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Study of gap and misalignment tolerances at hybrid laser arc welding of thick-walled steel with electromagnetic weld pool support system

Ömer Üstündağ^{a,*}, André Fritzsche^b, Vjaceslav Avilov^c, Andrey Gumenyuk^{a,b}, Michael Rethmeier^{a,b}

^aFraunhofer Institute for Production Systems and Design Technology, Pascalstraße 8-9, 10587 Berlin, Germany

^bFederal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin, Germany

^cOtto von Guericke University Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany

* Corresponding author. Tel.: +49-30-39006-440 ; fax: +49-30-39006-391. E-mail address: oemer.uestuendag@ipk.fraunhofer.de

Abstract

The hybrid laser arc welding (HLAW) process provides many advantages such as improved gap bridgeability, deep penetration and misalignment of edges, that is why the process is used increasingly in industrial applications e.g. shipbuilding, power plant industry and line-pipe manufacturing. The obvious encountered problem for single pass welding in flat position is the gravity drop-out at low welding velocities. With the usage of an electromagnetic weld pool support system, which is based on generating Lorentz forces within the weld pool, wide seams followed by reduced welding velocities could be achieved in this study leading to the realization of a gap bridgeability up to 1 mm, misalignment of edges up to 2 mm and a single pass weld up to 28 mm thickness with a 20-kW fibre laser. These developments expand the boundaries of the HLAW process for different industrial applications. As a result, less accurate preparation of the edges would be sufficient, which saves time for manufacturing.

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1. Introduction

The hybrid laser arc welding process is a coupling of laser beam welding process and arc welding process in the same weld pool. The concept was developed in the 1970s as arc augmented laser welding process [1]. In this way the synergetic effects of both welding processes can be used for a deep penetration, high welding speeds, influence of filler material to mechanical-technological properties of welded samples, low distortion and a greater tolerance to joint gaps such as gap bridgeability and misalignment of edges. Primarily the high and focused power density of the laser beam is used for the deep penetration and narrow welds while the filler material which is introduced into the process by the arc welding process enables the better gap bridgeability and other manufacturing tolerances [2].

The orientation of the GMAW has an influence on the penetration depth and gap bridgeability. For deep penetration and a better bridgeability of manufacturing tolerances an arc leading orientation of the process, small torch angle, short distance between the wire tip and the laser beam and a negative focus of the laser beam should be preferred [3]. A scheme of hybrid laser arc welding is shown in Figure 1, where a is the distance between wire tip and laser beam, β is the torch angle and Δz_f is the focus of laser beam.

In already published works the max. bridgeability was 0.8 mm for welding of structural steels with 15 mm thickness by a carbon-dioxide laser [4]. For solid state laser the max. bridged gap is approx. 0.3 mm by welding of 16 mm plates [5]. With scanner optics which allow a movement of the laser beam transversal to the welding direction, the max. gap bridgeability could be extended to 0.7 mm by hybrid laser arc welding of 16 mm thick plates [6]. One-pass 25 mm thick samples could be welded with 2.5 mm air gap. The gap was

filled with cut-wire particles. For protection of drop-outs a backing method such as ceramic or submerged arc welding flux was used [7]. The misalignment of edges up to 2 mm at 16 mm thick plates could be welded with optimization of the welding speed and with a variation of the focal position [8].

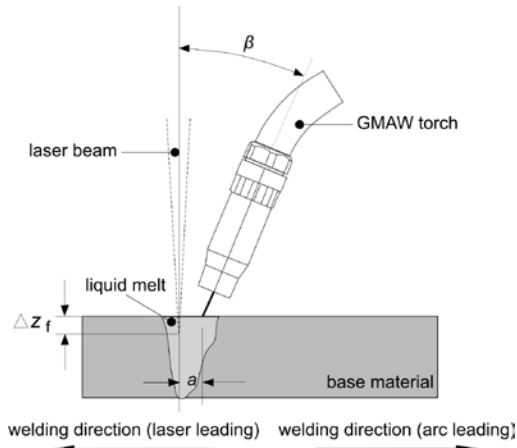


Fig. 1. Scheme of hybrid laser arc welding

Larger gaps can be bridged with reduced welding velocities. These welds can be produced only in horizontal position (2G) or with weld pool support systems because otherwise there is a gravity drop-out or sagging. In horizontal position the max. bridged gap is 1.5 mm [9]. The welding in 2G-position is not possible under severe conditions for industrial applications such as in shipbuilding with large diameters of welded samples. The gravity drop-out by welding in flat position can be avoided also at high welding velocities. It is observed experimentally, that single pass welding of thick materials in flat position without sagging and drop-out of the melt is given for welding speeds $> 1.8 \text{ m min}^{-1}$ [6]. Due to narrow welds at fast welding speeds the Laplace pressure and surface tension is sufficient to prevent sagging. This fact set the natural physical limitation on achievable weld thickness for single pass laser beam welding process in conjunction with the available laser power. So far up to 20 mm thick plates could be welded in single pass and flat position with a laser beam power of approx. 20 kW [5].

The electromagnetic weld pool support system described in the current investigation is applied for laser beam welding of aluminum alloys [10], austenitic [11] and ferromagnetic steels [12] and for hybrid laser arc welding of ferromagnetic steels successfully [13]. It is based on generating Lorentz forces in the liquid metal. An external oscillating magnetic field B produced by an AC magnet located under the workpiece, see Figure 2, generates eddy currents. The magnetic field is directed perpendicular to the welding direction while the electric current density j is parallel to it. The resulting Lorentz force F_L is directed in vertical direction and can compensate the hydrostatic pressure. The skin layer depth which is primarily dependent on the frequency of the oscillating magnetic field must be less than the material thickness to protect the electric arc from the oscillating magnetic field. In general welds at a slower welding speed could be realized with the support of an oscillating magnetic field. The scheme

of the electromagnetic weld pool support system is shown in Figure 2.

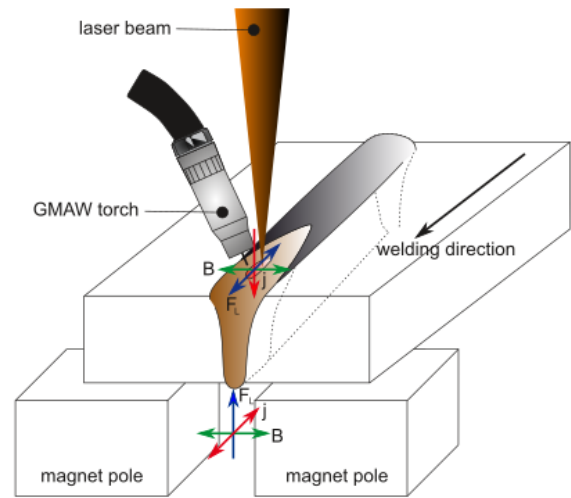


Fig. 2. Scheme of electromagnetic weld pool support system

2. Experimental Setup

A 20 kW fibre laser YLR-20000 with a wave length of 1064 nm and a beam parameter product of 11.2 mm x mrad was used. The focal length of the optics used for the experiments was 350 mm. The laser beam has been transmitted by an optical fibre with a diameter of 200 μm and focused to a diameter of 0.56 mm. The microprocessor controlled welding machine Qineo Pulse 600A was used as an arc welding power source. For the experiments the welding machine was operated in pulse mode with a pulse frequency of 180 Hz and a pulse time of 2.12 ms. All welds were executed with an arc leading orientation with a torch angle of 25°. The distance between the wire tip extension and the impact of the laser beam was 4 mm in the plane of the workpiece surface, a negative focus position relative to the workpiece surface of -8 mm to -12 mm has been selected. The welding speed was in a range of 0.5 m min^{-1} and 0.8 m min^{-1} .

The welds are produced in flat position where the AC magnet was in a fixed position 2 mm under the workpiece. The gap between the magnet poles was 25 mm. The magnet has been operated with a frequency of 1.2 kHz in a power range of 2 kW - 2.6 kW dependent on the material thickness and the resulting hydrostatic pressure. Laser head and GMAW torch were mounted on the robot arm. The robot arm and the AC magnet was stationary. The welding motion was realized through the movement of the workpiece by a x-y-positioning table. The Figure 3 shows the experimental set-up of hybrid laser arc full penetration welds in flat position with electromagnetic weld pool support system.

For the investigation of the gap bridgeability and tolerances to misalignment of edges 20 mm thick plates with a single Y-joint and a root face of 14 mm and 25 mm thick plates with square groove of structural steel S355J2 were used. The 28 mm thick plates were prepared with a single Y-joint an opening angle of 45° and a root face of 23 mm. The applied filler material was a solid welding wire G3Ni1 conforming to DIN EN ISO 14341 with a diameter of 1.2 mm.

The shielding gas was a mixture M21 (18% CO₂ in Ar) according to DIN EN ISO 14175 with a volume flow rate of 20 l min⁻¹.

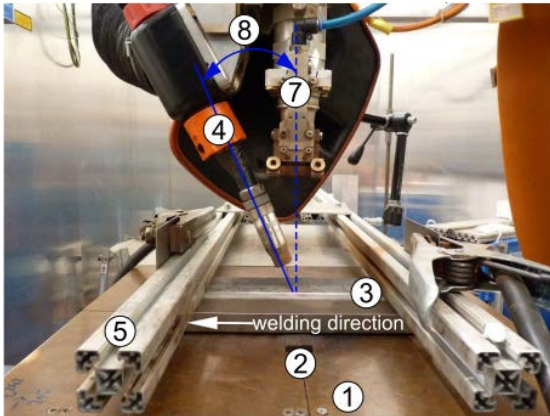


Fig. 3. Scheme of electromagnetic weld pool support system 1-AC magnet, 2-magnet pole, 3-workpiece, 4-GMAW torch, 5-aluminum profile, 6-workstation, 7-laser head and 8-torch angle

3. Results

The electromagnetic weld pool support system could be realized for hybrid laser arc welded structural steel S355J2 with a thickness of 20 mm, 25 mm and 28 mm successfully.

3.1. Single-pass welding of 20 mm thick plates with different gaps

Due to usage of an electromagnetic weld pool support system and resulting possibility of reduced welding velocity wider seams could be realized. This led to increase of a gap bridgeability up to 1 mm by welding of 20 mm thick plates in flat position. The welding velocity was 0.5 m min⁻¹. Through the reduction of the welding speed a laser power of 12.2 kW was necessary to weld 20 mm thick plates with a single Y-joint and a root face of 14 mm in a single pass. The wire feed speed had to be adapted with increasing gap width from 11 m min⁻¹ to 17 m min⁻¹. With an AC power of 1.8 kW at an AC frequency of 1.2 kHz the hydrostatic pressure and the root side metal outflow could be compensated ideally and a nearly flat root surface could be reached. An optimization of the magnet parameter was not required compared to the zero-gap case, as the hydrostatic pressure is dependent on the thickness of the welded material. This welded samples can be classified in the highest quality level B according to DIN EN ISO 12932. The root quality could be guaranteed over the entire seam length.

Figure 4 show the cross sections of welded samples with a zero-gap, 0.5 mm gap and 1 mm gap. It is evident that the welds are without sagging and gravity drop-outs. The groove is filled completely. There are no lacks of fusion.

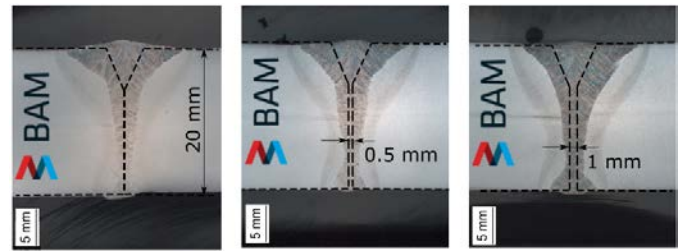


Fig. 4. Single-pass welded samples with different gaps

3.2. Single-pass welding of over 20 mm thick plates with a butt joint and investigation of misalignment of edges

The possibility of reduced welding velocity without gravity drop-out and sagging allows an increase of weldable material thickness with a maximal available laser beam power of 20 kW.

The welding of 25 mm thick plates of structural steel S355J2 in a single pass could be realized without sagging and according to the root quality requirements of the valid standard. A cross section of a 25 mm thick welded sample is shown in Figure 5a. The laser beam power was 20 kW at a welding speed of 0.9 m min⁻¹. The wire feed speed was 12 m min⁻¹. The magnet was operated at a frequency of 1.2 kHz and a power of 2 kW.

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 speed of 0.7 m min⁻¹ and a wire feed speed of 10 m min⁻¹, see Figure 5b. The magnet parameters remain unchanged. A faultlessly seam could be realized without formation of droplets on the root side and notches. The groove is filled.

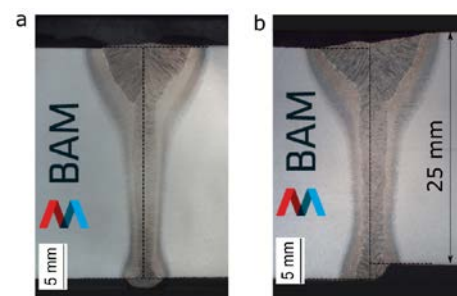


Fig. 5. (a) Single-pass in butt-joint welded 25 mm thick structural steel plates without gap and edges offset; (b) with an edge offset of 2 mm

A further reduction of the welding speed allows single-pass welds of thicker plates up to 28 mm. The sample was prepared with a single Y-joint and a root face of 23 mm. The welding speed had to be reduced to 0.5 m min⁻¹. Due to the increased plate thickness and resulting hydrostatic pressure, the magnet power is adjusted to 2.6 kW at the same frequency. The root quality can be classified in the highest quality level according to DIN EN ISO 12932. The Figure 6 shows a cross section of a single-layer welded 28 mm thick plate. There is a full

penetration weld without gravity drop-out and notches. Also, the groove is filled completely.



Fig. 6. 28 mm thick single-pass welded sample with electromagnetic weld pool support system

4. Discussion

The results in this paper shows that the possibility of reduced welding velocity extends together with using electromagnetic support system the boundaries of the hybrid laser arc welding regarding to the insensitivity to manufacturing tolerances such as gap and edge offset. An accurate preparation of the joining edges for hybrid laser arc welding process can be reduced and skips a necessity for costly hydraulic clamping. The components could possibly be clamped with a tack weld, which is a low-cost alternative to hydraulic clamping. Furthermore, the milling of the edges may be replaced by plasma cutting. In addition to the preparation of the edges, the post-processing of the seam root can be avoided.

Based on these additional information, the hybrid laser arc welding process is suitable for other industrial applications such as field applications involving extreme conditions and where an exact alignment of join partners is not possible.

5. Conclusion

The paper describes an experimental investigation of hybrid laser arc welding of thick-walled structural steel S355J2 starting from a thickness of 20 mm. Due to the possibility of reduced welding speed with an electromagnetic weld pool support system a gap bridgeability up to 1 mm by hybrid laser arc welding of 20 mm thick plates in flat position could be reached. Furthermore, an edge offset can be certainly bridged by welding of 25 mm thick plates. With a further

reduction of the welding velocity to 0.5 m min^{-1} 28 mm thick plate could be welded in flat position in a single layer without sagging and gravity drop-out. All produced welding seams could be classified in evaluation group B according to DIN EN ISO 12932 regarding the root quality. The welds were also crack and pores-free.

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