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Single-pass Hybrid Laser Arc Welding of Thick Materials Using Electromagnetic Weld Pool Support

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Abstract

Hybrid laser-arc welding process allows single-pass welding of thick materials, provides good quality formation of joints with minimal thermal deformations and a high productivity in comparison with arc-based welding processes. Nevertheless, thick-walled steels with a thickness of 20 mm or more are still multi-pass welded using arc welding processes, due to increased process instability by increasing laser power. One limitation factor is the inadmissible formation of gravity drop-outs at the root. To prevent this, an innovative concept of electromagnetic weld pool support is used in this study. With help of such system a stable welding process can be established for 25 mm thick steel plates and beyond. Sound welds could be obtained which are tolerant to gaps and misalignment of the welded parts. The adaptation of this system to laser and hybrid laser-arc welding process can dramatically increase the potential field of application of these technologies for real industrial implementation.

Keywords: Hybrid laser-arc welding; thick-walled structures; electromagnetic weld pool support; single-pass welding;

1. Introduction

The hybrid laser arc welding process developed in the 1970s is a coupling of arc welding and laser beam welding process in a common interaction zone [1]. The limits encountered in pure laser beam welding or arc welding are to be overcome by coupling the synergy effects of both welding processes. Due to its high-power density, the laser beam generates a narrow keyhole that allows deep penetration into the workpiece with low distortion and heat input. The arc welding process ensures better gap bridgeability and is tolerant

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to manufacturing inaccuracies because of the feed of additional material in the form of molten filler wire [2]. The hybrid laser arc welding process is used in industrial applications such as in the shipbuilding industry.

For deep penetration welds, a short distance between the wire tip extension and the laser beam, an arc leading orientation of the process and a small torch angle are preferred [3-4]. Fig. 1 shows a scheme of hybrid laser arc welding process, where *β* is the torch angle relating to the laser beam, *a* is the distance between the extended wire tip and the laser beam and z_f is the focal position of the laser beam.

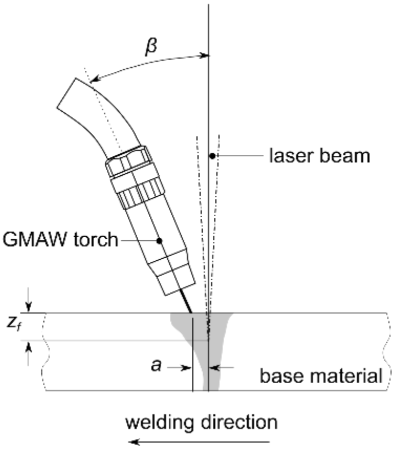


Fig. 1. Scheme of hybrid laser arc welding

Based on the latest developments, laser systems with an output of approx. 30 kW are already available on the market. Nevertheless, due to certain technological limitations their application for welding of thick sections is still far from real industrial scale and remains restricted to few cases mostly where the thickness of the parts does not exceed 15 mm – 20 mm. Materials with a thickness of more than 20 mm are still welded in multi-pass technology using arc welding processes [5]. One reason for the limiting factors in hybrid laser arc welding of materials with a thickness of more than 20 mm is the increasing process instability with increasing laser power. Another principal factor for process limitation is that the process can be realized only at a sufficiently high welding speed, especially at welding in flat (1G) position. The effect of gravity is the main reason for choosing a high welding speed. Otherwise it leads to gravitational drop-outs and sagging of the melt, if the hydrostatic pressure exceeds the surface tension. The hydrostatic pressure is influenced by the material thickness and increases with increasing thickness. The surface tension, on the other hand, decreases at the root side as the width of the root and thus the surface increases. This is especially the case at slow welding speeds. Therefore, a stable welding process is possible only at higher welding speeds. The stability criterion is given as follows [6], where *h* is the plate thickness, *w* is the width of the seam root and γ is the surface tension coefficient:

$$h * \frac{w}{2} < \frac{\gamma}{\rho g_0} \tag{1}$$

Fig. 2 shows the geometric sizes and the stability criterion.

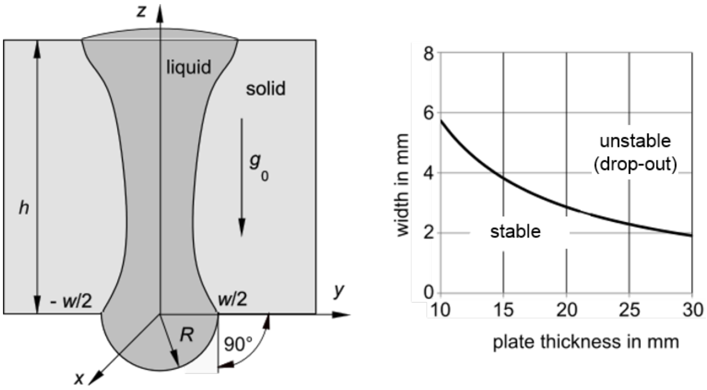


Fig. 2. Stability criterion for liquid steel, in accordance with equ. (1)

There are approaches to increase weldable material thickness for the hybrid laser arc welding process by using the multilayer technology. Steels up to 28 mm in two layers and 32 mm in three to five layers were successfully welded [7]. Combination of HLAW and arc-based welding processes is used for welding thicker materials, where the root face was welded by HLAW and the groove was filled by submerged arc welding [8] or GMA welding process [9].

Thick-walled materials can also be welded in horizontal position (2G) or with reduced welding velocity and use of weld pool supports such as ceramic supports, powder metal or slag protection gas [10-11]. The conventional supports require mechanical attachment and reworking of the root part, which can be time-consuming.

In addition to the usual weld pool support systems, the use of an oscillating electromagnetic field offers an alternative solution. It prevents gravity drop-outs and is based on the generation of Lorentz forces in the molten metal. An AC magnet generates an oscillating magnetic field B perpendicular to the welding direction, which induces eddy currents in the material. The electric current density j is parallel to the welding direction. This producing an upwardly directed resulting Lorentz force F_L which counteracts the hydrostatic pressure. The schematic structure of the electromagnetic weld pool support is shown in Fig. 3.

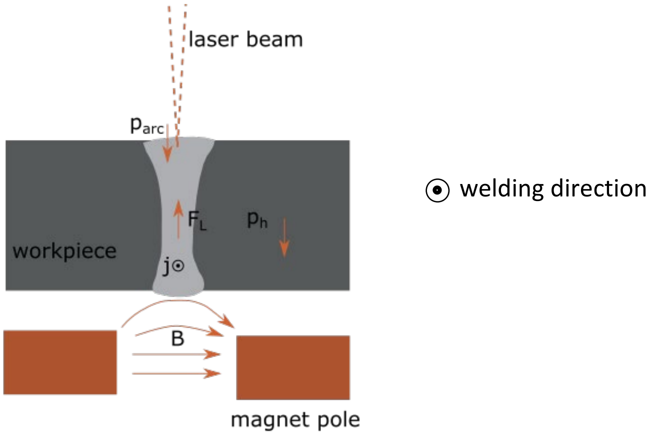


Fig. 3. Scheme of electromagnetic weld pool support system

Electromagnetic weld pool support has been successfully used for laser beam welding of aluminum alloys [6], austenitic [12] and ferromagnetic steels [13] and for hybrid laser arc welding of ferromagnetic steels [14-15]. In hybrid laser arc welding with the electromagnetic weld pool support, it must be ensured that the skin layer depth δ is smaller than the material thickness [14]. As the frequency decreases, the depth of the skin increases and is primarily dependent on the oscillation frequency of the magnetic field. This measure is particularly important to prevent the arc from being influenced by an oscillating magnetic field.

2. Experimental Setup

The welding tests were performed with a 20 kW Yb fiber laser YLR 20000, with a wavelength of 1064 nm and a beam parameter product of 11.2 mm x mrad in flat position (1G). The laser radiation was transmitted through an optical fiber with a core diameter of 200 µm. A laser processing head BIMO HP from HIGHYAG with a focal length of 350 mm providing a spot focus diameter of 0.56 mm was used. The Qineo Pulse 600A welding unit was used as the current source for arc welding and was operated with a pulse frequency of 180 Hz. The GMA torch was tilted 25° relative to the laser axis, where the laser axis was positioned 90° to the weld specimens. All tests were carried out with an arc leading orientation. The distance between the wire tip extension and the impact of the laser beam on the workpiece was defined as 4 mm. A negative focus position of the laser beam relative to the workpiece surface of -8 mm have been selected. The welding velocity was changed in the range of 0.5 m min^{-1} to 0.9 m min^{-1}.

The AC magnet was 2 mm under the workpiece in a fixed position. The movement of the workpiece for welding was realized via a turn table. The distance between the two magnetic poles was 25 mm. Depending on the material thickness and high hydrostatic pressure, the AC magnet was operated with an oscillating frequency of 1.2 kHz and a power of 2.4 kW - 2.6 kW. Fig. 4 demonstrates the experimental setup of a hybrid laser arc welding process with electromagnetic weld pool support.

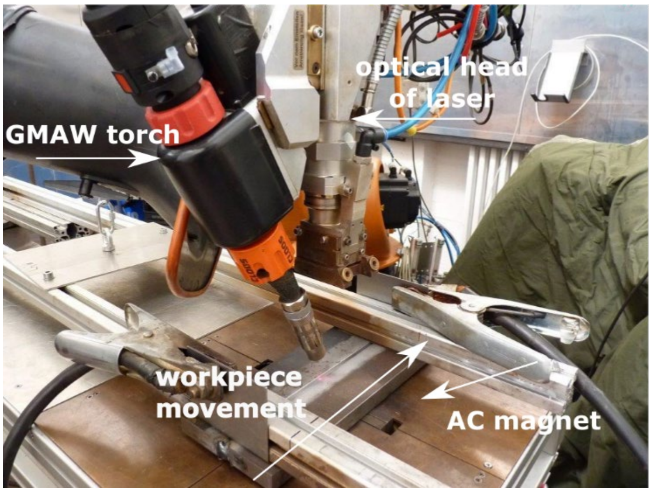


Fig. 4. Experimental Setup of hybrid laser-arc welds with electromagnetic weld pool support

For the tests, structural steel S355J2 with a material thickness of 25 mm, 28 mm and 30 mm were used. All welds were butt-joint welded in a single-pass. The parts with a thickness of 25 mm were assembled with a square groove. Thicker parts were prepared with a Y-joint and a root face of 24 mm. As a filler wire G3Ni1 according to EN ISO 14341 with a diameter of 1.2 mm was used. A mixture of argon with 18% CO_2 with a flow rate of 20 l min^{-1} served as shielding gas. The materials used, and their chemical compositions are shown in Table 1.

Table 1. Chemical composition of base material and filler wire, shown in wt%

Material/Element	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Fe
S355J2	0.08	1.3	0.29	0.019	0.004	-	-	-	0.08	bal.
G3Ni1	0.08	1.4	0.612	0.004	-	0.014	0.73	0.08	-	bal.

3. Results

The 25 mm thick plates could be welded in a single-pass without gravitational dropping of the melt. The required laser power for full penetration of 25 mm thick plates with a square groove butt joint was 19 kW at a welding velocity of 0.9 m min^{-1}. The wire feeding rate was 12 m min^{-1}. The root width is 4.3 mm. With an AC power of 2.4 kW at an AC frequency of 1.2 kHz, the hydrostatic pressure is ideally compensated. The root excess weld metal is 0.7 mm. The welded specimens can be classified in the highest evaluation group B in accordance with EN ISO 12932, which defines the quality levels for imperfections for hybrid laser arc welding of steels. Fig. 5 shows the root of a welded sample and a cross section.

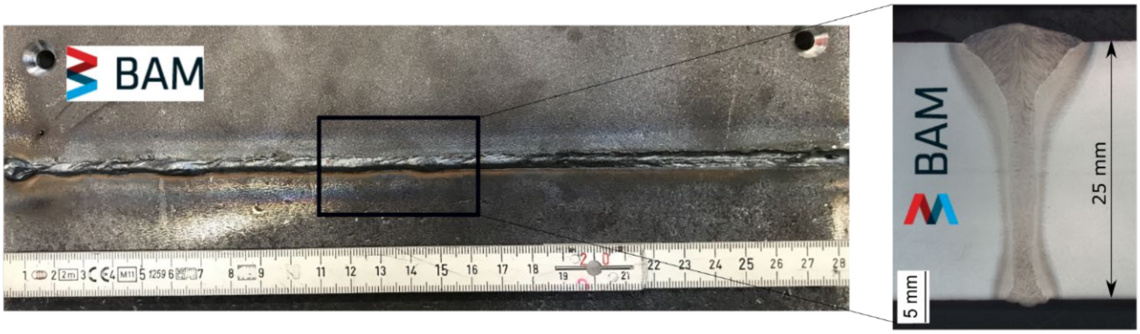


Fig. 5. Overview of a single-pass hybrid laser arc welded 25 mm thick square groove butt joint plate; cross section (right)

Radiographic test shows that the weld is faultlessly referring to cracks, lack of fusion and gas pores. An x-ray image is shown in Fig. 6. There are scattered spatters on the top side of the sample. It should be noted that the droplet in the start area (marked by a triangle) is not taken into consideration in this study due to non-optimisation of the start parameters.

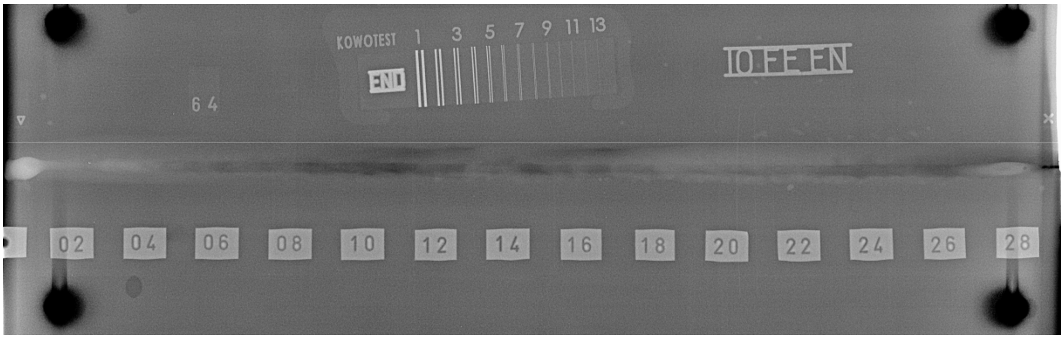
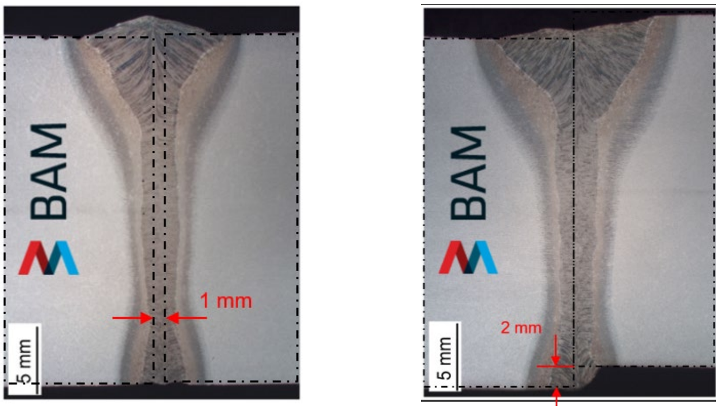


Fig. 6. X-ray image of a 25 mm thick hybrid laser-arc welded sample with electromagnetic weld pool support

Study of gap bridgeability for welding of 25 mm thick plates in flat position with reduced welding velocity shows that a gap up to 1 mm can be bridged ideally. The wire feed speed had to be adapted from 12 m min^{-1} to 14 m min^{-1}. In contrast, the laser power was reduced to 14.8 kW. With an AC power of 2.4 kW at an AC frequency of 1.2 kHz the hydrostatic pressure and dropping could be compensated ideally and a nearly flat root surface could be reached, see Fig. 7 (a). An optimization of the magnet parameter was not required compared to the zero-gap case. This welded samples can be classified in the highest quality level B according to DIN EN ISO 12932.

Furthermore, the misalignment of edges was investigated. A joint edge offset up to 2 mm was successfully bridged with a laser beam power of 19 kW at a welding speed of 0.7 m min^{-1} and a wire feed speed of 10 m min^{-1}, see Fig. 7 (b). The magnet parameters remain unchanged. The position of the optical head was unchanged, too. A faultless seam could be realized without formation of droplets on the root side and notches. The groove is filled. The cross sections were extracted in the middle of the welded sample.



a)

b)

Fig. 7. Cross sections for hybrid laser-arc welded 25 mm thick plates: (a) 1 mm gap; (b) 2 mm edge offset

A reduction of the welding speed and a joint preparation allows single-pass welding of plates with a thickness of 28 mm and 30 mm. For the full penetration, the required laser power was 19 kW and 20 kW, respectively. The welding speed was reduced to 0.5 m min^{-1}. The wire feeding rate was in a range of 10 m min^{-1} to 12 m min^{-1}. An AC power of 2.6 kW was necessary to prevent gravity drop-out at an oscillating frequency of 1.16 kHz. Figure 8 shows cross sections of single-pass welded 28 mm and 30 mm thick steel plates. It is recognizable, that the root is ideally compensated and nearly flat and the groove is filled completely.

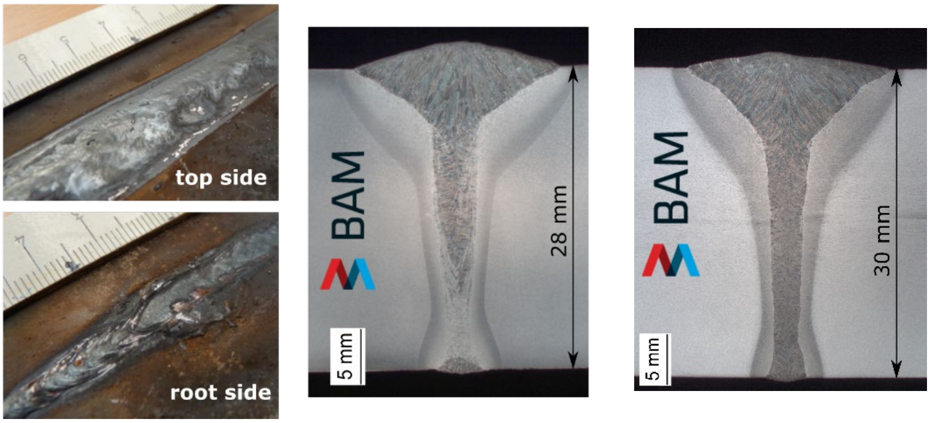


Fig. 8. Cross sections for single-pass hybrid laser-arc welded 28 mm thick plates (left) and 30 mm thick steel plates (right)

The following table summarizes the welding parameters for ideally compensated single-pass welds in hybrid laser arc welding of 25 mm to 30 mm thick plates of S355J2.

Table 2. Welding parameters for single-pass hybrid laser-arc welds

t in mm	Joint preparation	P_1 in kW	v_w in m min^{-1}	v_{wire} in m min^{-1}	f_{AC} in kHz	P_{AC} in kW
25	I-butt	19	0.9	12	1.2	2.4
28	Y-joint	19	0.5	12	1.2	2.6
30	Y-joint	20	0.5	10	1.2	2.6

4. Summary

It could be shown, that materials with a thickness of 25 mm could be welded by HLAW in a single-pass without imperfections such as gravity dropout. The reduction of the welding speed enables also an increase in the weldable material thickness at a laser power of 20 kW. The welds carried out in this article can be classified in the highest evaluation group B according to EN ISO 12932. The electromagnetic weld pool support proves to be an economically alternative to usual weld pool support systems. By adapting the electromagnetic weld pool support to the laser and laser hybrid welding process, the application potential of these technologies for industrial implementation can be drastically increased. For practical use, the AC magnet must be moved under the workpiece at the same speed as the welding head.

All samples were free of cracks and pores. In addition, the cooling time is favourable influenced due to the reduced welding speed, which improves the mechanical-technological properties.

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