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УДК 621.791.72

ОРБИТАЛЬНАЯ ГИБРИДНАЯ ЛАЗЕРНО-ДУГОВАЯ СВАРКА ТРУБОПРОВОДОВ С ИСПОЛЬЗОВАНИЕМ ВЫСОКОМОЩНЫХ ИСТОЧНИКОВ ЛАЗЕРНОГО ИЗЛУЧЕНИЯ

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Целью настоящей работы являлось исследование орбитального гибридного лазерно-дугового процесса для оценки его применимости для сварки кольцевых неповоротных стыков толстостенных труб большого диаметра.

На трубах диаметром 36" с толщиной стенки 16 мм успешно продемонстрирована сварка кольцевого стыка в два полуорбитальных прохода на спуск со средней скоростью процесса 2 м/мин и мощностью лазера 19 кВт. Потолочное положение сварки (участок от 150° до 180°) является наиболее сложным с точки зрения обеспечения качественного формирования корня. Адаптация скорости подачи сварочной проволоки, скорости сварки, а так же применение формирующего газа заметно улучшают качество корня в потолочном положении сварки. Сканирующая оптика зарекомендовала себя как эффективный инструмент позволяющий расширить допуски на зазоры в стыке, а так же компенсировать небольшие ошибки позиционирования сварочной головки относительно стыка. Установленная для сваривемой толщины 16 мм величина зазора, при котором еще возможен стабильный процесс без дефектов сплавления, составляет 0,7 мм. При сварке обычной оптикой без сканирующего модуля величина максимально допустимого зазора кромок составляет 0,3 мм. С применением предварительного подогрева достигнуто увеличение времени охлаждения $t_{8/5}$ с одной секунды до 16 секунд, что способствовало значительному снижению микротвердости в зоне термического влияния.

Настоящие исследования проведены в рамках проекта MNPQ FK19/07 при финансовой поддержке Федерального Министерства образования и исследований Германии. Авторы выражают благодарность партнерам со стороны производства, фирмам Vietz GmbH и HIGHYAG, за плодотворное сотрудничество и предоставление оборудования для проведения экспериментов.

Ключевые слова: сварка, гибридная лазерно-дуговая сварка, орбитальная сварка, трубопроводы высокого давления, оптоволоконные лазеры.

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1. Introduction

The growing necessity of constructing onshore and offshore pipelines for transporting oil and gas was the economic and technical background of this study. In pipeline construction, conventional manual or semi-automated arc welding processes are still used, which very often lead to a higher occurrence of weld imperfections compared to the fully automated arc welding processes [1]. Oil and gas transmission pipe lines are very large constructions, e. g. with outer diameters of 1.22 m (48") and wall thicknesses of 32 mm. Multi-pass welding is a method commonly used for joining thick plates and, in conjunction with arc welding, it is a highly elaborate and time-consuming process [2].

For fast, economically efficient and safe construction as well as laying of future pipelines, it is necessary to apply new welding techniques which will be able to join pipes fully automatically in a single operation.

The only applicable method for solving this task seems to be laser welding, or laser-hybrid welding which is a combination of two processes, i.e. a laser beam welding process and an arc welding process. The electron beam welding process has a significantly higher technical complexity and can therefore not be used for these applications [3].

For joining a pair of pipes, the so-called girth welding process is applied, where the welding head is moved around the pipe circumference.

Girth pipeline welding has long been known, and there are also many examples showing the applicability of the laser beam in all-position welding. Many experiments have been carried out to establish the girth welding process using CO_2- and Nd:YAG-lasers for pipelines with wall thicknesses ranging from 10 mm to 15 mm. It has been shown that a stable process can be realized in all welding positions with a 12 kW CO_2-laser for maximum wall thicknesses of 13 mm [4]. With greater thicknesses, welding should be carried out in a horizontal welding position to prevent droplet formation. The required wall thickness could not be welded using Nd:YAG-lasers on grounds of a comparatively poor beam quality, so that the final pass should be performed by gas metal arc (GMA) welding [5]. It could be shown that laser-hybrid welding has in principle a significant advantage over laser welding because of the lower requirements as regards the gap and edge mismatch. The positive effects on the crystalline structure of the welds have been pointed out in [6]. It was furthermore clear that laser welding does not provide sufficient weld quality with increasing wall thickness. Weld imperfections occurring at the centre line of laser welds are typical in thick plate welding [7].

With the recent introduction of multi-kilowatt fibre lasers combining high beam quality with an impressive energy efficiency, it was possible to broaden the spectrum of laser beam and laser-hybrid welding applications widely. Application of these lasers for welding thick-walled structures, such as pipes with wall thicknesses from 16 mm onwards, is interesting, because the fibre lasers with output power of above 15 kW offer sufficient penetration depth to allow economically efficient welding of the pipes, i.e. with a reduced number of welding passes and with a lower amount of filler material.

The focus of this paper is to show the application of a laser-hybrid welding process using a 20 kW fibre laser and a GMA torch for orbital welding of pipelines with a wall thickness of 16 mm. The main goal of the investigation is to realize a stable and crack free girth welding process for the complete circumferential weld.

2. Materials, joint preparation and experimental setup

The plates (16 mm x 70 mm x 300 mm) and pipe rings of X65 with outer diameter of 36″ and a wall thickness of 16 mm were used for the welding experiments. The rings were cut out from a pipe manufactured in accordance with the American Petroleum Industry (API) standard which corresponds approximately to EN 10208-2. The chemical composition of the base material is given in Table 1.

For both materials, the percentage of phosphorus and sulphur are below the accepted level for laser beam welding [8].

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

material, t = 16 mm	*C* in wt.-%	*Si* in wt.-%	*Mn* in wt.-%	*P* in wt.-%	*S* in wt.-%
plates	0.04	0.34	1.48	0.006	0.001
pipe rings	0.089	0.363	1.56	0.012	0.001
	Cr in wt.-%	*Ni* in wt.-%	*Cu* in wt.-%	*Mo* in wt.-%	*Fe* in wt.-%
plates	0.17	0.03	0.20	0.01	balance
pipe rings	0.03	0.043	0.022	0.008	balance

The gas mixture ARCAL 21 (8% CO2 in Ar) was used as shielding gas in accordance with EN 439-M21. The welds were produced using the filler wires G3Si1 and G3Ni1 with a diameter of 1.2 mm in accordance with DIN EN 440.

The welding experiments were performed with a 20 kW Yb fibre laser (IPG) (wave length 1.07 µm, beam parameter product 11.2 mm * mrad). A micro-processor controlled welding machine GLC 603 Quinto (Cloos) with a rated output of 600 A was used as the GMA power source. The experimental hybrid welding system used for welding experiments with plates 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.

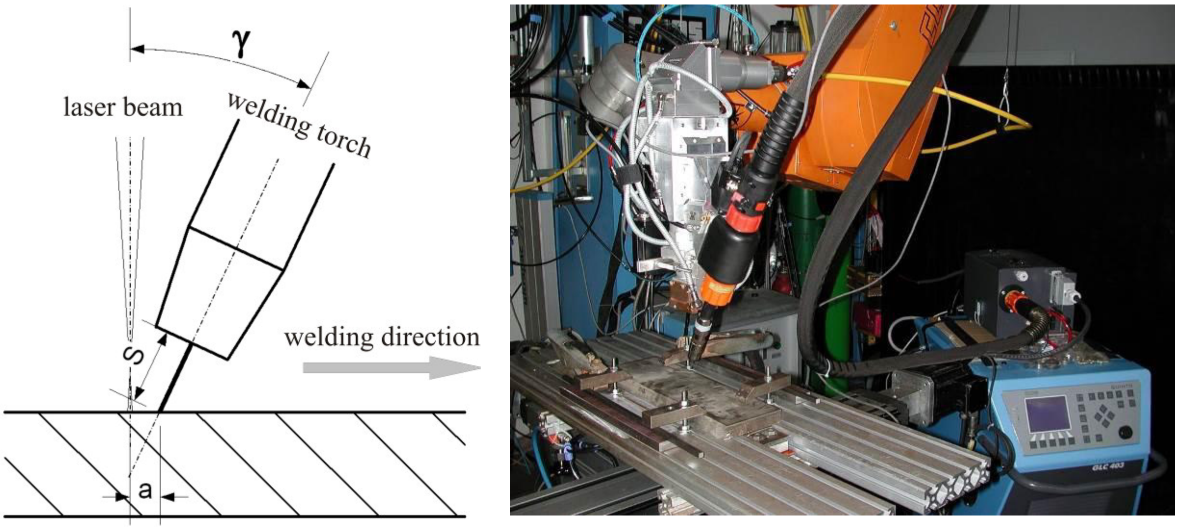


Fig. 1: Hybrid welding system used for the welding experiments with plates and experimental execution

An orbital welding device (Vietz) was used for producing the girth welds, Fig. 2. The device includes a guide ring (1) and an orbital carriage (2) that can be motor-displaced along the guide ring. A hybrid welding head (3) that combines the laser optic (HighYag) (4) and the GMA torch (5) is mounted on the orbital carriage. The specimen (6) can be fixed centrally to the guide ring. The radial alignment of the specimen was adjusted with mounting screws (7).

The optic used for the experiments with plates had a focal length of 300 mm and optic used for the girth welds had a focal length of 350 mm. The laser beam was transmitted by an optical fibre with a core diameter of 0.2 mm and focussed to the diameter of 0.5 mm and 0.56 mm accordingly. A scanner optic with a scanner mirror was also tested for the girth welds. The diameter of the beam focus spot delivered by this optic was 0.42 mm. The plates and pipe rings were butt welded in one pass.

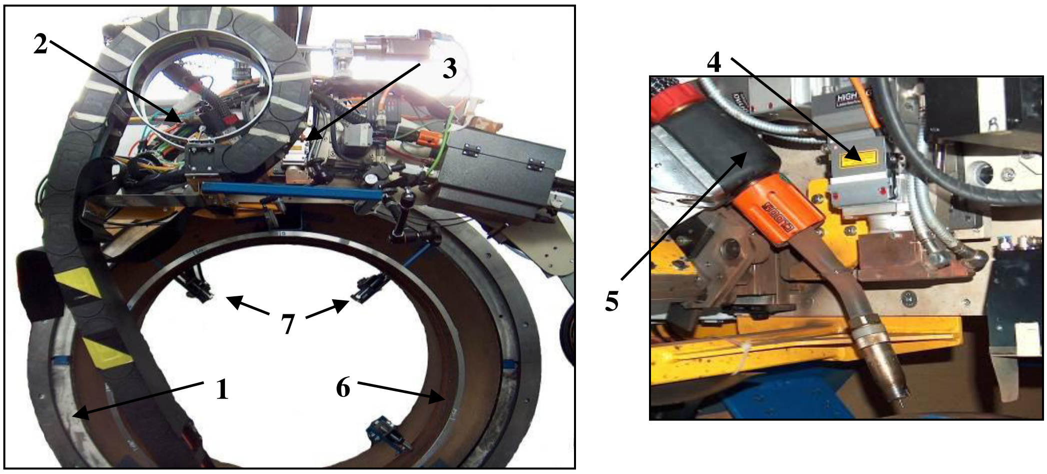


Fig. 2: Orbital welding device with welding head

3. Results and discussion

3.1 Welding experiments in discrete positions

In the first step of the study, the relationship between material behaviour, e.g. outer appearance of the weld bead and welding parameters, was investigated for welding in discrete positions. The experiments in positions PF (up) and PG (down) at angles of 30°, 60° and 90° were performed for 16 mm plates of X65. The experimental setup is shown in Fig. 3.

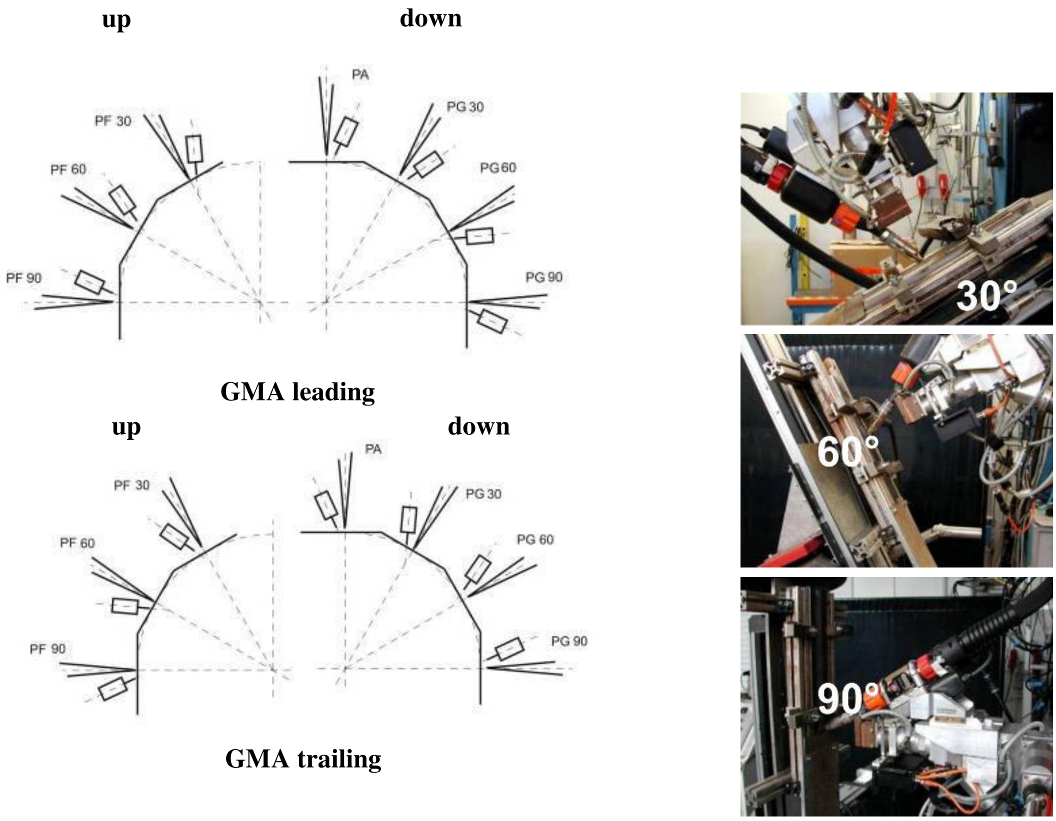


Fig. 3: Experimental setup for positional welding

The first results indicated 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. 4).

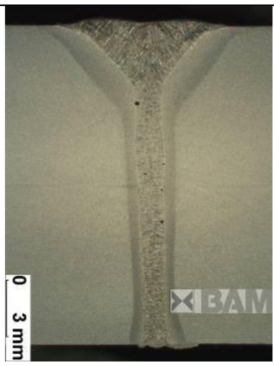
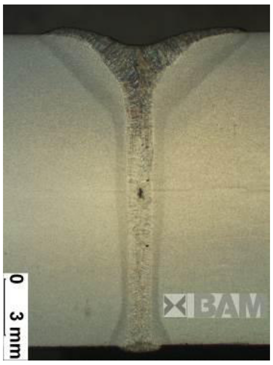
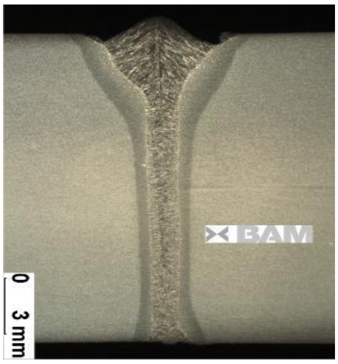
			
Position PA v_d = 15 m/min I_{LB} = 364 A U_{LB} = 35.6 V	Position PG 30° v_d = 15 m/min I_{LB} = 364 A U_{LB} = 35.6 V	Position PG 60° v_d = 12 m/min I_{LB} = 339 A U_{LB} = 34.2 V	Position PG 90° v_d = 8 m/min I_{LB} = 245 A U_{LB} = 29.9 V

Fig. 4: Positional welding PG (down), PL = 17 kW, v_s = 2 m/min, t = 16 mm

For PG 30°, the same welding parameters as for PA can be used. With increasing angle, the welding parameters of the GMA process have to be adapted. 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. 5).



t = 16 mm

P_L	=	17 kW
v_w	=	2 m/min
Δz	=	-4 mm
v_d	=	10 m/min
I_{LB}	=	272 A
U_{LB}	=	29.5 V

Fig. 5: Positional welding PF (up) 30°

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. 6).

Position PG 90° (up) was not suitable for welding with the laser-hybrid process. Good results were achieved with laser beam welding (see Fig. 7). Additional use of a cold wire led to better results with a tendency towards a weld reinforcement instead of a weld sink (see Fig. 7 right).

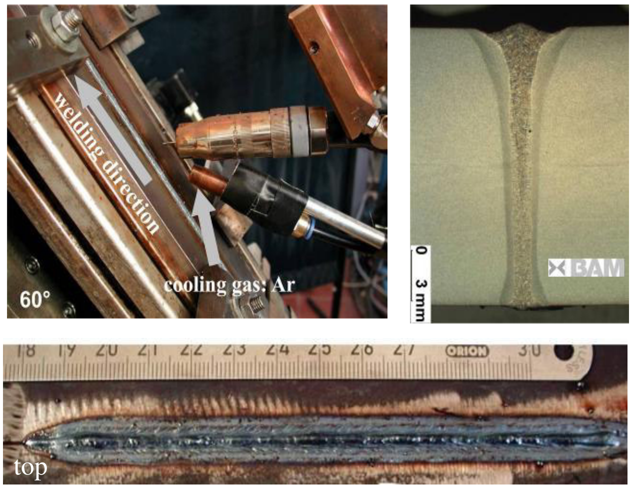


Fig. 6: Positional welding PF (up) 60°, t = 16 mm

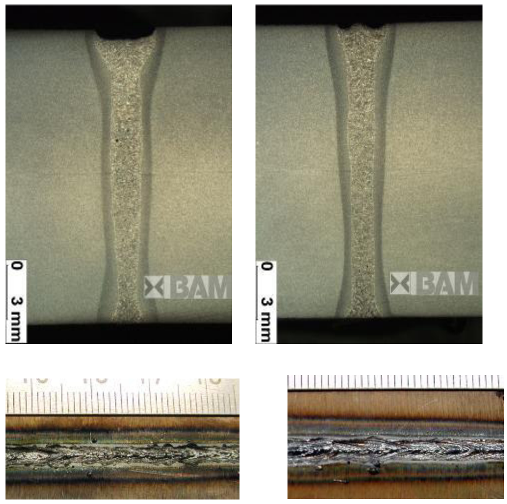


Fig. 7: Positional welding PF (up) 90°, t = 16 mm

3.2 Girth welding experiments

The girth welding experiments were performed in vertical down position, so that the girth weld can be completed in two halves. The welding parameters used for the experiments are given in the Table 2.

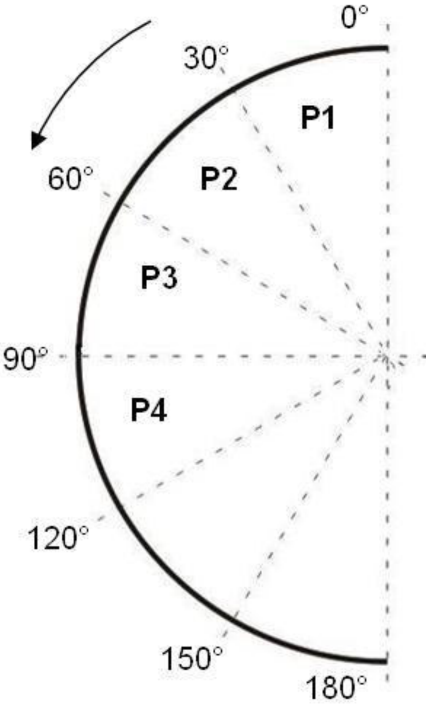
Tab. 2: Welding parameters

Laser power P_L in kW	19
Welding speed v_s in m/min	1.8…2.2
max. Arc current I in A	410
max. Arc voltage U in V	33
Arc mode	Pulse U/I
Arc length L_{LB} in %	-12…5
Wire feed speed v_d in m/min	6…15
Flow rate of shielding gas in l/min	22…30

Continuous welding from the flat (0°) to the overhead position (180°) was performed by interpolating proper welding parameters which were obtained from the discrete welding positions. The distance between the laser beam and the arc was fixed to be 3.5 mm, based on the results of preliminary examinations.

As shown in Fig. 8, a girth weld can be completed in the positions from 0° to 180° with four sets of welding parameters (P) which can be sequentially changed according to the actual welding position by using a corresponding control system.

A beam power of 19 kW was used in order to get full penetration welds at an acceptable welding speed of about 2 m/min. Too low welding speeds (<1.8 m/min) resulted in the appearance of droplets on the root side, especially in the flat position. The beam power and welding speed were kept constant for all welding positions. An acceptable weld bead configuration could be obtained by adaptation of the wire feed speed. The wire feed speed at the start of the welding should be reduced from 14 m/min in the flat position to 8 m/min in the 90° position.



Laser:
P_L = 19 kW
v_s = 2,2 m/min

GMAW:
P1: v_d = 14 m/min
L_{LB} = 5 %
P2: v_d = 10 m/min
L_{LB} = 0 %
P3: v_d = 8 m/min
L_{LB} = -5 %
P4: v_d = 6 m/min
L_{LB} = -12 %

Fig. 8: Schematic diagram of the girth welding experiments with adapted process parameters

From this position through to the overhead position (180°), the wire feed speed had to be kept at 6 m/min to avoid outflow of metal from the molten pool. In addition to the wire feed speed, the arc length had to be controlled, i.e. decreased from +5 % to -12% relative to the appropriate arc length for the GMAW parameters (arc current and arc voltage) by travelling from the flat position to the overhead position. The shorter arc with accordingly higher arc pressure acting on the molten pool resulted in a good bead formation on the top side of the welds in the overhead position.

Figure 9 shows cross-sections as well as outer appearances of the welds made using the welding parameters indicated in Fig. 8.

A visual inspection of the welds shows that the most stable weld bead formation was obtained from the flat position of 0° through to the vertical position of about 150°. Slight underfilling on the top side of the welds could however be observed in the positions from about 50° to 80°.

In the welding positions between 150° and 180°, it was most difficult to obtain a weld bead with an acceptable root side quality. In these positions, the critical problem was lack of molten metal on the back side because it hung down under the force of gravity. On the other hand, the process was very sensitive to the precision of the welding head positioning relative to the butt joint. The laser beam displacements of about 0.3 mm from the butt resulted in a lack of side-wall fusion on the back side. The adaptation of welding parameters such as welding speed and wire feed speed did not lead to stable and reproducible results in these positions.

The most promising results were obtained by adopting a method for beam modulation using a scanner optic.

Some specimens have been tacked with a predefined misalignment of up to 2.0 mm. It was possible to produce sound welds as already shown in [9].

3.3 Welding experiments using a scanner optic

The experiments using a scanner optic were carried out to investigate the possibilities of influencing errors arising from welding head positioning and from dimensional tolerances such as a gap.

The applied scanner optic has a mirror module with a scanner mirror made of copper and silver coated. The scanner mirror can be rotated by a motor at an adjustable angle, so that a maximum scan width of about 13.2 mm (±6.6 mm) can be achieved. The scanner frequencies up to 1 KHz can be supported by the control unit. The chosen wave form was sinus.

First, several test welds were produced in the flat position on the 16 mm plates of X65 without gap with a variation of the scanner amplitude and frequency. It was seen that a stable welding process is realizable with a frequency in the range from 200 Hz to 400 Hz and a scan width of up to 1.0 mm. An increased molten area can be also seen on the cross-sections of welds in Fig. 10.

The results were transferred onto pipe rings where the process was investigated for discrete welding positions as well as for half circumferential welds (from 0° to 180°). The experiments have shown that the application of a scanner optic yield an improved weld bead formation, especially for the overhead position.

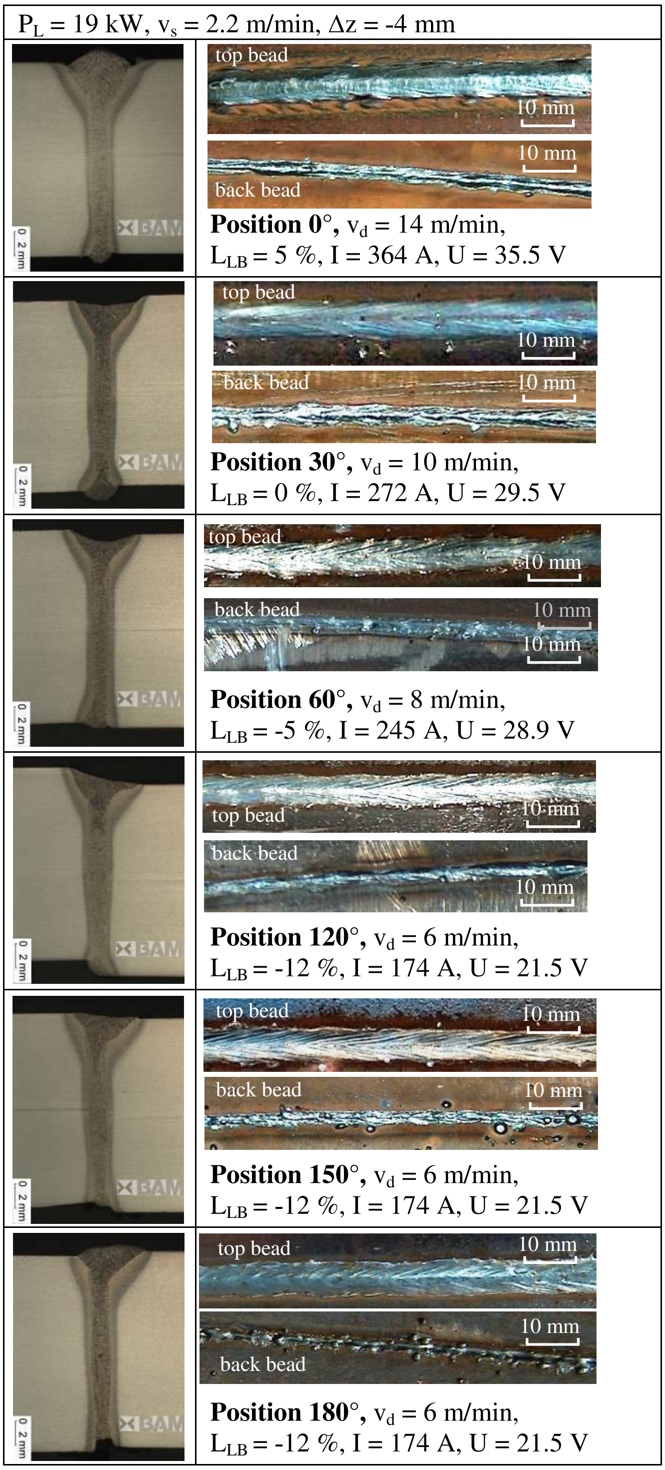


Fig. 9: Cross-sections and outer appearances of the laser-hybrid welds of 16 mm thick pipes X65 with outer diameter of 36″

Thus, the bead width could be adapted so that errors due to deviations in positioning of the welding head with respect to the butt joint were compensated and therefore a stable welding process with good side-wall fusion was obtained, Fig. 11. However, further investigations have to be made in order to reduce the occurring welding splashes.

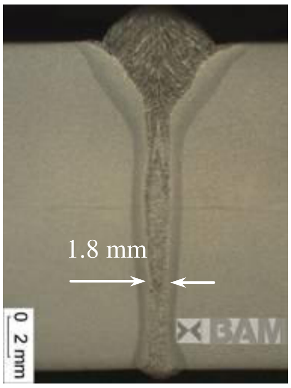
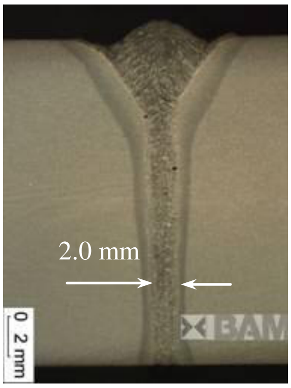
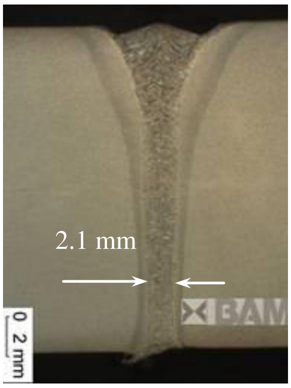
Scan width		
0 mm	0.5 mm	1.0 mm
		
P_L = 19 kW, v_s = 2.2 m/min, v_d = 14.0 m/min, frequency = 200 Hz, gap = 0 mm		

Fig. 10: Cross-sections of laser-hybrid welds of 16 mm plates X65 using a scanner optic

P_L = 19 kW, v_s = 2.2 m/min, v_d = 6.0 m/min	
	  **Position 180°**, frequency = 200 Hz, scan width = 0.7 mm

Fig. 11: Cross-section and outer appearance of a laser-hybrid weld in the 180° position produced using a scanner optic

The influence of scanner parameters on the gap bridging ability was investigated. The 16 mm plates of X65 with gap widths ranging between 0.2 mm and 0.7 mm were welded to identify an acceptable criterion of the gap width, at first for the flat position.

As Fig. 12 shows, an acceptable shape of the weld bead can be obtained with the gap widths of up to 0.7 mm. A tolerable gap width using conventional optic for this thickness was limited to about 0.3 mm [9, 10, 11]. Larger gaps resulted in lack of side-wall fusion and undercuts, Fig. 12 left.

Further welding experiments with gap and mismatch will be made on the pipe rings to investigate dimensional tolerances of edge misalignment in all welding positions.

4. Conclusions

This study has investigated the process of girth laser-hybrid welding of pipelines using a 20 kW fibre laser. The welding process was examined for pipe rings of X65 with an outer diameter of 36″ (914 mm) and wall thickness of 16 mm. The results obtained may be summarised as follows:

(1) An acceptable weld bead can be obtained in principle in each welding position ranging from flat position (0°) to overhead position (180°). The most difficult welding position to obtain a weld bead with an acceptable root side quality is a section between 150° and 180°.
(2) The welding parameters were found to establish an appropriate laser-hybrid welding conditions for the 16 mm thick pipe of X65. Beam power and welding speed can be kept constant for all welding positions. The wire feed speed and arc length should be adapted by travelling from the flat position to the overhead position.
(3) The scanner optic is an effective tool for the compensation of errors due to deviations in positioning of the welding head with respect to the butt joint and different gap sizes. By applying this technique, acceptable root quality could be obtained for the welds produced in overhead position where the process is very sensitive to the positioning of the welding head relative to the butt joint. The upper limit of the gap obtained for the plates of X65 in flat position was 0.7 mm which is more than two times bigger as without a scanner optic.

Acknowledgement

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<table>
<tr><td colspan="3">Gap size</td></tr>
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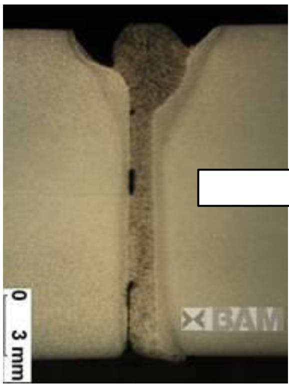
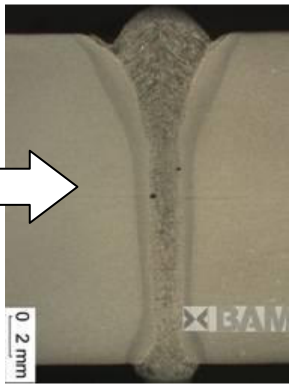
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>without scanner</td><td colspan="2">scan width 0.7 mm,
frequency 200 Hz</td></tr>
</table>

Fig. 12: Cross-sections of laser-hybrid welds of 16 mm thick plates X65 with gaps

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Orbital Hybrid Laser-arc Welding Using a High-power Fibre Laser for Pipeline Construction

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Abstract – Recently developed fibre lasers provide multi-kilowatt beam power with high quality at impressive energy efficiency. Combined with gas metal arc welding (GMAW) equipment these lasers can be used in a hybrid process to weld thick-walled constructions single-pass, that are currently welded using multi-pass techniques. The main benefits are a reduction of heat induced distortions, due to the low heat input, as well as savings in filler material and process time. Probable applications can be found in power generation, ship building and pipeline constructions.
An orbital (girth) laser-hybrid process using a 20 kW fibre laser and a GMAW torch is currently examined at the BAM, Berlin. The aim of this research is to obtain a stable and crack free girth welding process and to demonstrate its application in pipeline construction. The experiments are carried out on 16 mm thick plates as well pipe rings with 36" (914 mm) pipe diameter of X65. Particular welding parameters, such as welding speed, GMAW power, arc length are varied and their influence on the appearance of the weld in the different welding positions is analyzed.
Even though issues remain that demand further research it could already be shown that the rings can be welded using a girth hybrid process that is divided into two half girth processes in downward direction.

Keywords: high-power fibre laser, pipeline, laser-hybrid welding, thick plates.