Full penetration hybrid laser arc welding of up to 28 mm thick S355 plates using electromagnetic weld pool support

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Abstract. The laser hybrid welding process offers many advantages regarding deep penetration, increased welding velocity and with the help of the supplied filler wire an improved bridgeability to gap and misalignment tolerances. High power laser systems with a power of approx. 30 kW are already available on the market. Nevertheless, multi-layer technology with an arc process is still used for welding of plates from a thickness from 20 mm. A potential cause is the process instability with increasing laser power. It is inevitable that gravity drop-out due to the high hydrostatic pressure at increasing wall thickness especially at welding in flat position and with a low welding speed. The surface tension decreases with increasing root width resulting from low welding velocities. To prevent such inadmissible defects of the seam a use of weld pool support is required. Usual weld pool support systems such as ceramic or powder supports require a mechanical detachment which is time-consuming. The electromagnetic weld pool support system described in this work shows an alternative weld pool support which works contactless. It is based on generating Lorentz forces in the weld pool due to oscillating magnetic field and induced eddy currents. This innovative technology offers single pass welds up to 28 mm in flat position and reduced welding velocity with a laser power of just 19 kW. It also leads to improved mechanical-technological properties of the seams because of the slow cooling rate. With usage of an electromagnetic weld pool support the limitation of the hybrid laser arc welding process in the thick sheet metal will be extend.

1. Introduction

The hybrid laser arc welding process is a coupling of laser beam welding and arc welding process in a common interaction zone and was developed in the 1970s [1]. The aim of this coupling is to exploit the synergy effects of both welding processes and overcome problems that often occur in pure laser beam welding or arc welding. The high power density of the laser beam creates a narrow keyhole, which enables a deep penetration effect at high welding speeds and low distortion of the welded metal. The additional material, which is fed to the process in the form of molten filler wire enables a better bridgeability against gap and other manufacturing tolerances [2]. Furthermore, the mechanical-technological properties of the welded samples can be positively influenced by using of an aimed filler metal and the additional energy of the arc in general, which reduces the cooling rate.

For deep penetration welds, an arc leading orientation of the process, a short distance between the wire tip and the laser beam and a small torch angle are preferred. Moreover, the focal position of the laser beam should be below to the top surface [3-4]. Figure 1 shows scheme of hybrid laser arc welding process with the principal factors, which have an influence on the penetration effect, where a is the distance between the extended wire tip and the laser beam, β is the torch angle relating to the laser beam and z_f is the focal position of the laser beam.

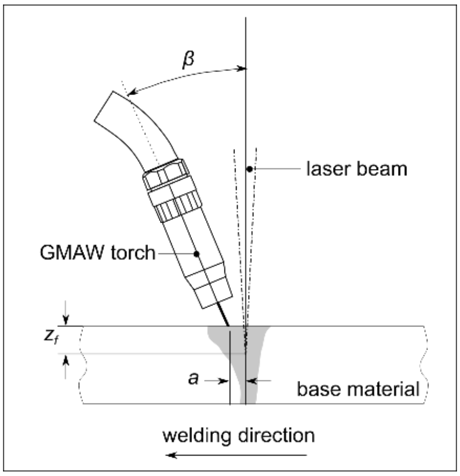

Figure 1. Scheme of hybrid laser arc welding

High power laser systems with a power of approx. 30 kW are already available on the market due to latest developments in laser technology. The hybrid laser arc welding process is used for industrial applications such as in the marine industry. The German shipyard Meyer Werft and the Fincantieri shipyard in Italy have successfully introduced this technology [5]. The hybrid laser arc welding process is used for single-pass welds up to max. 20 mm. Material thicknesses beyond this, can be welded with the hybrid laser arc welding process in multi-layer technology. Plates with a thickness up to 28 mm could be welded in two layers, and 32 mm thick plates in three to five layers, successfully [6]. Alternatively, the root face of thick materials is welded by hybrid laser arc welding process. In the following process the groove is filled by an arc welding process such as submerged arc welding [7] or GMA welding process [8]. In most instances, multi-layer technology with an arc process is still used for welding of plates from a thickness more than 20 mm.

A potential cause of the restricting factors for hybrid laser arc welding of materials with a thickness greater than 20 mm is the increasing process instability with the growing laser power. Another process limitation is that the process can be realized only at a sufficiently high welding speed in particular in flat position. The main reason for choosing a high welding speed when welding thick materials in flat position is the action of the gravitational force leading to sagging of the molten metal. Gravity drop-out results when the hydrostatic pressure exceeds the surface tension. The hydrostatic pressure is dependent on the material thickness and grows by increasing thickness. The surface tension decreases with increasing width of the root side, which occurs at slow welding velocities. This explains why the stable welding process is possible only for higher welding speeds.

Thick materials can be welded at lower welding speeds in horizontal position (2G) or with weld pool support systems. Conventional weld pool supports such as ceramic backing, powdered metal or anti-slag gas are used [9-10]. Ceramic baking and powdered metal as weld pool support require a mechanical detachment and rework of the root part, which is time-consuming.

An alternative solution consists in using oscillating electromagnetic fields to prevent sagging and gravity drop-out. It is based on generating Lorentz forces in the weld pool. An oscillating magnetic field B perpendicular to the welding direction is produced by an AC magnet and generates eddy currents in the material. The electric current density j is parallel to the welding direction. The resulting Lorentz F_L force is directed upwards and counteracting the hydrostatic pressure. A schematic drawing of the electromagnetic weld pool support is shown in Figure 2.

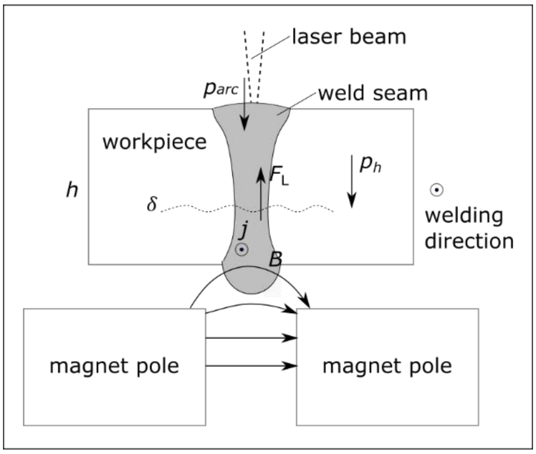

Figure 2. Scheme of electromagnetic weld pool support system

This technology was demonstrated for laser beam welding of aluminum alloys [11], austenitic [12] and ferromagnetic steels [13] and for hybrid laser arc welding of ferromagnetic steels [14] successfully. For application of electromagnetic weld pool support at hybrid laser arc welding, it will be necessary to ensure, that the skin layer depth δ must be smaller than the material thickness [14]. The skin depth is primarily dependent on the oscillating frequency of the magnetic field and increases at decreasing frequency. This is especially important for preventing the electric arc on the top side of the weld sample to be influenced by oscillating magnetic field.

2. Experimental Setup

All welding experiments were executed in flat (1G) position using a 20-kW-Yb fibre laser YLR-20000 with a wave length of 1064 nm and a beam parameter product of 11.2 mm x mrad. The focal length of the optics was 350 mm. An optical fibre of 200 µm was used for transmission of the laser beam. The focus diameter was 0.56 mm. The welding machine Qineo Pulse 600A functioned as arc welding power source. For the experiments the welding machine was operated in pulse mode with a pulse frequency of 180 Hz. All hybrid laser arc welds were executed with an arc leading orientation and a torch angle of 25° relating to the laser beam. The distance between the wire tip extension and the impact of the laser beam on the workpiece was 4 mm. A negative focus position of the laser beam relative to the workpiece surface of -8 mm to -13 mm. The welding speed was 0.5 m min^{-1} to 1 m min^{-1}.

During experiments the laser head and GMAW torch was mounted on the robot arm. The AC magnet was in a fixed position 2 mm under the workpiece. The robot arm and the magnet have not been moved, in order to ensure that the weld seam was centred between the magnet poles. The welding motion was realized through the movement of the workpiece by a turn-table. Figure 3 shows the experimental set-up of full penetrated hybrid laser arc welds with electromagnetic weld pool.

The gap between the two magnet poles was 25 mm, see figure 3 (bottom right). A distance of 2 mm between the surface of the magnet and the work piece has been selected. The magnet was operated with a oscillating frequency of 1.1 kHz to 1.2 kHz and in a power range of 1.6 kW to 2.6 kW dependent on the material thickness and increasing hydrostatic pressure.

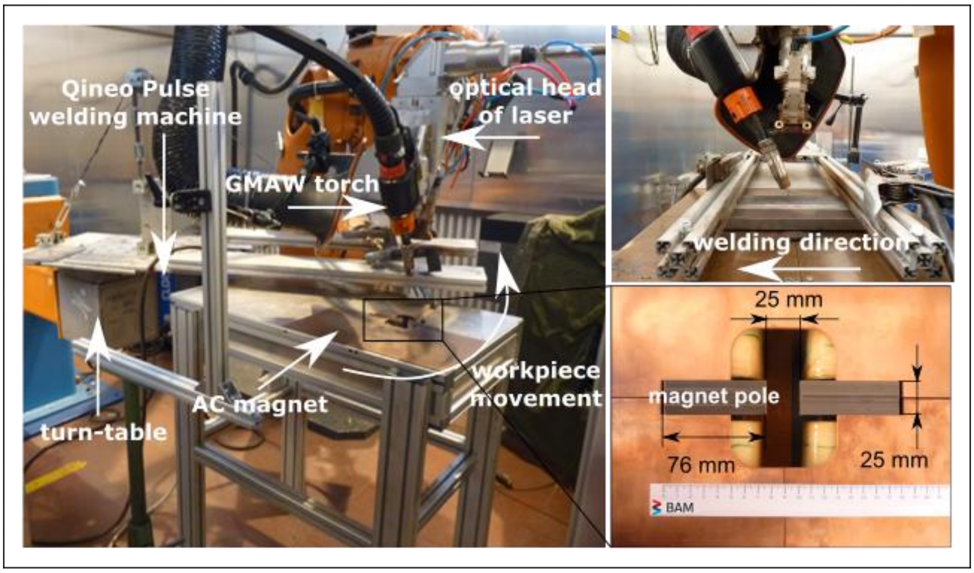

Figure 3. Experimental Set-up of hybrid laser-arc welds with electromagnetic weld pool support (left), enlarged view (top right) and overview of used electromagnet

For this study, materials of steel grade S355J2 with a plate thickness of 20 mm, 25 mm and 28 mm were used. The parts with a thickness of 25 mm were assembled into a butt joint configuration with a square groove. A Y-joint preparation was provided for 20 mm (root face of 14 mm) and 28 mm (root face of 23 mm). All weld samples have been previously milled on the welded side. For the filler wire, different wires of types G3Ni1 (solid wire) according to EN ISO 14341 and a flux-cored wire T 69 6 Mn2NiCrMo M M 1 H5 (Megafil 742M) according to EN ISO 18276 with a diameter of 1.2 mm were chosen. The shielding gas was a mixture of argon with 18 % CO_2 with a flow rate of 20 l min^{-1}. The chemical composition of the used material and filler wires are shown in table 1.

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

Material/Element	C	Mn	Si	P	S	Cr	Ni	Mo	Al	Cu	Fe
S355J2	0.08	1.3	0.29	0.019	0.004					0.08	bal.
Megafil 742M	0.05	1.6	0.4	0.015	0.015	0.5	2.2	0.5	0.003	0.12	bal.
G3Ni1	0.08	1.4	0.612	0.004		0.014	0.73	0.08			bal.

3. Results

Plates with a thickness of 20 mm, 25 mm and 28 mm could be welded in a single-pass without sagging and gravity drop-out. With an AC power of 1.6 kW at an AC frequency of 1.2 kHz, an ideal compensation of the hydrostatic pressure with a nearly flat root surface could be reached for full penetration welds 20 mm thick structural steel S355J2. According to EN ISO 12932, which defines the quality levels for imperfections for hybrid laser arc welding of steels, the welded 20 mm thick plates can be classified in the highest evaluation group B. The figure 4 shows the comparison for single-pass welded 20 mm thick samples with and without electromagnetic weld pool support system. The laser power was 12.2 kW, an arc power of 11.2 kW and a welding velocity of 0.5 m min^{-1} have been selected. The root excess weld metal is approx. 0.3 mm and the width of the root is 5 mm. The groove is filled completely. A laser profile scan of the root part is also shown in figure 5 for a qualitative evaluation over the entire seam length. It is evident that the root is steady over the entire seam length. The limits of root excess weld metal for different evaluation groups according to EN ISO 12932 are also marked. The root reinforcement can be affected by changes of the AC magnet power, see [14].

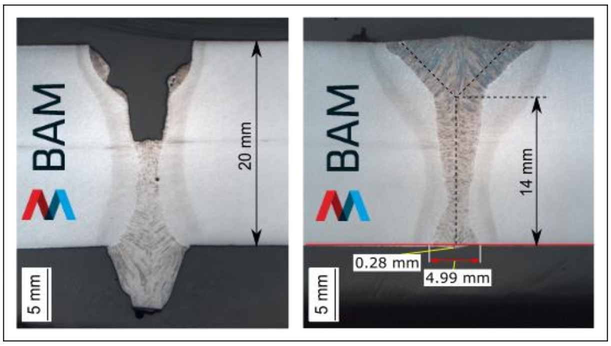

Figure 4. Cross section of 20 mm single-pass welded sample; (left) reference and (right) with electromagnetic weld pool support

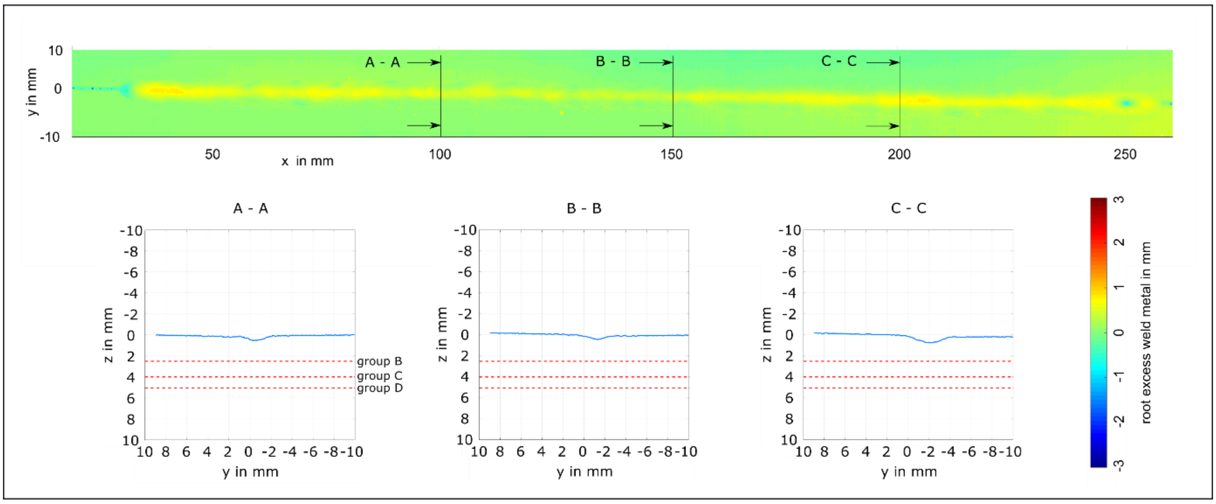

Figure 5. Evaluation of ideally compensated hybrid laser arc welded 20 mm thick plate with a laser profile scanner (top), weld root with maximum acceptable root excess weld metal according to EN ISO 12932 (bottom)

The possibility of reduced welding velocity allows an increase of weldable material thickness with a laser beam power of 20 kW. Single-pass hybrid laser arc welding of 25 mm thick square groove butt joints could be realized without sagging and according to the root quality requirements of the valid standard at a welding velocity of 0.9 m min^{-1} with a laser power of 19 kW and a wire feeding rate of 12 m min^{-1}. A focal position of -5 mm was selected. The magnet was operated at a frequency of 1.2 kHz and an AC power of 1.9 kW. The root is compensated ideally, see figure 6. Due to the higher welding velocity comparing to hybrid laser arc welded 20 mm thick plates, the root width decreases to 4.3 mm. The root excess weld metal is 0.7 mm.

A reduction of the welding speed and a joint preparation allows a single-pass weld thicker plates up to 28 mm. A Y-joint preparation with a root face of 23 mm was selected. The required laser power was 19 kW at a welding speed of 0.5 m min^{-1}. The wire feeding rate was 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 7 shows a cross section of a single-pass welded 28 mm thick steel plate. It is recognisable, that the root is ideally compensated and nearly flat and the groove is filled completely. The root width is 4.2 mm.

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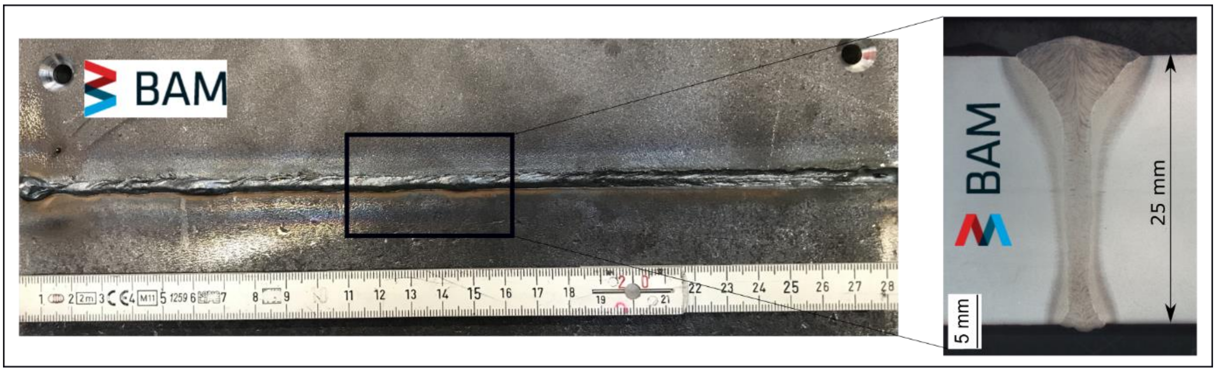

Figure 6. Overview of a single-pass hybrid laser arc welded 25 mm thick square groove butt joint plate; cross section (right)

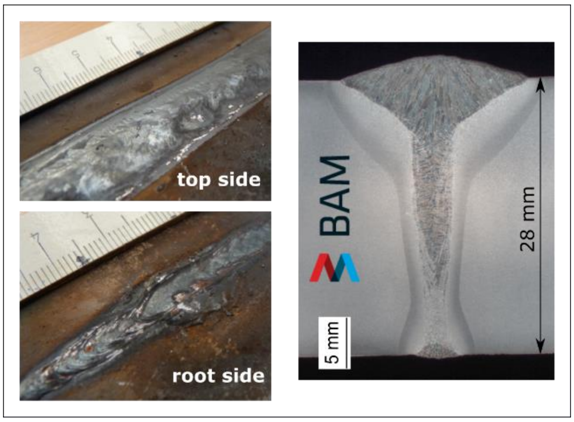

Figure 7. Single-pass hybrid laser arc welded 28 mm thick structural steel S355J2 with electromagnetic weld pool support

The welding parameters for ideal compensated single-pass welds with hybrid laser arc welding are summarized in table 2.

Table 2. Welding parameters for single-pass welds of thick materials with different thicknesses

t in mm	Joint preparation	Root face in mm	P_l in kW	v_w in m min^{-1}	v_{wire} in m min^{-1}	f_{AC} in kHz	P_{AC} in kW
20	Y	14	12.2	0.5	11	1.2	1.6
25	I-butt		19	0.9	12	1.2	1.9
28	Y	23	19	0.5	12	1.16	2.6

4. Summary

In summary, single-pass hybrid laser arc welds of 20 mm, 25 mm and 28 mm thick plates of structural steel S355J2 could be welded without gravity drop-out successful. The reduction of the welding speed allows an increase of weldable material thickness with a laser beam power of 20 kW. All welds can be classified in the highest evaluation group B according to EN ISO 12932. The electromagnetic weld pool support system, described in this study, makes the reduction of welding speed possible without imperfections such as inadmissible root excess weld metal. By use of this system at hybrid laser beam welding process the potential field of application of this technology for real industrial implementation can dramatically increase and become a suitable alternative to conventional processes, which are still used for multi-layer welding of thick plates. For practical use, the AC magnet must be moved under the workpiece with the same velocity of weld head.

The reduction of the welding speed is also favorable for the cooling time and mechanical-technological properties of welded structures. All welds were also crack and pore-free.

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