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WELDING THICK STEEL PLATES WITH FIBRE LASERS AND GMAW






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ABSTRACT

The results of a collaborative research project on laser beam weldability of carbon steels of high sheet thickness are presented. That includes single and multiple pass welding of 16 mm and 20 mm thick plates, as well as the investigation of acceptable tolerances i.e. gap bridgeability and edge misalignment. For the welding experiments fibre lasers with 8 kW, 20 kW laser power and different GMAW-techniques were used in various applications. With the 20 kW fibre laser 16 mm plates could be welded with a single pass, 20 mm required a seam preparation or alternatively preheating of the material. For multi pass welding with 8 kW laser power a joint preparation with a single V-butt joint with a broad root face (Y-groove) was applied. The root pass was always welded with a hybrid process, the filler passes with a hybrid process as well as a GMAW process which produced the best results.

IIW-Thesaurus keywords: *Arc welding; Carbon steels; Combined processes; Fibre lasers; Gas shielded arc welding; GMA welding; Multirun welding; Reference lists; Steels; Unalloyed steels.*

1 INTRODUCTION

Joining thick steel plates with conventional GMAW processes used for example in the field of shipbuilding or pipe laying requires a high number of different weld passes. Single pass GMA welding is not a suitable process at a sheet thickness far above 5 mm, as the melt pool becomes very large, which is difficult to control and comes along with a very high heat input into the base material. As a solution processes such as modern hybrid welding systems employing high power lasers are sought-after. Expected benefits are the reduction of required weld passes, the increase of welding speed and the decrease of the heat input, which leads to less distortion and thus less rework for straightening [1, 2]. Following the first ideas of Steen [3] implementations have been made in the past combining CO_2-lasers or Nd:YAG lasers with high powers with a GMAW process to a hybrid process [4]. Fields of application are thick section welding [5-7], e.g. pipe production.

The possibility to transport the laser beam in an optical fibre offers a high degree of freedom for solid state lasers. With the introduction of fibre lasers into welding technology, laser powers of 20 kW and more in cw mode with an excellent beam quality combined with high efficiencies at high laser powers, solid state lasers have become a viable alternative to CO_2 lasers in the above mentioned fields [8], especially due to the additional high degree of mobility for the recent solid state

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laser concepts. Pipe laying [9] or shipbuilding [10] are examples for applications.

In order to study the potential of fibre lasers together with GMAW-hybrid technique for such kind of applications, a joint project was run with, for example, the purpose of qualifying laser and laser-GMA-hybrid welding processes using lasers of high power and beam quality in the field of heavy industry, shipbuilding, and pipe production for thick materials of plate thickness between 16 mm and 32 mm. The focus in this paper is on 16 mm material which was extensively tested as well as on 20 mm welds. The objectives strived for in particular are the determination of the process boundaries correspondent to the maximum achievable plate thickness for one pass welding as well as acceptable production tolerances (gap and edge misalignment) during welding of low alloyed steels with laser-GMA hybrid welding technique. Further tasks were the determination of a process window for single pass welding providing a good quality of the root pass and developing a strategy for multi pass welding.

2 EXPERIMENTAL WORK

2.1 Material

As a base material for this set of experiments, steel with reduced contents of carbon has been chosen. This steel grade is thermo mechanically rolled and rapidly cooled and has a high yield strength (at least 460 MPa) and a high impact toughness (at least 450 J at -40 °C). It is used for manufacturing large diameter pipes and is specified as X65 according to API 5L standard. The chemical composition of the welded material is given in Table 1. The dimensions of the material used for the experiments were 300 mm × 40 mm with a thickness of 16 mm and 20 mm for single pass welding, as well as 350 mm × 200 mm with a thickness of 16 mm for multi pass welding.

As filler wire electrodes of type G3Si1 and G4Si1 according to DIN EN 440 standard have been used.

The shielding gases for the laser-GMA-hybrid welding process have been chosen according to European standard DIN EN 439, M21. Gas mixtures with 82 % Ar and 18 % CO_2 as well as 90 % Ar and 10 % CO_2 have been used.

Especially for welding multiple passes a joint preparation with a single V-butt joint with a broad root face (Y-groove) was used, Figure 1. Two different included angles were applied, using α = 45° and α = 60°. The root face c varied from 6 mm to 10 mm and the size of the gap b ranged from 0 mm up to 1.2 mm. All experiments were done in flat position.

2.2 Experimental setup 8 kW-laser

The experimental setup for laser-GMA-hybrid welding consisted of a YLR-8000 S fibre laser source with 8 kW output power, a DalexVario MIG 600 I(w)-B power source, an Abicor Binzel APD wire feed unit and a hydraulically operated clamping device. A special feature of the YLR-8000 S fibre laser is the 100 µm feeding fibre coming from the beam combiner and not being interrupted by an optical coupler or a beam switch, thus acting as the processing fibre at the same time. This configuration of the fibre laser allows a very high brightness of the laser beam and consequently a very high beam quality of 4.2 mm*mrad. The fibre was connected to a 160 mm Optoskand collimator mounted on a Trumpf BEO D70 laser welding head with a 280 mm focusing lens. Together with a specially developed GMAW torch, the laser welding head was mounted to a gantry robot work station, Figure 2.

The welding torch was fixed at an angle of 22° and can be used in a trailing as well as a leading position. For the welding experiments, the torch was applied exclusively in the leading position. By using the fine adjustment the position of the torch relative to the laser beam could be changed. Table 2 gives an overview of the parameters used for the experiments.

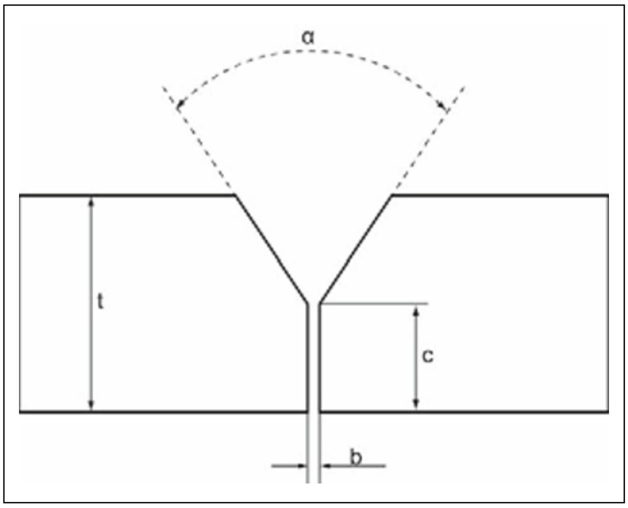


Figure 1 – Joint preparation

Table 1 – Chemical composition of the material used

Chemical Analysis (mass parts in %)													
C	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Ti**	**Nb**	**Cu**	**Al**	**Mo**	**V**	**B**
X 65, t = 16 mm													
0.04	0.34	1.48	0.006	< 0.001	0.17	0.03	0.012	0.04	0.02	0.03	< 0.01	0.003	< 0.0001
X 65, t = 20 mm													
0.08	0.28	1.67	0.012	< 0.001	< 0.01	< 0.01	0.012	0.05	< 0.01	0.03	< 0.01	0.002	< 0.0001

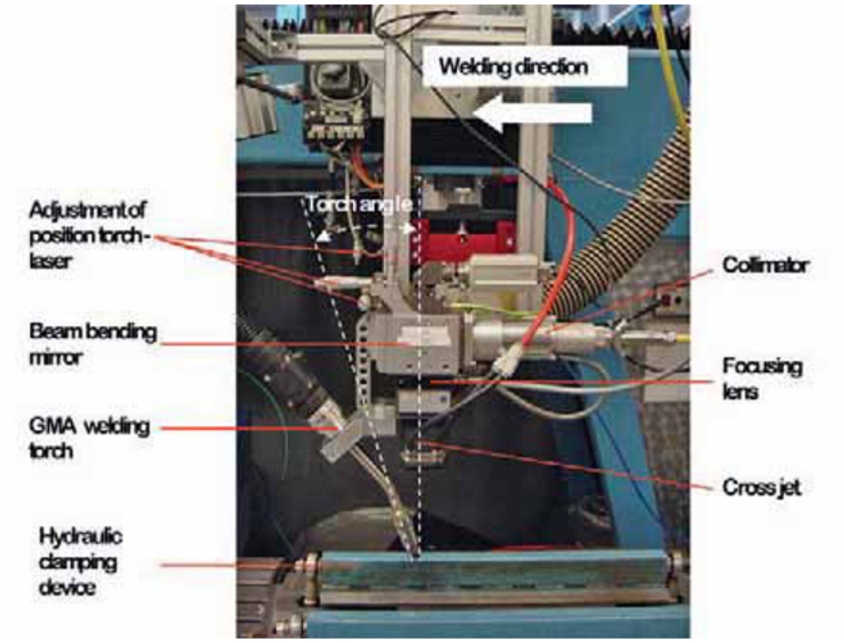


Figure 2 – Experimental setup for laser-GMA-hybrid welding with 8 kW

2.3 Experimental setup 20 kW-laser

A 20 kW Yb fibre laser oscillator from IPG Photonics with a 200 μm optical feeding fibre was used for welding 16 mm and 20 mm thick material using the single laser beam for welding as well as combined with GMAW to a hybrid process. The laser has a BPP of ca. 11.5 mm*mrad. As a focusing optic the optical head of HIGHYAG with a 125 mm collimator and 350 mm focal length was used for this set of experiments. The correspondent theoretical focal spot diameter was 560 μm and the Rayleigh length 5.7 mm. As a GMAW power source digital equipment Quinto QLS 403 has been used. It has an integrated pull-push drive allowing filler wire feed rates up to 30 m/min. The power source allows a welding current up to 400 A at 60 % duty cycle. In this series of experiments the maximum average current of up to 550 A at a maximum welding time of 10 s has been applied. The integrated air cooled GMAW torch has been mounted on the welding optics with a constant inclination angle of 25° to the beam axis, and has the possibility to move its position in 3 directions, Figure 3. Most important for this set of experiments was the possibility to shift the torch in a direction parallel to the beam axis. The relative movement between the laser beam and workpiece was realised by a numerically controlled X-Y coordinate table. For changing the spatial orientation of the optics and control of the height a 6-axis Cloos robot supporting the welding optics and hybrid equipment has been used.

Table 2 – Parameters used for multipass welding experiments

Parameters for setup and material		Process parameters	
Laser type	IPG YLR 8000 S	Joint type	V-butt with broad root face
Laser power	8 kW	Root face size	6-10 mm
Focal length	280 mm	Joint gap size	0-1.2 mm
Focal spot diameter	0.22 mm	Included angle	45°, 60°
Welding torch position and angle	Leading at 22°	Welding position	PA
		Welding speed	0.4-1.8 m/min
Parent metal and thickness	X 65, t = 16 mm,	Filler wire feed rate	6.0 m/min - 13.5 m/min
Filler wire and diameter	Union K56 S (G46 4M G4Si1), Ø 1.2 mm	Wire stick out	12 mm
		Current	210-420 A
		Voltage	22-35 V
		Laser-arc distance	3 mm
		Focal position	-2 mm*, 0 mm**
		Shielding gas and flow rate	90 % Ar + 10 % CO_2 at 20 l/min
** Relating to the top of the root face for the root pass.* *** Relating to the top of the process for the filler passes.*			

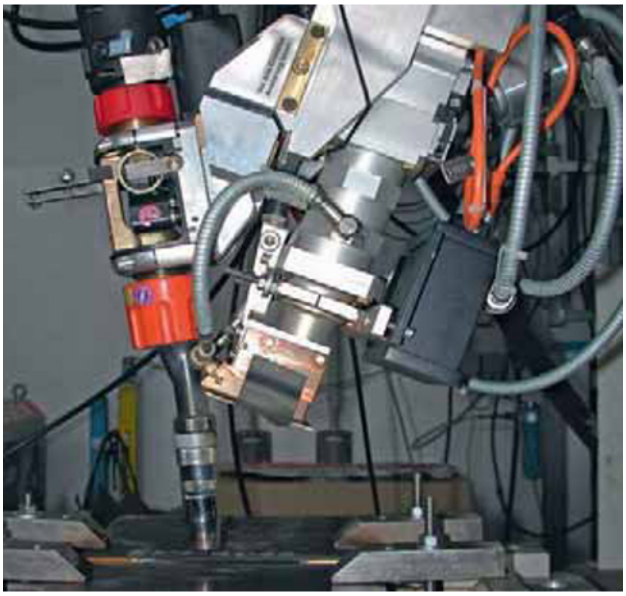


Figure 3 – Hybrid welding head consisting of a 350 mm focal length (right) and a GMAW torch (left) used with 20 kW laser power

3 RESULTS

3.1 Single pass welding

3.1.1 Autogenous laser welding

With 20 kW of laser power it was possible to weld 16 mm and 20 mm in a single pass autogenously. Joining 20 mm thick plates as shown in Figure 4 required 19 kW of laser power at a welding speed of 1.3 m/min with a focal position of -6 mm. A slotted gas nozzle placed above the actual welding process improved the weld seam quality. The top of the weld seam is of acceptable quality, the root side shows a shrinkage groove.

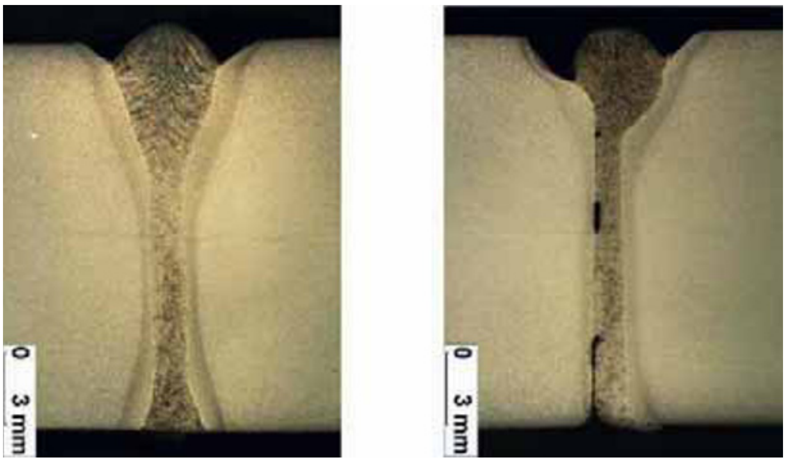
Figure 4 – Single pass welding of 20 mm thick material with an autogenous laser process

3.1.2 Variation of air gap sizes in hybrid welding

With 16 mm thick material, gaps up to a size of 0.35 mm could be successfully bridged, with a laser-GMA-hybrid process, welding a single pass using a square butt joint. However, gaps as large as 0.5 mm were difficult to weld with a single pass at these material thicknesses, Figure 5. The parameters are listed in Table 3.

3.1.3 Variation of edge misalignment in hybrid welding

Hybrid welding 16 mm thick material with vertical misalignment showed results with an acceptable root up to a misalignment of 1 mm. Drops start to form at the root side with a vertical misalignment above 2 mm, see Figure 6 and Table 4 for parameters used. The drop formation could be reduced or fully avoided by using adapted parameters; i. e. increased welding speed or

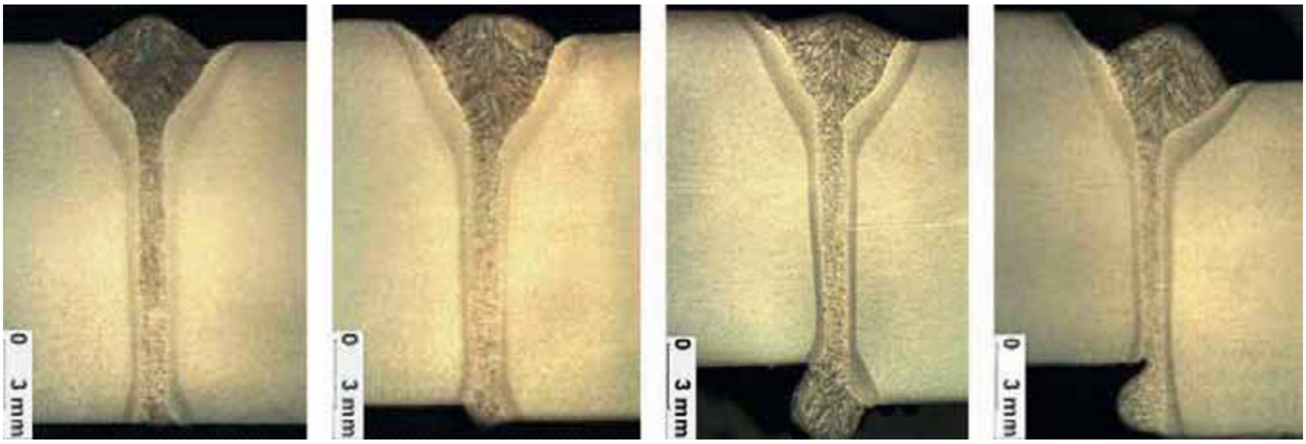


a) 0.35 mm gap **b) 0.5 mm gap**

Figure 5 – Single pass welding of 16 mm material bridging gaps, without joint preparation

Table 3 – Parameters for welded samples with gap in a single pass

Laser power [kW]	Welding speed [m/min]	Wire feed speed [m/min]	Current (mean) [A]	Voltage (mean) [V]	Gap [mm]	Focal position [mm]
17	2.1	15	381	35.8	0.35 / 0.5	-4



a) Linear misalignment of 0 mm **b) Linear misalignment of 1 mm** **c) Linear misalignment of 2 mm** **d) Linear misalignment of 3 mm**

Figure 6 – Single pass welding of 16 mm material with linear misalignment varying from 0 mm to 3 mm

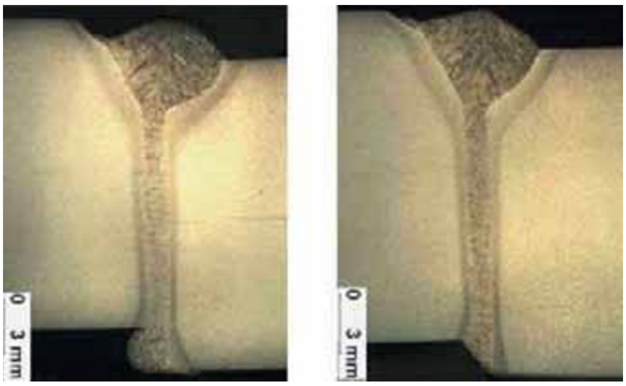
Table 4 – Parameters for welded samples with linear misalignment in a single pass, Figures 6 and 7

Laser power [kW]	Welding speed [m/min]	Wire feed speed [m/min]	Current (mean) [A]	Voltage (mean) [V]	Gap [mm]	Focal position [mm]
Figure 6						
17	2.3	16	436	37	0	-4
Figure 7a)						
17	2.5	16	443	37.2	0	-4
Figure 7b)						
17	2.5	16	439	37.1	0	0

a variation of the focal position. The best result was achieved using another focal position, Figure 7.

3.1.4 Hybrid welding of 20 mm plates

For welding 20 mm thick plates with a hybrid process, either a joint preparation or preheating the material was necessary to join these plates with a single pass. For the joint preparation a 16 mm root face and a 30° included angle was chosen, Figure 8 a). The preheated material had a temperature of 160 °C when welded and was joined with a square butt joint, figure 8 b). The parameters for the welds are given in Table 5.



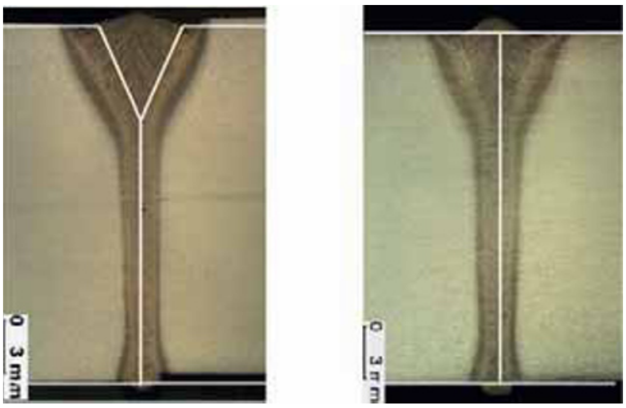
a) Welding speed increased **b) Focus position changed to surface of upper plate**

Figure 7 – Single pass welding with adapted parameters of 16 mm material with linear misalignment of 2 mm

3.2 Multipass welding

3.2.1 Root pass welding

Applying multiple passes with a laser-GMA-hybrid welding process required a different approach to join 16 mm plates or thicker material. With 8 kW laser power available, a joint preparation with root faces between 6 mm and 10 mm and included angles of 45° to 60° was needed for multi pass welding.



a) with joint preparation **b) with preheating**

Figure 8 – Single pass welding of 20 mm material

Table 5 – Parameters for single pass welding of 20 mm material

Root face [mm]	Included angle [deg.]	Laser power [kW]	Welding speed [m/min]	Wire feed speed [m/min]	Current (mean) [A]	Voltage (mean) [V]	Gap [mm]	Focal position [mm]
Figure 8a (with joint preparation)								
16	30	17	1.8	18	509	38.1	0	-4
Figure 8b (preheated to 160°C)								
-	-	19	1.9	16.5	422	33.7	0	-4

Welding the root pass also with variation of gap and linear misalignment, worked well with a hybrid process. A root face of 6 mm with the joint unchanged as well as 8 mm root face with linear misalignment of 0.5 mm and a root face of 8 mm with a gap of 0.8 mm could be welded, see Figures 9 to 11 and Table 6 for parameters. The crack visible in Figure 11, on the top side of the weld bead, is of minor importance in the root pass. It will be re-melted when welding the second pass and then disappears, or can be easily avoided by preheating the material before welding.

3.2.2 Variation of air gap sizes

When welding 16 mm thick material with a root face of 10 mm and an included angle of 60°, with a laser-GMA-hybrid welding process, it was possible to bridge gaps up to 1.2 mm wide with one root pass. Gaps were successively increased by 0.2 mm starting from 0 mm to 1.2 mm. A second layer, also welded with a hybrid process, was needed to fill the remaining groove. The welding speed for the second layer was gradually reduced to be able to fill the remaining groove properly. For sufficient gap bridging, the wire feed rate for the root pass was increased with the gap becoming wider. Pores occurred in all welded samples, undercuts in those with insufficient filler material fed during welding. Figures 12 to 14 show cross sections with gap sizes 0 mm, 0.6 mm and 1.2 mm. Table 7 shows the parameters used for welding.

3.2.3 Variation of edge misalignment

In addition to variation of the gap in a weld seam, edge misalignment was introduced. The 16 mm material was welded with a V-butt joint, root face of 8 mm, gap 0.5 mm and an included angle of 60°. A sound root with both edges melted properly was achieved with a value for edge misalignment of 0.5 mm. Values

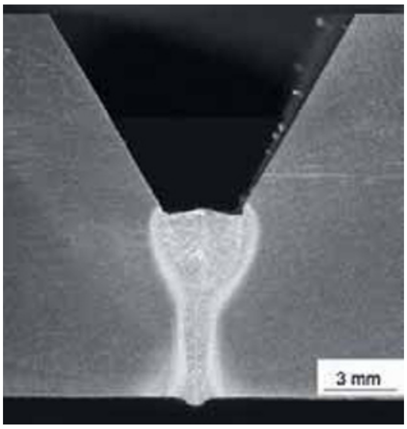


Figure 9 – Cross-section of a root pass of a hybrid welded sample with 0 mm gap

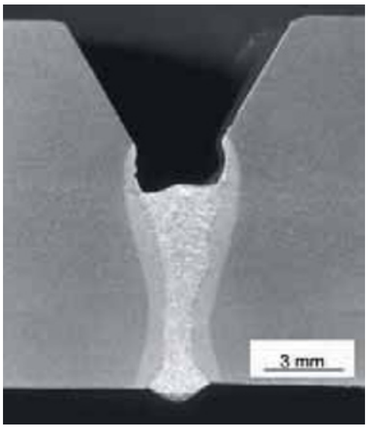


Figure 10 – Cross-section of a root pass of a hybrid welded sample with 0.8 mm gap

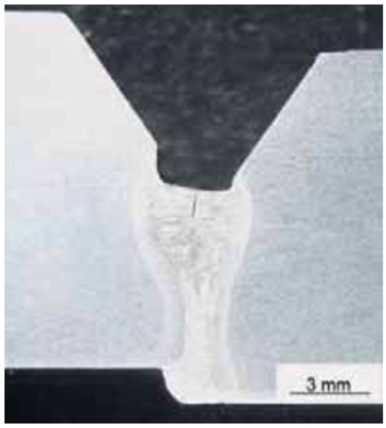


Figure 11 – Cross-section of a root pass of a hybrid welded sample with 0.5 mm gap and linear misalignment of 0.5 mm

Table 6 – Parameters for samples with root pass welded

Layer no.	Root face [mm]	Included angle [deg.]	Laser power [kW]	Welding speed [m/min]	Wire feed speed [m/min]	Current (mean) [A]	Voltage (mean) [V]	Gap [mm]	Focal position [mm]
Figure 9 (0 mm gap)									
1	6	60	7.6	1.8	6.5	229	23.6	0	-2
Figure 10 (0.8 mm gap)									
1	8	60	7.6	1.6	8.5	298	27.3	0.8	-2
Figure 11 (0.5 mm gap, 0.5 mm linear misalignment)									
1	8	60	7.6	1.8	7.5	330	23.7	0.5	-2

Figure 12 – Cross-section of a hybrid welded sample with 0 mm gap

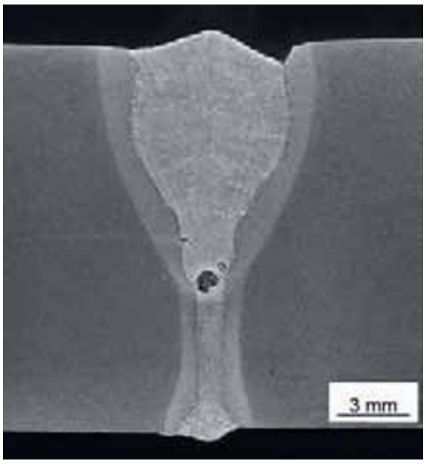


Figure 13 – Cross-section of a hybrid welded sample with 0.6 mm gap

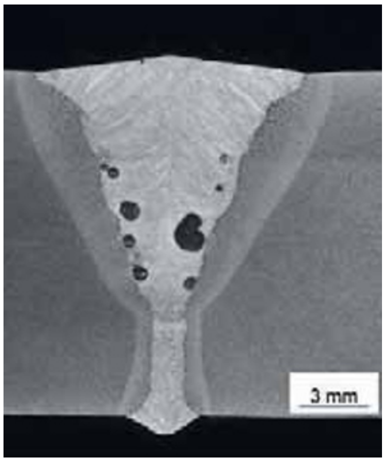


Figure 14 – Cross-section of a hybrid welded sample with 1.2 mm gap

Table 7 – Parameters for welded samples with gap

Layer no.	Root face [mm]	Included angle [deg.]	Laser power [kW]	Welding speed [m/min]	Wire feed speed [m/min]	Current (mean) [A]	Voltage (mean) [V]	Gap [mm]	Focal position [mm]
Figure 12 (0 mm gap)									
1	10	60	7.6	1.4	7.0	210	24.3	0	-2
2	10	60	2.0	1.4	13.5	347	33.6	-	0
Figure 13 (0.6 mm gap)									
1	10	60	7.6	1.4	8.5	232	26.5	0.6	-2
2	10	60	2.0	1.1	13.0	375	35.8	-	0
Figure 14 (1.2 mm gap)									
1	10	60	7.6	1.4	10	277	30.1	1.2	-2
2	10	60	2.0	0.5	12.5	327	32.6	-	0

beyond 0.5 mm produced a root with improper fusion of the melt between the misaligned faces with droplets which started to form on the root side. Pores and cracks occurred only in the filler passes, which were also welded with a hybrid process. Figures 15 to 17 and Table 8 give an overview of welded samples and the parameters used.

3.2.4 Multi pass welding with GMA filler passes

Since acceptable filler passes with a hybrid welding process could not be achieved under the given conditions, it was decided to weld the filler passes with conventional arc welding and use the hybrid process for the root pass only, in order to obtain acceptable

Figure 15 – Cross-section of a hybrid welded sample with 0.5 mm gap and 0.5 mm linear misalignment

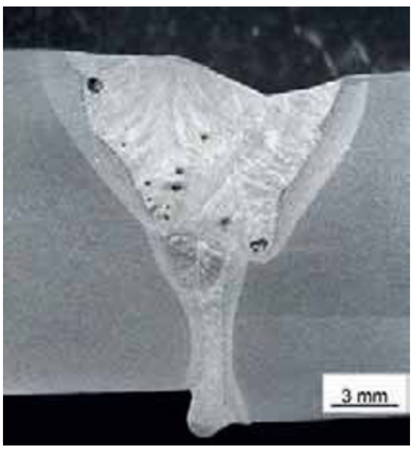


Figure 16 – Cross-section of a hybrid welded sample with 0.5 mm gap and 1.5 mm linear misalignment

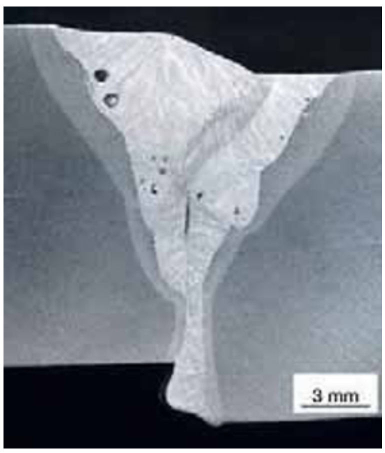


Figure 17 – Cross-section of a hybrid welded sample with 0.5 mm gap and 3 mm linear misalignment

Table 8 – Parameters for welded samples with linear misalignment

Layer no.	Root face [mm]	Included angle [deg.]	Laser power [kW]	Welding speed [m/min]	Wire feed speed [m/min]	Current (mean) [A]	Voltage (mean) [V]	Gap [mm]	Focal position [mm]
Figure 15 (0.5 mm linear misalignment)									
1	8	60	7.6	1.8	8.0	234	26.7	0.5	-2
2	8	60	0	0.4	10.5	-	-	-	0
Figure 16 (1.5 mm linear misalignment)									
1	8	60	7.6	1.8	8.0	339	23.8	0.5	-2
2	8	60	4.0	1.6	11.0	413	31.9	-	0
3	8	60	4.0	0.8	10.0	329	29.3	-	0
4	8	60	4.0	0.8	10.5	334	29.2	-	0
Figure 17 (3.0 mm linear misalignment)									
1	8	60	7.6	1.8	6	231	22.6	0.5	-2
2	8	60	2.0	1.6	12.5	422	30.5	-	0
3	8	60	2.0	0.8	10.0	310	29.7	-	0
4	8	60	2.0	0.8	10.0	318	29.5	-	0

welds. An optimised parameter set was applied for welding 16 mm thick material. Figure 18 shows a cross-section of a sample welded with two passes, the first one with a laser-GMA-hybrid welding process and the second one with a conventional GMAW welding process. The root face was chosen to be 10 mm with an included angle of 45°, to have a groove remaining as small as possible which has to be filled with conventional welding. A gap of 0.5 mm was necessary for full penetration of the material. Parameters for the welded sample shown are given in Table 9.

4 DISCUSSION

Concerning the welding of multiple passes for joining 16 mm thick materials, laser-GMA-hybrid welding for the root passes showed satisfactory up to good results, especially for bridging large gaps. Using a gap also helped to increase the penetration depth of the laser beam as shown in Figures 12 and 13 where it was not possible to fully penetrate a prepared seam with 10 mm root face and 60° included angle when the two plates were joined without a gap. The restrictive feature for the lower penetration depth – compared to autogenous laser welding in this case – is the leading arc process in combination with the chosen seam preparation and the hybrid process. The arc burns above the root face in the groove, the laser beam has to penetrate the melt pool of the arc process and the base material joined with a zero gap. An increase of the gap to 0.2 mm already helped to successfully penetrate the material; a gap size around 0.5 mm as shown above produced the best results in the experiments carried out. Concerning the filler passes, a successive reduction of the welding speed starting from 1.4 m/min down to 0.5 m/min did not help to reduce the formation of pores in the weld seam. The only beneficial effect of reducing the welding speed was a better filling of the remaining groove where undercuts could be avoided.

In contrast to the experiments with no edge misalignment, where a gap of 0.5 mm to 0.6 mm supported the melting of the fusion faces, welding with edge misalignment proved to be difficult. An increase of the wire feed rate added up to the formation of drops on the root side, but did not help in wetting and/or melting both faces of the workpiece. Regarding the multiple passes welded, as shown especially in Figures 16 and

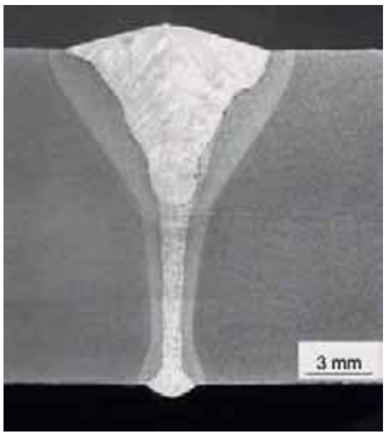


Figure 18 – Cross-section of a hybrid welded sample with optimised parameters for 0.5 mm gap

Table 9 – Parameters for the welded sample shown in Figure 18

Layer no.	Root face [mm]	Included angle [deg.]	Laser power [kW]	Welding speed [m/min]	Wire feed speed [m/min]	Current (mean) [A]	Voltage (mean) [V]	Gap [mm]	Focal position [mm]
1	10	45	7.6	1.6	9	372	25.9	0.5	-2
2	10	45	-	0.4	8.5	290	28.3	-	0

17, where 4 passes were used altogether, altering the parameters did not change the result in terms of pores or cracks. A reduction of the laser power for the filler passes of 50 %, compare parameters for samples depicted in Figures 16 and 17, for example, did not have any effect on the welded seam. Also altering the welding speed from 1.6 m/min to 0.8 m/min within the same weld seam did not benefit the quality.

A successful method to utilise the benefits of a laser-GMA-hybrid welding process as well as the conventional GMAW welding process was to weld the root pass first with the hybrid process and secondly use a GMAW process for filling up the remaining groove. Two passes were needed which produced an acceptable root quality and a pore and crack free weld seam. Despite that successful weld, the big disadvantage of that strategy is the slow welding speed of only 0.4 m/min – the advantages of the laser hybrid process vanishes to a certain extent. Kristensen [11], who also observed pores in the root of the second pass of a multi pass hybrid weld, suggests the low welding speed as the origin of the pores. Due to the much higher speeds used in this investigation (up to 1.4 m/min) compared to that work (0.5 m/min) it is questionable, whether this explanation will hold. Further work has to be done in this field.

5 CONCLUSION

Despite the fact that these are preliminary results of ongoing work, it has shown successful welding within the following limits:

– Autogenous laser welding was used to join plates up to 20 mm thickness with 19 kW at 1.3 m/min without a seam preparation.

– Laser-GMA-hybrid welding of 16 mm thick material was possible with a square butt joint and a single pass at 17 kW and 2.1 m/min.

– 20 mm material welded with a hybrid process required 19 kW and a joint preparation. As an alternative, square butt joint welding was possible when using preheating to 160 °C, which also increased the stability of the process.

– Edge misalignment up to 2 mm and gaps up to 0.35 mm could be bridged when joining 16 mm material with single pass hybrid welding.

– Concerning multi pass welding, gaps up to 1.2 mm and edge misalignment up to 0.5 mm could be bridged with hybrid welding the root pass.

The defects observed in these experiments have been droplet formation at the root, pores in the filler layer and cracks at the top of root passes. It was shown that:

– The permissible edge misalignment is essentially limited by the droplet formation.

– Pores in the filler passes could not be avoided with the parameters used in this investigation when applying hybrid welding for the filler passes. Using the hybrid process for welding the root pass and then applying a GMAW process, yielded a sound weld.

– Some cracks can be observed at the top of root welds, but these disappear during remelting by the first filler pass.

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