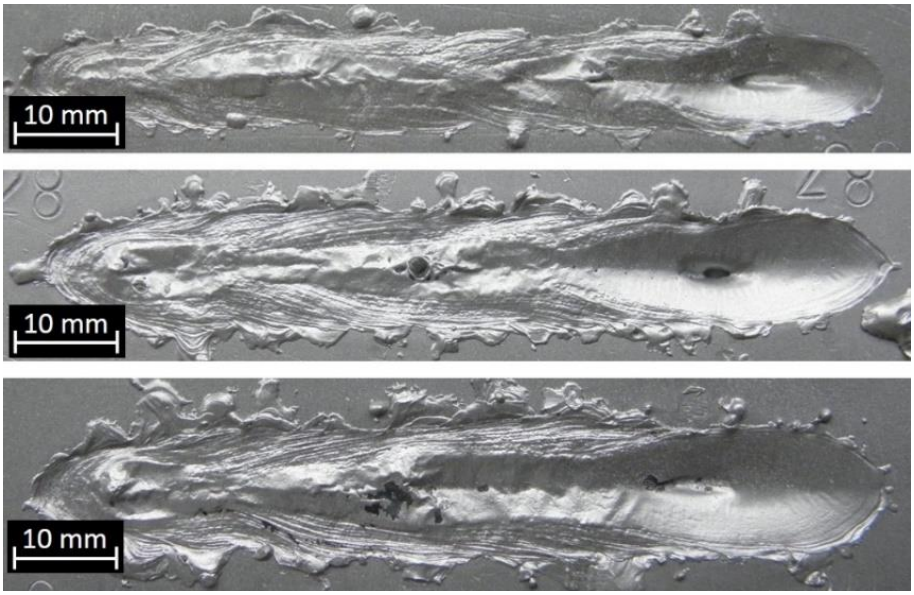


Fig. 4. Beam power 30 kW (top); beam power 40 kW (center); beam power 50 kW (bottom)

It can be observed that the width and the length of the molten pool are increasing with increasing power. While with a beam power of 30 kW, a width of approximately 9 mm and a molten pool length of 21 mm are observed, see Fig. 4 (top), with a beam power of 50 kW already a width of 12 mm with a length of approximately 27 mm is determined, see Fig. 4 (bottom). The increased occurrence of welding spatters was observed during each weld test.

Regarding the penetration depth, a proportional increase to the pre-set beam power is observed, see Fig. 5.

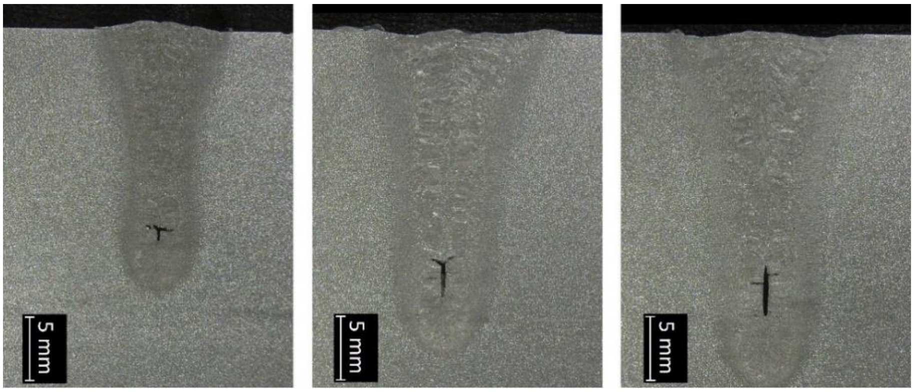


Fig. 5. Beam power 30 kW (left); beam power 40 kW (center); beam power 50 kW (right)

With a beam power of 30 kW, a penetration depth of approximately 20 mm is obtained. The penetration depth is 26 mm with a beam power of 50 kW. The shape of the welded seam does not change significantly. The width of the upper regions of the welded seams is differing. In the center and the root region, the welded seams have a similar width with each approximately 4.5 mm. A crack-like defect in the region is, moreover, recognisable which is independent of the beam power. With increasing beam power, the volume of the defect is also increasing.

Further test series under the same conditions (just the travel speed was raised) brought about comparable results – also with defects in the root region – however, with, on average, reduced penetration depth.

By the adaptation of the focus position to 5 mm below the workpiece surface with otherwise unchanged welding parameters, the defect in the root region can be suppressed, see Fig. 6.

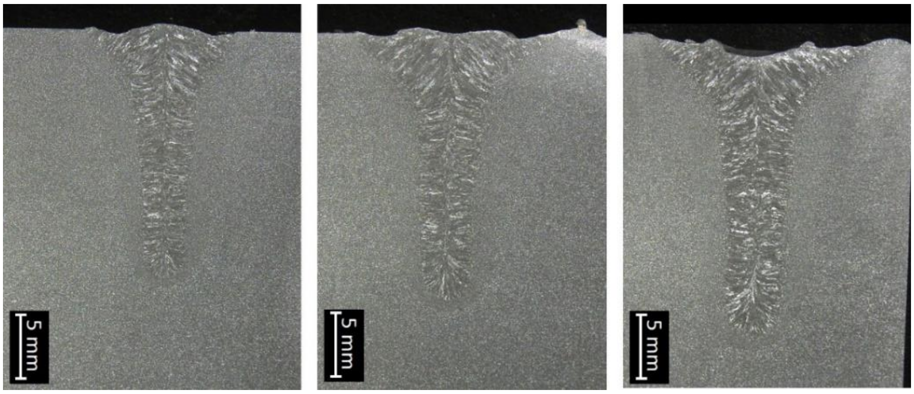


Fig. 6. Beam power 30 kW (left); beam power 40 kW (center); beam power 50 kW (right)

The outer weld appearance, the penetration depth and also the shape of the welded seam do not show significant changes compared with the previously discussed weld specimens.

3.2. With gap

Beside the weld-in tests, also joint welding with pre-determined joining gaps, a beam power of 50 kW and otherwise different weld parameters were carried out. In the following, welding carried out with a travel speed of 1 m/min, a focus position of -1 mm and a pre-set joining gap of 0.5 mm, see Fig. 7, and also welding carried out with a travel speed, a focus position of -10 mm and a pre-set joining gap of 0,8 mm, see Fig. 8, are discussed by way of example.

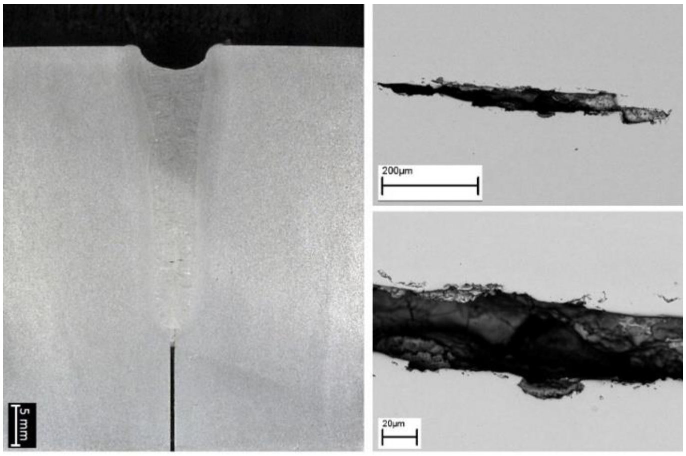


Fig. 7. Beam power 50 kW, joining gap 0.5 mm

In the welded seam carried out with a travel speed of 1 m/min, a penetration depth of approximately 28 mm was obtained, see Fig. 7 (left). The width of the welded seam is, over the entire depth, similar and is on average approximately 4 mm. The top side of the welded seam is, due to the joining gap, slightly concave. In the root region, horizontally oriented, crack-like defects are observed. This type of structure separation is often due to insufficient material quality. Further SEM examinations, see Fig. 7 (right) show that the crack faces have a positive-negative shape, which points to hot cracking.

The weld seam made with a travel speed of 0.3 m/min and a pre-determined joining gap of 0.8 mm has a fundamentally different shape of the weld, see Fig. 8

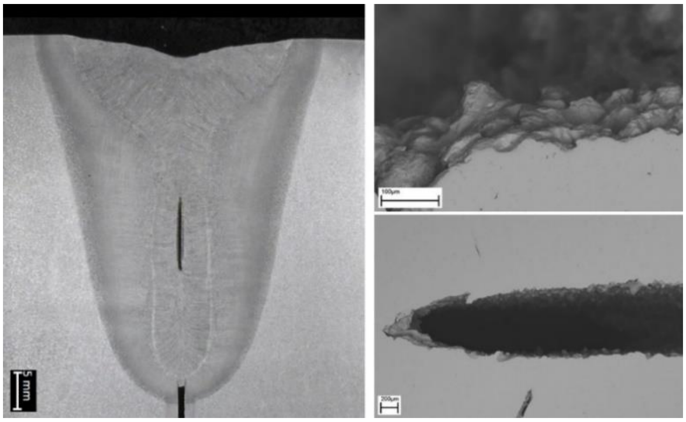


Fig. 8. Beam power 50 kW, joining gap 0.8 mm

The upper region of the weld seam is, with approximately 27 mm, clearly wider than the remaining part of the welded seam with approximately 7 mm. The interface is bell-shaped. The penetration depth is approximately 43 mm. There is, moreover, a crack-like defect with a length of approximately 9 mm in the center rib. Further detailed SEM examinations of the defect showed that a positive-negative shape of the edges was not observed, see Fig. 8 (right). This defect is rather some kind of shrinkage cavity.

Especially when this type of joint is welded, there is a large molten region. The micro-section, see Fig. 8 (left), depicts that the weld region above the defect is narrower than that in the region of the defect. The narrower region above the defect solidifies thus faster than that in the region of the defect. In the lower weld region, therefore, an enclosed, still liquid region exists as from a certain point in time. Here, the solidification fronts are growing vertically towards one another and are, at the same time, subject to volume shrinkage. The dendrite growth stops due to a lack of flowing molten metal (enclosed liquid region) and the result is a cavity (shrinkage cavity) where the edge surfaces show not-deformed dendrite structures.

The hardness measurements show a hardness curve which is typical of a laser beam welded seam, see Fig. 9.

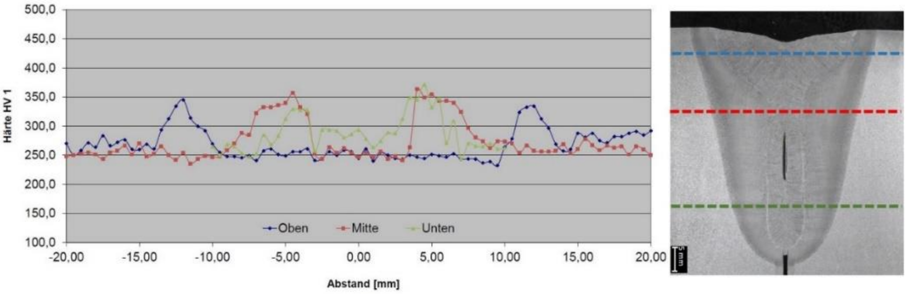


Fig. 9. Beam power 50 kW, joining gap 0.8 mm; hardness testing

The hardness of the uninfluenced base material and also of the weld seam is approximately 250 HV1. In the region of the heat affected zone, a hardness increase of up to 350 HV1 is observed.

3.3. Thorough penetration welding with backing support

Besides the previously discussed welding-in tests with and without pre-set joining gap, further penetration welding in the form of joint welds were carried out. Within the framework of this test series, joining partners with a plate thickness of 25 mm with zero-gap and ceramic backing support were welded, see Fig. 10.

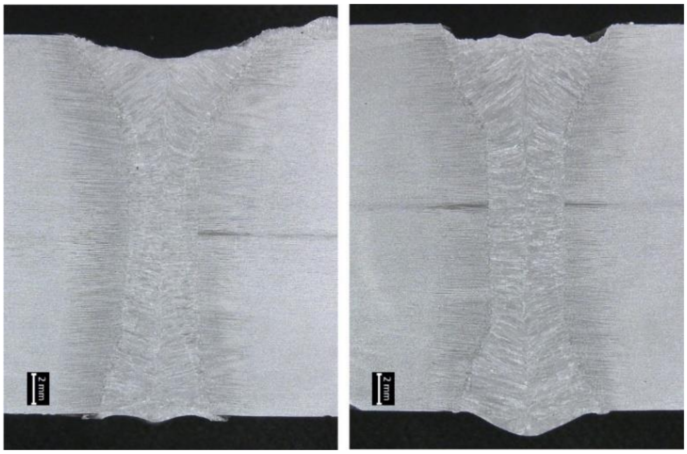


Fig. 10. Plate thickness 25 mm; backing support; beam power 50 kW; focal position -8 mm (left); focal position -10 mm (right)

The travel speed for both weld tests was 0.7 m/min with a laser beam power of 50 kW. Fig. 10 (left), shows a weld specimen which was welded with a focus position of -8 mm. Fig. 10 (right), shows a weld specimen which was welded with a focus position of -10 mm. Both weld seams have a similar shape. The root is, in both cases, neatly shaped which led to a slight concavity of the upper bead. Due to the changed heat dissipation in the lower region of the weld seam, the problem of the shrinkage cavity is completely eliminated. Not one weld specimen of this series showed defects of this type.

In further tests, a joining gap with a width of 0.5 mm was set. For the weld seam which is depicted in Fig. 11, a travel speed of 1 m/min and a focus position of -9 mm were chosen. The laser beam power was 50 kW.

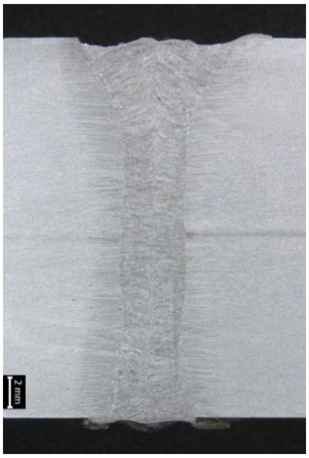


Fig. 11. Plate thickness 25 mm; backing support; beam power 50 kW; welding travel speed 1 m/min;

The weld seam also shows a high quality degree. The width of this weld seam is similar to the seams which are depicted in Fig. 10.

3.4. T-joint

Subsequently, welding of fillet welds with a laser beam power of 50 kW and different plate sizes and travel speeds was tested. The focus of the laser beam was, in each case, positioned at 10 mm below the part surface. Fig. 12 depicts the welding result obtained with a plate thickness of 20 mm and a travel speed of 1 m/min.

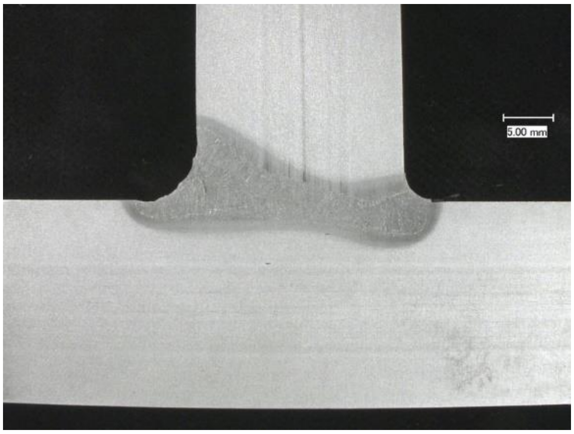


Fig. 12. Plate thickness 20 mm; beam power 50 kW; welding travel speed 1 m/min

Both parts are, over their entire length, completely joined. The welded seam has a high degree of quality. Pores and other defects are not observed. The weld upper and underside are uniform in shape.

Another weld test carried out with a plate thickness of 25 mm and a travel speed of 0.6 m/min did not result in complete fusion, see Fig. 13.

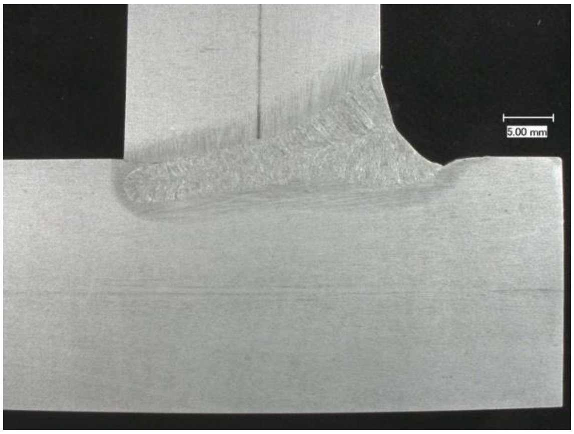


Fig. 13. Plate thickness 25 mm; beam power 50 kW; welding travel speed 0.6 m/min

The weld seam also has a high degree of quality. Pores and other defects are not observed. The penetration depth is approximately 26 mm, so that with a steeper angle of incidence complete fusion would probably have been obtained.

4. Summary / Perspectives

In this work, first the results of welding-in tests made with laser beam powers of between 30 kW and 50 kW are presented and discussed. The occurring defects in the root region of the welded seams were prevented by adjustment of the focus position.

Moreover, joint welds with and without pre-set joining gap were carried out. While crack-like defects in the welding-in joints were observed, welded seams with a high quality degree were obtained for the penetration welds.

Final tests on T-joint in the plate thickness range of between 20 mm and 25 mm resulted in welded seams with high degrees of quality. For the T-joint with a plate thickness of 20 mm, a penetration weld with clean root shape was obtained.

Against the background of preventing the occurring shrinkage cavities during penetration welding with joining gap, further focus positions or different angles of incidence of the laser optics should be tested. It should be the objective to obtain another weld formation/shape in order to avoid the generation of enclosed, still liquid regions in the part interior.

The complete fusion of both joining partners on T-joint for a plate thickness of 25 mm, compare: Fig. 13, may be obtained by a steeper angle of incidence of the laser beam. It may be possible to join joining partners with a plate thickness other than 25 mm using double-sided single pass welding.

References

Gericke, A., 2013. Wirtschaftliches UP-Quer-Schweißen an größeren Blechdicken in der Offshorestruktur- und Schiffskörperendmontage, DVS-Berichte Band 296, Große Schweißtechnische Tagung, Essen, DVS-Verlag, p. 1229-1234

Hoops, K., Schumacher, P., 2011. Wirtschaftliche schweißtechnische Produktion von Großkomponenten für Offshore-Windenergieanlagen, DVS-Berichte Band 277, Schweißen im Schiffbau und Ingenieurbau, p. 47 - 52

Houldcroft, P.T., 1989. Submerged-Arc Welding, Woodhead Publishing Series in Welding and Other Joining Technologies, Woodhead Publishing, p. 9 -26

Reisgen, U., Olschok, S., Jakobs, S., Engels, O., 2016. Modern hybrid welding process for structural steelwork engineering – Laser submerged arc hybrid welding, Journal of Laser Applications 28

Reisgen, U., Olschok S., Jakobs S., Turner C., 2015. Laser Beam Welding in Vacuum – Overview of Thick-Plate Steel Application and Beyond, Lasers in Manufacturing Conference 2015

Seffer, O., Lindner, J., Springer, A., Kaierle, S., Wesling, V., Haferkamp, H., 2012. Laser GMA hybrid welding fort hick wall applications of pipeline steel with the grade X70, International Congress on Applications of Lasers and Electro Optics, Anaheim, USA, p. 494 – 501

Vollertsen, F., Rethmeier, M., Gumenyuk, A., Grünewald, S., Reisgen, U., Olschok, S., 2010. Welding thick steel plates with fibre lasers and GMAW, Welding in the World 54, p. 62 – 70