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Gap bridging ability in laser GMA hybrid welding of thin 22MnB5 sheets

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Abstract

In this paper, laser GMA hybrid welding of thin ultra-high-strength steel sheets (22MnB5) is investigated. A single-mode laser beam oscillating transversal to the welding direction is used in order to minimize the heat input during the process. The sheets have a thickness of 1.5 mm each and are fixed in overlap configuration. The gap between the sheets was 0.8 mm during experiments in order to simulate typical gap width in industrial manufacturing processes. It is shown that a stable weld seam has been achieved for this gap width in case of a welding speed of 6 m/min. The gap bridging ability is caused by the interaction of the arc and the laser beam process. The laser beam process produces deeper penetration in the bottom sheet. Thus, the arc is stabilized by the laser beam.

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Keywords: Hybrid welding; GMA; ultra high-strength steel; 22MnB5, bridgeability

1. Introduction

Nowadays, lightweight constructions in automotive are required in order to achieve environmental protection goals. Especially high strength steel gains importance in the sector of lightweight design. With new ultra high strength presshardened steel sheet out of 22MnB5 wall thicknesses of structural elements, like the B-pillar, can be reduced. Additionally, according to Göschel et al. (2011), process efficiency is increased by cycle time reduction.

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The need of investigating weldability is clearly demanded by automotive industry as Larsson et al. (2009) state. Investigations on laser beam welding of presshardened steel have been carried out by Kim et al. (2011). Analyses of weld seams show a negative influence of the AlSi coating which is applied on the 22MnB5 for oxidation prevention during presshardening. Aluminum and silicon forming intermetallic phases along the fusion line which is significantly weakening joint strength in investigations of Kim et al. (2011).

Process combination of GMAW and laser beam welding is well known in industrial applications. Advantages of process combination are investigated by Cui (1991). Higher welding speed and higher penetration depth compared to a GMAW can be achieved. Regarding a laser beam welding process Bagger and Olsen (2005) point out higher gap bridgeability is achieved by process combination. Hybrid welding on aluminum by Cassalino et al. (2013) shows that laser leading configuration achieves deeper penetration and higher process velocity than with arc leading configuration. Amongst others, these advantages are used for welding aluminum by Verwimp and Gedopt (2007), welding steel by Grünenwald et al. (2010), or even welding of multimaterial joints of steel and aluminum by Walter et al. (2008).

The positive effect of combining laser and arc welding according to Cui (1991) is due to the laser induced plasma. Laser radiation accordingly has stabilizing influence on the arc welding process. This effect was proofed by Stute et al. (2007) even with very low laser energy input of a few hundred watts. On the other hand, hybrid welding process by Rippl (2008) using multi-kilowatt lasers power allows T-joint welding of 15 mm thick steel sheets without weld preparation.

2. Experimental

2.1. Material

In these shown experiments ultra-high strength 22MnB5 steel sheets with thickness of 1.5 mm were welded. For the GMA welding G3Si1 (1.5125) filler wire was used with a diameter of 1 mm.

Table 1. Chemical composition of used materials. General information of EWM (2014) and ThyssenKrupp Steel (2014).

Material	C	Si	Mn	P	S	Al	Nb	Ti	Cr+Mo	B
	max.	max.	max.	max.	max.	min.	max.	max.	max.	max.
22MnB5	0.25	0.40	1.40	0.025	0.010	0.015	0.10	0.05	0.50	0.005
G3Si1	0.08	0.9	1.5	0.015	0.012	-	-	-		-
										values in weight percent

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2.2. Set-up

Investigations were carried out using a hybrid process with a GMAW source and a laser in order to weld 22MnB5 sheets in fillet weld configuration with gap. All influences were analyzed with a gap of 0.8 mm. According to SEP 1220 (2011) overlap of the sheets was 16 mm.

An IPG YLR 1000 SM single mode laser with a fiber diameter of 15 µm was used. In this set-up collimation length of 160 mm and a focal length of 200 mm were chosen resulting in a focused spot size of 24.5 µm. Measurement of the focus diameter was carried out with MicroSpotMonitor by Primes. Throughout the experimental phase the laser beam was focused on the bottom sheet surface. Laser beam oscillation was realized with a DC-ILV-Scanner by Co. Arlt. This system enables a laser beam oscillation transverse to the welding direction.

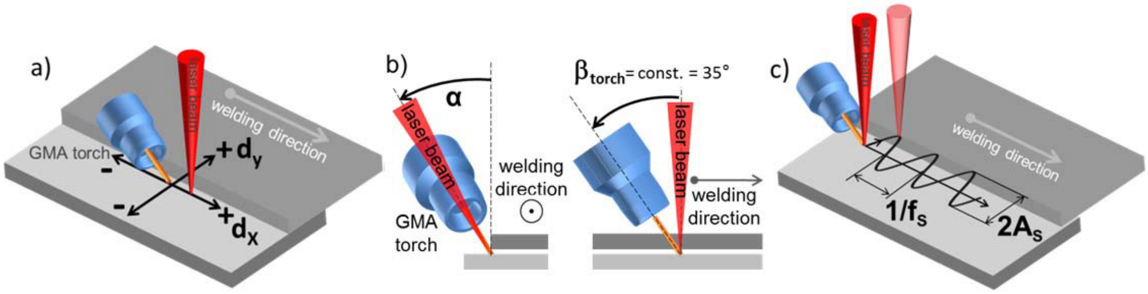

Fig. 1. Schematic illustration of process parameters. a) distance between GMAW process and laser beam (d_x) and displacement of hybrid process to upper sheet edge (d_y), b) fillet weld angle (α) and c) laser beam oscillation parameters frequency (f_s) and amplitude (A_s).

As GMAW source, an EWM alphaQ 552 with additional Phoenix drive wire feeder and a EWM GMAW torch was used. This power supply enables a pulsed arc welding which is used during these experiments.

Figure 1 illustrates orientation of the laser and GMAW process. The parameter d_x describes distance of the GMAW process to the laser beam process. Displacement of welding processes to the upper sheet edge is given with the parameter d_y. This displacement was always identical for each process. The laser beam was orientated orthogonal to the fillet throughout this experimental phase. Fillet weld angle α was varied for both processes, laser and GMAW, always simultaneously. Additionally to process positioning parameters for adjusting laser beam oscillation were defined. Laser beam movement is described by frequency f_s and amplitude A_s.

For these experiments a shielding gas composed of 82 % argon and 18 % CO_2 was used with a flow rate of 15 l/min.

2.3. Method

Weld seams were evaluated by metallurgical analyses. In cross sections measurements geometric properties were determined. Measuring critical length S_{RL}, seam angle Θ and penetration depth S_{ET} is illustrated in Figure 2. For each value a mean value out of four cross sections is determined.

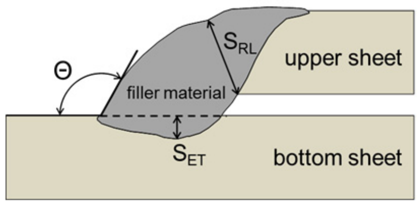

Fig. 2. Geometrical measured quantities in cross sections.

2.4. Program

In these presented investigations effects of parameters, like process positioning, wire feeding rate and laser beam oscillation configuration, were analyzed and evaluated with certain geometric values. To achieve comparability standard parameter as listed in Table 2 were not changed during experimental phase. Variation range of each parameter is shown in Table 3.

Table 2. Standard process parameters.

parameter		unit	value
Laser power	P_L	kW	1
Focus height	f_z	mm	0
Arc current	I	A	~ 256
Arc voltage	U	V	~ 30
Voltage correction	ΔU	V	+ 2
Arc trim		%	+ 10
Arc polarity			DCEP
Wire feeding rate	v_D	m/min	11
Electrode stickout		mm	13.7
Process velocity	v_S	m/min	6
Gap	d_S	mm	0.8

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Table 3. Process parameter variation range.

parameter		unit	minimum	maximum
Laser-GMAW-distance	d_x	mm	- 1	+ 0.5
Hybrid process movement	d_y	mm	- 0.5	+ 1
Fillet weld angle	α	°	0	30
Laser beam oscillation frequency	f_S	Hz	0	350
Laser beam oscillation amplitude	$2A_S$	mm	0	2.4

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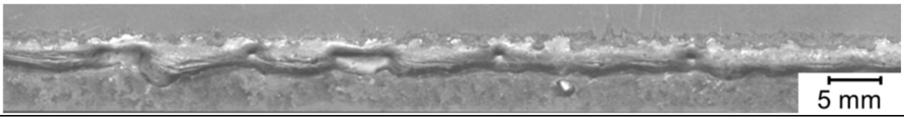
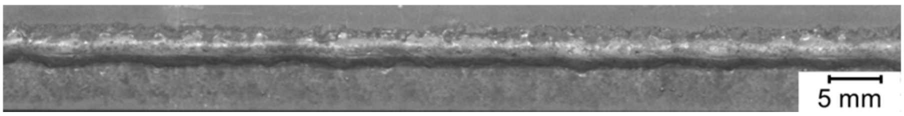
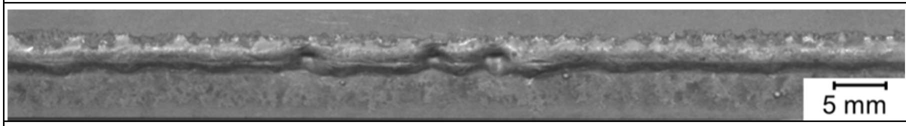
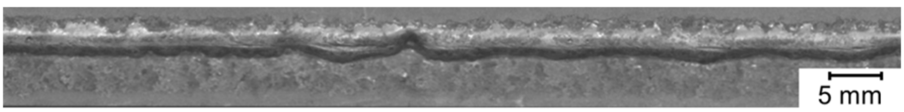
3. Results

3.1. Influence of process movement

3.1.1. Relative movement of laser-GMAW-distance (d_x)

In Table 4 weld seam appearances can be observed. Variation of laser-GMAW-distance has clearly influence in weld seam continuity. Partially weld seam defects can be observed when positioning the laser beam on the same spot as the GMAW (d_x = 0 mm) or having the laser beam leading (d_x > 0 mm). However, trailing the laser 0.5 mm behind the GMAW results in a more constant seam appearance. This configuration means also that the laser beam crosses the wire axis respectively the arc. A trailing laser beam with a distance of 1 mm to the GMAW process results in even more discontinuities than a leading laser beam.

Table 4. Weld seam pictures of laser-GMAW-distance (d_x) variation with parameter set.

<table>
<tr><th>Weld seam pictures</th><th>d_x values</th><th></th></tr>
<tr><td></td><td>- 1 mm</td><td rowspan="4">P_L = 1 kW
f_z = 0 mm
U ~ 30 V
I ~ 256 A
d_s = 0.8 mm
v_s = 6 m/min
v_D = 11 m/min
d_x = variable
d_y = + 0.5 mm
α = 30°
f_S = 200 Hz
$2A_S$ = 0.7 mm</td></tr>
<tr><td></td><td>- 0.5 mm</td></tr>
<tr><td></td><td>0 mm</td></tr>
<tr><td></td><td>+ 0.5 mm</td></tr>
</table>

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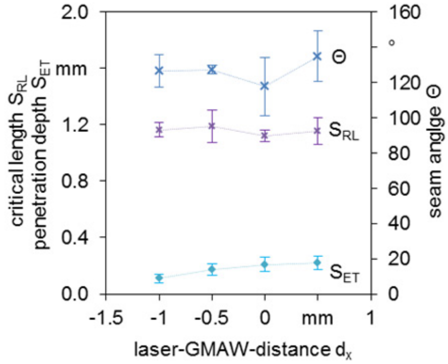

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Fig. 3. Effect of variation in laser positioning relative to GMAW.

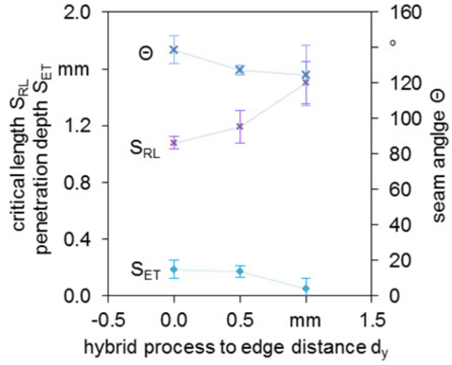

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Fig. 4. Effect of hybrid process offset relative to upper sheet edge.

Figure 3 shows, with respect to the standard deviations, constant critical lengths for these different laser-GMAW-distances. Likewise, seam angles are not affected significantly. Standard deviations are, in case of dx = 0 mm and dx = 0.5 mm, over 10 % of the mean value. However, penetration depth is clearly affected by laser-GMAW-distance. Trailing the laser (dx < 0 mm) reduces penetration depth, whereas a leading laser (dx > 0 mm) and a laser beam positioning on the same spot as the GMAW (dx = 0 mm) result in similar penetration depth.

3.1.2. Relative movement of the hybrid process to upper sheet edge (d_y)

Weld seam appearances of different positioning of the hybrid process to upper sheet edge is shown in Table 5. Guiding the process slightly onto the upper sheet (d_y = 0.5 mm) results in a constant weld seam shape without discontinuities. Few discontinuities can be observed for d_y = 1 mm. Whereas a positioning of the hybrid process directly in the fillet (d_y = 0 mm) or with a distance to the upper sheet (d_y = - 0.5 mm) increases appearance of discontinuities. For d_y = - 0.5 mm too less constant welded seam sections are available for analyzes. Therefore, Figure 4 shows only three values each geometric property.

Table 5. Weld seam pictures of hybrid process to edge distance (d_y) variation with parameter set.

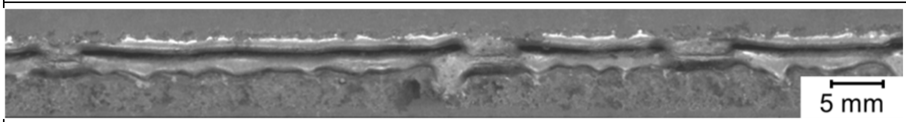
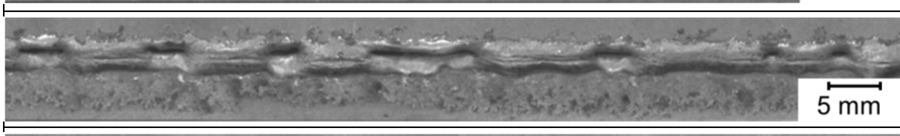
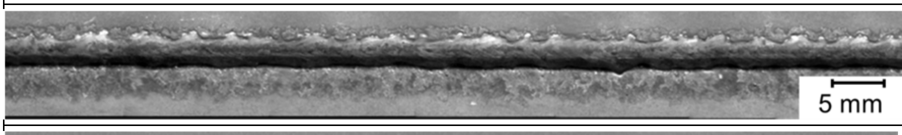
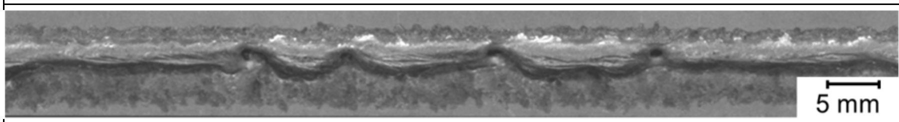
Weld seam pictures	dy values	
	- 0.5 mm	P_L = 1 kW f_z = 0 mm U ~ 30 V
	0 mm	I ~ 256 A d_s = 0.8 mm v_s = 6 m/min
	+ 0.5 mm	v_D = 11 m/min d_x = - 0.5 mm d_y = variable
	+ 1 mm	α = 30° f_S = 200 Hz $2A_S$ = 0.7 mm

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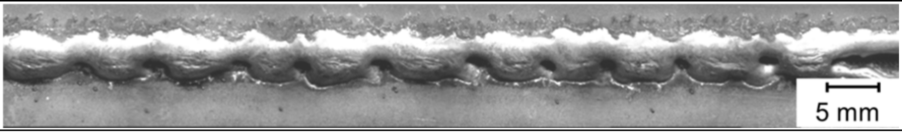
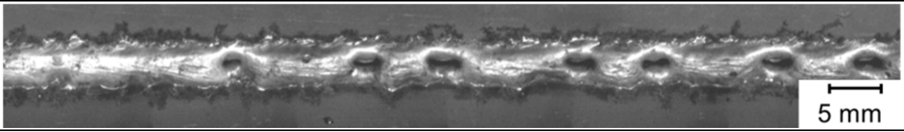
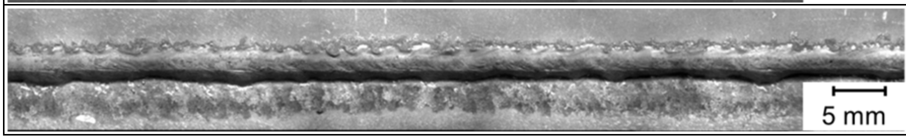
Table 6. Weld seam pictures of fillet weld angle (α) variation with parameter set.

Weld seam pictures	α values	
	0°	P_L = 1 kW f_z = 0 mm U ~ 30 V I ~ 256 A d_s = 0.8 mm v_s = 6 m/min v_D = 11 m/min d_x = - 0.5 mm d_y = + 0.5 mm α = variable f_S = 200 Hz $2A_S$ = 0.7 mm
	15°	
	30°	

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Moving the welding position of the hybrid process on the upper sheet reduces penetration depth significantly. With a welding position moved 1 mm onto the upper sheet penetration depth is reduced to 0.05 mm. Simultaneously critical length is increased from 1.1 mm to 1.5 mm by moving onto the upper sheet. Furthermore, steeper weld seams appear for higher d_y values which is shown by a decrease of seam angles.

3.2. Influence of fillet weld angle configuration

Variation of fillet weld angle has a significant influence on weld seam appearance, as shown in Table 6. Welds with fillet weld angle configuration of α = 0° show periodic discontinuities. With a fillet weld angle of α = 15° discontinuities are present but comparatively fewer and aperiodic. Constant weld seams without discontinuities are observed with fillet angle configuration of α = 30°.

Metallurgical analyzes of fillet weld angle configuration α = 0° cannot be made because there is no region of constant conditions where a measurement of geometric values for evaluating weld seam quality is representative. However, geometric properties of fillet weld angle configurations of α = 15° and α = 30° are shown in Figure 5. For increased fillet weld angles penetration depth is decreased from 0.26 mm to 0.18 mm. Differences in critical length S_{RL} and seam angle Θ are within standard deviations and therefore not significant.

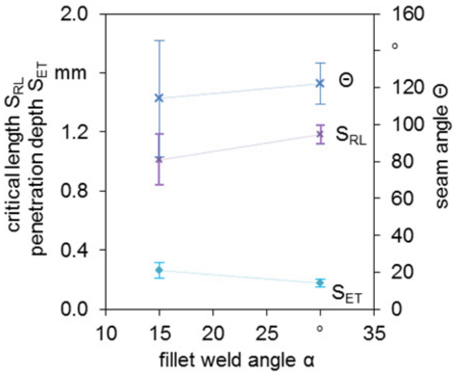

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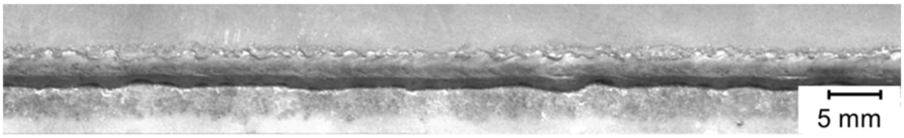
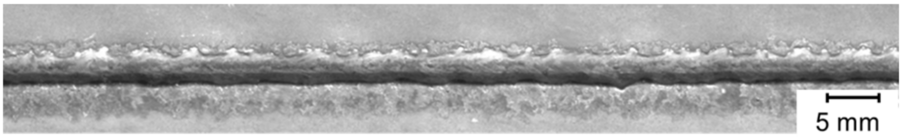
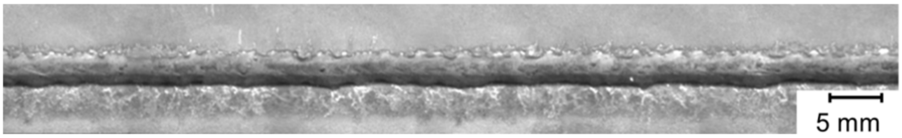
Fig. 5. Effect of fillet weld angle variation.

Table 7. Weld seam pictures of laser beam oscillation frequency (f_s) variation with parameter set.

Weld seam pictures	f_S values	
 5 mm	0 Hz	P_L = 1 kW f_z = 0 mm U ~ 30 V I ~ 256 A d_s = 0.8 mm v_s = 6 m/min v_D = 11 m/min d_x = - 0.5 mm d_y = + 0.5 mm α = 30° f_S = variable $2A_S$ = 0.7 mm
 5 mm	200 Hz	
 5 mm	350 Hz	

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3.3. Influence of laser beam oscillation configuration

In Table 7 weld seam appearances for laser beam oscillation frequency variations are shown. At first sight there is no difference between different frequencies or without a beam oscillation at all. Moreover, geometrical properties shown in Figure 6 do not show any significant influence of laser beam oscillation frequency. Critical length, welding penetration and seam angle stay constant within standard deviations.

In contrast laser beam oscillation amplitude variation does affect weld seam appearance. This is shown in Table 8. For laser beam oscillation amplitudes of $2A_S$ = 1.4 mm and $2A_S$ = 2.4 mm discontinuities are observed. With increased amplitude the quantity of discontinuities is increased. Without beam oscillation ($2A_S$ = 0 mm) as well as with an amplitude of $2A_S$ = 0.7 mm a constant weld shape results. With a beam oscillation of $2A_S$ = 0.7 mm weld seam has a more steady width.

In Figure 7 geometric properties of laser beam oscillation amplitude variation is illustrated. Weld seam angles show higher standard deviations than measured value divergence. However, laser beam oscillation amplitude increases penetration depth.

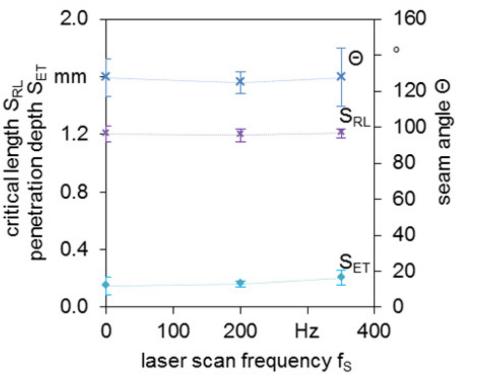

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Fig. 6. Effect of laser beam oscillation frequency.

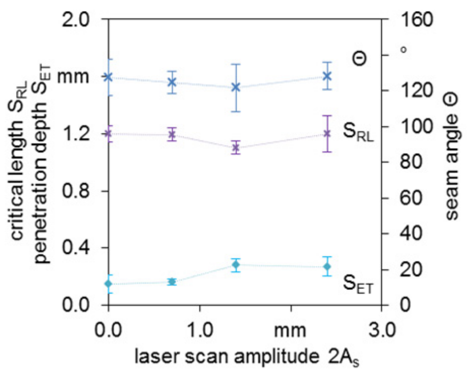

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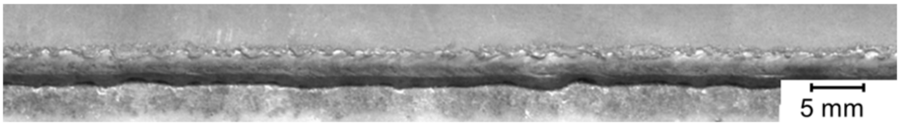
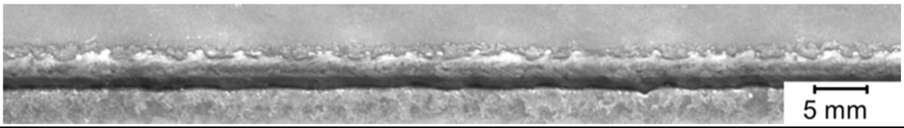
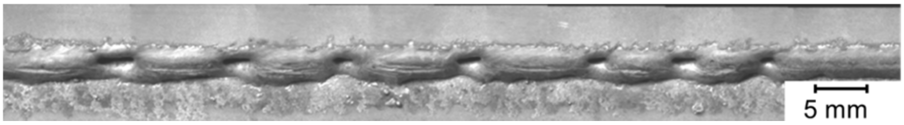
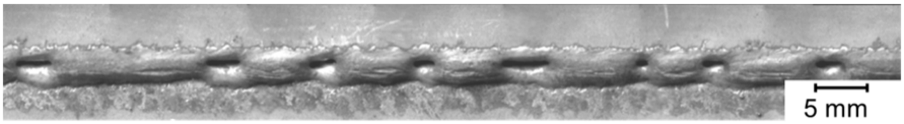
Fig. 7. Effect of laser beam oscillation amplitude.

Table 8. Weld seam pictures of laser beam oscillation amplitude ($2A_s$) variation with parameter set.

Weld seam pictures	2AS values	
	0 mm	P_L = 1 kW f_z = 0 mm U ~ 30 V I ~ 256 A d_s = 0.8 mm v_s = 6 m/min v_D = 11 m/min d_x = - 0.5 mm d_y = + 0.5 mm α = 30° f_S = 200 Hz $2A_S$ = variable
	0.7 mm	
	1.4 mm	
	2.4 mm	

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4. Discussion

High process velocities, like v_S = 6 m/min, require increased wire feeding rates. In this case wire feeding rate is v_D = 11 m/min. High speed videos proof that there is a melt flow ahead which leads to a lack of material rear of the GMAW process (cf. Figure 8). Melts on the upper and bottom sheet do not have contact anymore which is needed to bridge the gap. Hence, gap between the sheets, d_S = 0.8 mm in this case, and this lack of material lead to discontinuities. With support of the laser beam this melt flow can be controlled. Laser beam process in a leading configuration heats up this melt flow wave, whereas a trailing laser beam process flattens melt flow wave ahead because of generating a hot spot trailing the GMAW process. For laser-GMAW-distance of d_x = - 1 mm the laser beam is partially hitting weld droplets and thereby disturbs the GMAW process. Having the laser trailing and getting laser power absorbed in the arc is reasonable for less penetration depth compared to a leading laser beam process. Therefore a distance of d_x = - 0.5 mm is an optimum compromise to prevent melt flow ahead and thereby caused lack of material rear of the process.

Even more sensitive for the process is a distance variation relative to the upper sheet edge. Increasing the distance of the hybrid process to the upper sheet edge (d_y = - 0.5 mm) barely achieves a weld seam (cf. Table 5). This can be attributed to a lack of material for bridging the gap of d_S = 0.8 mm. Sound welds are achieved when compensate this lack of material by melting off upper sheet edge. With a hybrid process positioning slightly on the upper sheet (d_y = 0.5 mm) best weld seam appearance is achieved. Using this extra material enhances critical length but simultaneously decreases penetration depth because of less energy input directly in the bottom sheet.

Heat input in the bottom sheet and melting off the upper sheet edge are additionally affected by fillet weld angle variation. A perpendicular set-up of the hybrid process results in higher penetration depth but less weld material and therefore a smaller critical length. In contrast a fillet weld angle of α = 30° melts off more of the upper sheet edge and has less energy input into the bottom sheet. Welds with fillet weld angle configuration of α = 0° are too inconstant for analysis so that this effect can be seen in a variation of α = 15° to α = 30° in a weakened magnitude (cf. Figure 5). However, fillet weld angle of α = 30° provides weld seams without discontinuities whereas other fillet weld angle configurations cannot achieve sound welds.

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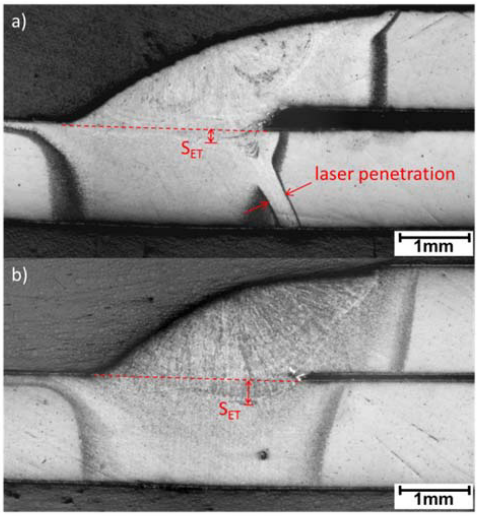
Fig. 8. Picture of melt flow ahead out of a high speed video observing the hybrid welding process.



BIAS ID 140992

Fig. 9. Cross sections of weld seams a) without laser beam oscillation and b) with laser oscillation of f_S = 200 Hz and A_S = 1.4 mm.

Laser beam oscillation distributes locally limited energy input of the single mode fiber laser. This achieves more continuous and deeper penetration depth of the hybrid process (cf. Figure 7). In Figure 9 it is shown that a not oscillating laser beam welds through the bottom sheet. This was not measured as penetration depth for the weld because it is not significantly for evaluating seam strength. Provided laser energy in case of no beam oscillation is not used efficiently. Nevertheless, weld seams with high amplitudes $2A_S$ >0.7 mm show discontinuities. It is considered that an increased weld seam width cannot be filled by provided molten filler material volume. Material accumulates at the hottest spots which are laser beam oscillation turning points. Molten material is too less to bridge the gap when oscillation amplitudes exceed 0.7 mm. Hence, surface tension pulls the melting apart and accumulation of molten material remains at the upper sheet edge and the bottom sheet surface (cf. weld seam pictures in Table 8). Previous investigations by Möller et al. (2013) to zero gap condition welding have also shown dependence of laser beam oscillation to penetration depth. In the presented investigations with a gap of d_S = 0.8 mm enhanced penetration depth through laser beam oscillation can be confirmed. However, influence of laser beam oscillation frequency is negligible (cf. Figure 6 and weld seam pictures in Table 7).

In this investigation it is shown that gaps of d_S = 0.8 mm are feasible. This is a clear improvement of regular laser beam welding like e.g. Kim et al. (2011) carried out. The impact of laser beam radiation to the stability of GMAW as it was described by Stute et al. (2007) can be confirmed. Investigations without laser beam oscillation point out 1 kW as sufficiently laser power provided to the process because of full penetration to the steel sheet. By using laser beam oscillation penetration depth is enhanced. However, this is in conformity with results from Cui (1991) even though a single-mode laser with much smaller spot size was used. Cui (1991) was using a CO_2 multi-mode laser. Hence, it is expected that the generation of metal vapor is the key mechanism for stabilizing the arc. Amount of vapor, spot size, or power distribution of laser radiation obviously have minor influence.

5. Conclusion

Welding 22MnB5 in overlap configuration with a gap of 0.8 mm is feasible. Presented investigations point out that positioning of the hybrid process and both individual processes to each other is much more important than laser beam oscillation adjustments. The laser beam, even without oscillation, stabilizes GMA welding of 22MnB5 with gap at high process velocity of $v_S = 6$ m/min. Laser beam oscillation increased weld penetration depth and therefore enhances process reliability.

Acknowledgements

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