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Evaluation of a laser-hot-wire hybrid process for producing deep net-shape welds

J. Näsström[a,*], J. Frostevarg[a]

[a] *Luleå University of Technology, SE-971 87 Luleå, Sweden*

Abstract

Joining thick steel sheets is a challenge for heavy constructions such as vehicle and offshore industries. This is usually accomplished through time and resource consuming arc welding techniques; producing welds with wide HAZ. Laser welding is often a valid option, having improved but limited penetration depths and gap bridging capabilities. Here an alternative laser welding technique is applied, utilizing a laser beam to melt a resistance-heated filler wire, to fill a narrow gap in multiple passes. To increase availability, the process uses readily available weld laser (defocused) and welding equipment to heat and deliver heated filler wire. Using macroscopy, SEM and high speed imaging, the presented process and its individual phenomena has been evaluated; identifying process strengths and limitations. It is shown that the technique can produce multi-pass welds with a sound, near net-shaped surface. From evaluation, recommendations are derived to help suppress imperfections such as centre-line cracking.

Keywords: Thick steel; Laser; Welding; Hot wire; High Speed Imaging; Multi-pass

1. Introduction

Being able to join thick steel sheets is of utmost importance for heavy constructions such as vehicle and offshore industries. There are however known limitations for known procedures used in current factories. Gas Metal Arc Welding (GMAW) requires wide joint preparations with several weld passes to fill, as mentioned by Karadeniz et al. (2007). Laser Beam Welding (LBW) is faster, has a narrow heat affected zone and introduces fewer distortions, as mentioned by many, including Khan et al. (2013). But LBW does have other limitations, such as limited gap bridging capabilities, mentioned by e.g. Ohnishi et al. (2013). The

* Corresponding author. Tel.: +46-920-491-518.
E-mail address: Jonas.nasstrom@ltu.se.

power needed to produce acceptable welds drastically increases in relation to welding depth, as indicated by Hann et al. (2011) and further so by Kim and Ki (2014). Gap bridging capabilities can be significantly improve by adding wire to supply filler material for the gap, according to Dilthey et al. (1995). If Laser Arc Hybrid Welding (LAHW) is used speeds and penetration depths can be increased but there still are limitations, as mentioned by e.g. Grünenwald et al. (2010) and Pan et al. (2016). LAHW can also struggle with welding imperfections such as root humping formation when welding too deep from a single side, observed by Powell et al. (2015). If welding is only possible from one side, thick sheets can still be joined by welding in multiple passes, even without an arc, as described by e.g. Yu et al. (2013) and Zhang et al. (2011). Process complexity does however increase with an increasing number of parameters, as stated by Syed and Li (2005). To ensure a stable process, Torkamany et al. (2015) states that the entire wire should be irradiated by the laser, either through defocusing or oscillation of the beam. Efficiency of the joining process can be improved by pre-heating the wire using an electrical current, according to Wei et al. (2015). Researchers have successfully welded thick steel and aluminium applications using specialized scanner optics, Fig. 1a by Schedewy et al. (2013) and Tsukamoto et al. (2011), and customized wire feeding equipment, Fig. 1b by Karhu and Kujanpää (2015).

In an attempt to make similar capabilities more available to industries, a process using more readily available welding equipment and laser optics has been tested. Evaluation of these (non-optimized) results and recommendations for the process are presented here.

2. Methodology

2.1. Equipment and materials

A 15 kW IPG Yb:fibre laser (fibre core diameter 400 µm, BPP 10.3 mm·mrad, wave length 1070 nm) was used as the primary heat source operated in a continuous wave mode. The laser was focused above the surface using 300 mm focusing optics, resulting in a 4 mm spot size. The large spot ensured that the full width of the gap was irradiated. The wire feeding system was a Fronius gas metal arc welding source. The welding source could provide either a constant current or constant voltage through the wire. The welding source was semi-manually controlled, requiring a target current and voltage to be programmed before processing. During processing, once one of these parameters was reached the other would continuously adapt to keep the first parameter constant.

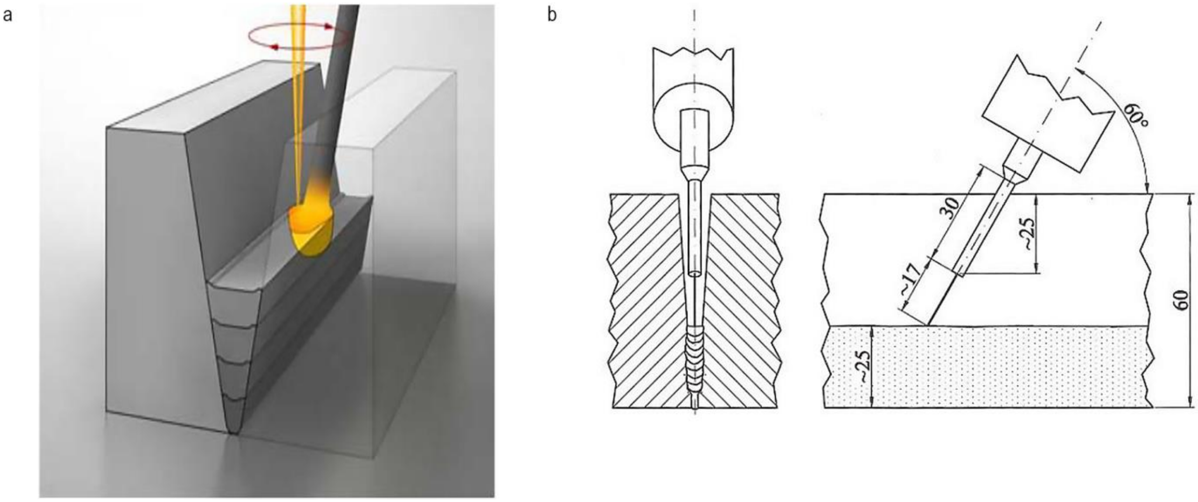

Fig. 1. (a) Multi-layer laser-wire welding with scanned laser beam, Schedewy et al. (2013); (b) specialized wire guidance nozzle, Karhu and Kujanpää (2015)

A 6-axis Motoman industrial robot was used for positioning of the laser optics and GMAW nozzle. 8 mm thick S355J+N was used as base material. The filler wire used was a 1 mm Ø ESAB OK Autrod 12.64 (EN ISO 14341-A). See Table 1 for chemical composition of both plates and wire. The applied shielding gas was Mison18 (82% Ar, 18% CO2, EN 439).

Table 1. Material table

	C	Si (max)	Mn	P (max)	S(max)	Cr	Ni	Mo	B	Al
S355J+N	0.22	0.55	1.6	0.035	0.035	0.3	-	0.08	-	0.02
EN ISO 14341-A	0.08	0.85	1.7	-	-	-	-	-	-	-

2.2. Experimental procedure

In the performed experiments the sheets to be welded were positioned to form a 3 mm wide straight-sided gap, with added root support. The sheet edges were plasma cut and the surfaces were then hand brushed to remove pre-existing oxides.

Each pass was produced at 1 m/min, using 6 kW laser power and 40 l/min shielding gas flow. To prevent back reflections, the defocused laser beam was inclined -7° in the welding direction. The wire was extruded into the front of the melt pool, 0 1 mm from laser spot centre and 32° in the welding direction. An illustration of the process is shown in Fig. 2. Note that wire positioning fluctuated due to insufficient straightening of the spooled wire. Wire feed rate, average wire voltage and current were all set according to table 2. In subsequent passes the thickness of the achieved weld was measured and the height of the process head was adjusted according to the previous layer height.

Table 1. Parameter table

	Wire feed rate (m/min)	Average voltage (V)	Average current (A)	Process head adjustment (mm)
Surface pass	7	7,5	92	6,6
Third pass	7	6,4	88	4
Second pass	7	6,3	84	1,9
Bottom pass	8	6,3	85	0

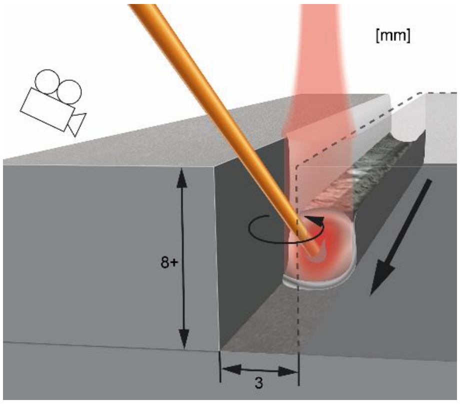

Fig. 2. Illustration of applied welding process

2.3. Analysis

A range of the produced welds was selected for empiric analysis. The process was evaluated using High Speed Imaging (HSI), as used by Frostevarg et al. (2014), in order to find factors relating to process robustness. The welds were also evaluated by macroscopy, looking at weld surface and cross sections. Scanning Electron Microscopy (SEM) was used to evaluate origins of potential weld imperfections.

3. Results and discussion

Following are the HSI and macrographic results and evaluation of using a defocused laser beam and resistance heated wire for joining thick steel.

3.1. High speed imaging

HSI of the bottom, intermediate and top passes for a sample are shown in Fig 3. By observation, the process showed stable melting and wetting behaviour of the filler wire and melt pool.

No discernible differences in process behaviour were observed between passes that had similar geometrical characteristics. Bottom and intermediate passes looks similar, having concave melt pool surfaces, indicated by melt surface reflections in Figs. 3b-c. In the top passes, Fig. 3a, the laser widens the gap by melting the edges. This results in a wider, less high weld cap with a flat surface. Even with minor modifications in process parameters, in addition to wire positing fluctuations (non-straight wire), wire melting behaviour was stable.

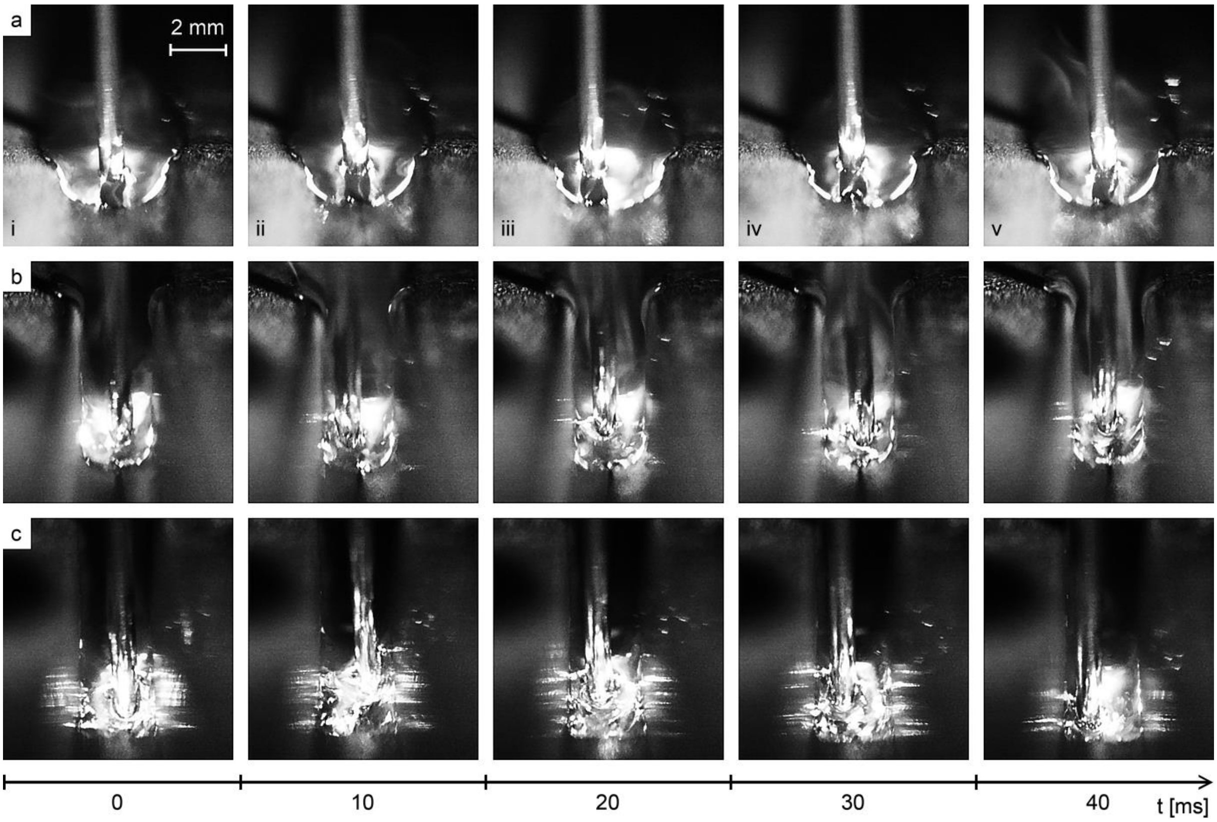

Fig. 3. High Speed Imaging sequences (a) Surface pass; (b) Intermediate passes; (c) Bottom pass.

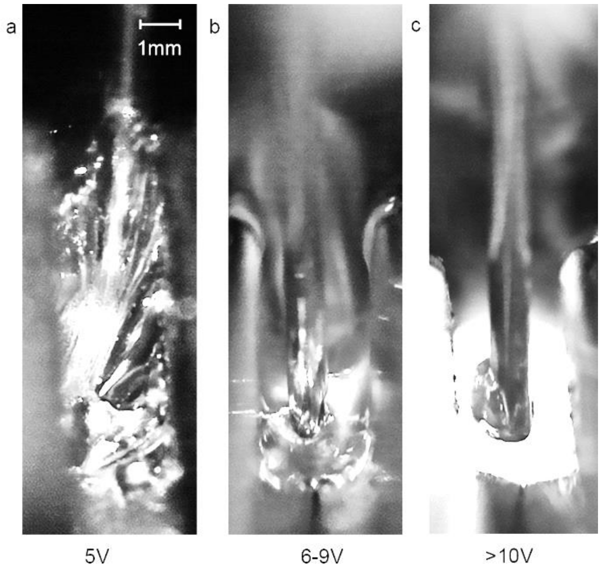

Fig. 4. High Speed Imaging depicting comparison of differing voltage

In some welds, imperfections occurred due to improper parameter settings. One important setting is the voltage for heating the wire. A comparison of process behaviour in depending on wire voltage is shown in Fig. 4. Experiments revealed that there are certain thresholds where the behaviour of the process changes drasticly. If the voltage is too low, Fig. 4a, the wire does not melt properly, causing lack of fusion, cavities in the melt and unregular weld surface. When the voltage is too high, arc formation can occur. When an arc is formed, the extruded wire has less predictable melting, occuring at different heights within the gap, Fig. 4c . A reliable process window for these materials and setup was found to be between 6 and 9 V, Fig. 4b.

3.2. Macrographs

The resulting weld caps where observed ocularly and the cross cuts by microscope and SEM.

3.2.1. Topology

An example weld cap of welds using proper settings can be seen in Fig. 5a. The surface is near sheet net-shape, meaning that the weld cap height in level with the base material. In order to achieve this weld cap shape, the filler material deposition rate has to be precise, according to Eq. 1. This involves gap size, number of intended weld passes, wire dimension and travel speed. Note that volume expansion caused by crystal structures in the material is not considered.

$$v_{wire} = \frac{h_{gap} \cdot w_{gap} \cdot v_{weld}}{n_{passes} \cdot {r_{wire}}^2 \cdot \pi} \tag{1}$$

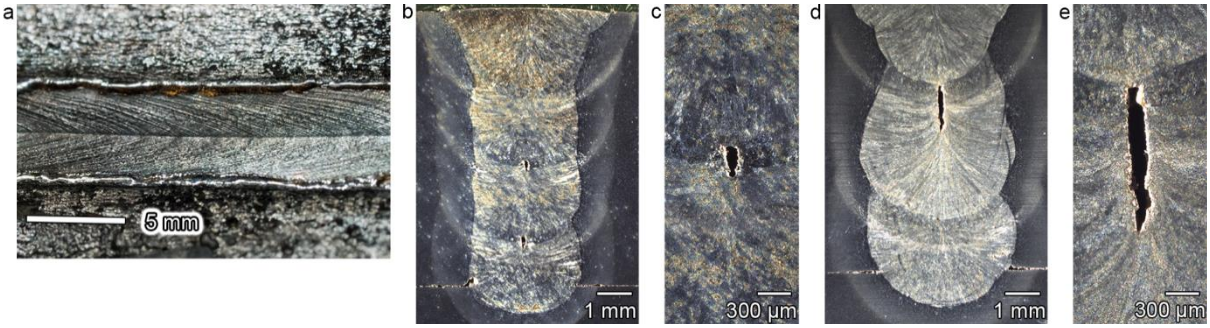

Fig. 5. Macrographs (a) Photograph of resulting weld surface; (b) Full weld including bottom to top pass; (c) Magnification of crack between 2nd and 3rd pass in sample in b; (d) Full weld sample that exhibited arcing with an average wire voltage of 19V; (e) Magnification of crack between 2nd and 3rd pass in sample shown in d.

3.2.2. Cross sections

Macrographs of cross sections showed signs of centre line cracking in bottom and intermediate passes, see Figs. 5b-e. Imperfections formed in the upper parts of intermediate layers, such as these centreline cracks are partially re-melted and sealed by subsequent passes. This implies that the welding procedure has a form of self-repairing behaviour. When arcs form due to having too high voltage in the wire, centre-line cracks can be several times deeper, Figs. 5c,e. Also, arcing leads to excessive melting of the gap walls, Fig. 5d. Top passes fulfilling the criteria of Eq. 1, did not exhibit any centre-line cracking, shown in Figs. 5a-b. The resulting weld cap should provide good fatigue properties. The process was found to produce a small Heat Affected Zone of 1 mm or less, shown in Fig. 5b. Pores were at times found in the lower corners of the bottom pass where root support and gap walls connect, Fig. 5b.

SEM analysis of the observed cracks showed that the bottom edges of the cracks were not sharp but rounded, shown in Fig. 6a. This indicates that it is probable that the cracks formed before the weld was completely solidified. This suggests that it is possible to suppress crack formation by using a wire with a more suitable composition. When changing wire composition, acquiring new weld parameter settings could be required. The imperfection at the root of the weld, Fig. 6b, was found to be pore with a round structure.

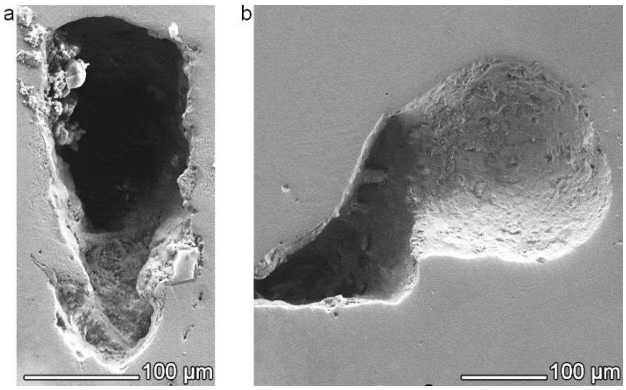

Fig. 6. SEM of weld imperfections, visible in Fig.5b-c (a) Crack between 2nd and 3rd pass; (b) Pore in lower left corner of bottom pass.

These results show great potential for the here applied narrow gap laser-hot-wire welding technique. In accordance with recommendations from Torkamany et al. (2015), the full width of the filler wire can be irradiated using a defocused laser beam, which increases process robustness in spite of varying wire positioning. Also, in agreement with Wei et al. (2015), electrical pre-heating of the wire allows for substantial wire feed rate and travel speed. With further investigation and development, this technique can be well able to join thick steel sheets.

4. Conclusions

The analysis of the results of applying laser hot-wire welding using readily available optics and welding equipment can be concluded as:

- It is possible to weld steel sheets thicker than 7 mm in multiple passes using the presented technique. This technique could potentially join as thick sheets as would allow sufficient wire positioning and beam reach.
- Observations indicate that center-line crack formation in intermediate passes is mainly due to hot cracking
- Top passes that are in level with base material surface show no signs of cracking
- Wire voltage settings should be adjusted to avoid arc formation or insufficient wire melting
- The smooth, near net-shape weld cap produced with this technique present a minimum number of stress raisers; allowing less stress concentration in produced welds, and thus increasing product life expectancy.

Acknowledgments

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