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Thermal cycles and charpy impact toughness of single-pass hybrid laser-arc welded thick-walled structures

Ömer Üstündag[a,*], Nasim Bakir[a], Andrey Gumenyuk[a,b], Michael Rethmeier[c,a,b]

[a]Bundesanstalt für Materialforschung und -prüfung, Unter den Eichen 87 , 12205 Berlin, Germany
[b]Fraunhofer Institute for Production Systems and Design Technology, Pascalstraße 8-9, 10587 Berlin, Germany
[c]Institute for Machine Tools and Factory Management, Technische Universität Berlin, Pascalstraße 8-9, 10587 Berlin, Germany

Abstract

The study deals with the influence of the heat input on the thermal cycles and Charpy impact toughness for hybrid laser-arc welding of 25 mm thick structural steel S355J2 using a 20-kW high-power laser in combination with an electromagnetic weld pool support. The main focus is on the change of the mechanical properties over the entire seam thickness. The cooling times were measured using a pyrometer in combination with an optical fibre in three different locations near to fusion lines corresponding to different heights of the seam. Also, Charpy impact specimens were taken from different parts of the weld joint corresponding to the different heights. The influence of the heat input was investigated for 1.8 kJ mm^{-1} and 3.2 kJ mm^{-1}. Despite the observed decreased values of both $t_{8/5}$-cooling time and the Charpy impact toughness in the root part of the seam, the required values could be reached in dependance on applied heat input.

Keywords: hybrid laser-arc welding; thick-walled structures; Charpy impact toughness; thermal cycles

1. Introduction

The hybrid laser-arc welding (HLAW) process is a coupling of arc welding and laser beam welding process in a common interaction zone and was first developed in the end of the 1970s by Eboo et al., 1978 and only achieved the industrial breakthrough in the shipbuilding industry in the early 2000s as reported by Roland et al., 2004. The idea of the coupling is that the limits encountered in pure laser beam welding or arc welding process are to be overcome by coupling the synergy effects of both welding processes. The laser beam

* Corresponding author. Tel.: +49-30-81043150.
E-mail address: oemer.uestuendag@bam.de.

generates a narrow keyhole due to its high-power density, which allows deep penetration into the workpiece with low distortion and heat input. The arc welding process ensures a better gap bridgeability and is tolerant to manufacturing inaccuracies because of the feed of additional material in the form of molten filler wire as reported by Olsen, 2009. In addition, the mechanical properties of the hybrid laser-arc seams are to be positively influenced with the aid of a suitable filler material. As already shown by the advantages of the coupling listed, the HLAW offers many potential industrial applications especially in the thick sheet range. Thus, there are numerous studies dealing with the use of the HLAW process for thick materials by using laser powers up to 100 kW. With a use of a laser beam source with a maximum output power of 32 kW by combining two 16-kW laser systems, single sided laser hybrid welded joints in 40 mm thickness, covered by two GMA welds at the top and bottom could be realized successful as reported by Nielsen, 2015. With the double-sided welding technique, thick steel sections with a plate thickness up to 45 mm was welded with the HLAW process by Bunaziv et al., 2017. The HLAW process with a laser beam power of 20 kW was used by Rethmeier et al., 2009 and Üstündag et al., 2018 to join 32 mm and 28 mm thick steels in multi-pass or single-pass using an electromagnetic weld pool support respectively. Katayama et al., 2015 has presented attempts to join 70 mm thick steels with double-sided welding technique using a high-power laser beam source with a maximum output power of 100 kW.

Although there are existing laser sources with an output power of 100 kW, the industrial application of the HLAW is restricted to few cases mostly where the thickness of the parts does not exceed 15 mm. There are some technological and process-specific limitations, which inhibits the use of the HLAW process for welding of thicker plates. One of the limiting factors is the increasing process instability with increasing laser power and material thickness and the formation of droplets due to the gravitational forces especially by welding in 1G-position. The droplets can be prevented at a sufficiently high welding speed, so that the hydrostatic pressure of the melt can be compensated only by 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. Avilov et al., 2012 has defined the geometry dependent stability criterion for welding of steels as shown in Fig. 1:

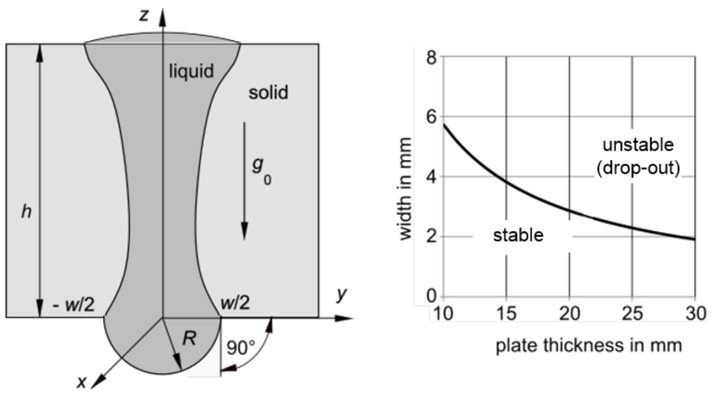

Fig. 1. (left) Geometrical sizes of a single-pass HLAW; (right) Stability criterion for liquid steel.

With increasing welding speed and resulting thin seam root width, the gravitational dop-outs can be eliminated. In contrast, high welding speeds can lead to deterioration of the mechanical properties of the seam, why the implementation of the HLAW in the industrial practice is restricted. Due to the short cooling times, the hardness level, in particular in the root part of the hybrid weld, exceeds the requirements of the standards. It is a big challenge, primarily for welding of high-strength steels. Trials to reduce the cooling rate by preheating the samples up to 100 °C showed no significant improvements regarding to mechanical properties as reported by Atabaki et al., 2014. As a result, high cooling rates lead to formation of big amount of martensite in the weld metal. The use of the appropriate filler wire to affect the microstructure in the root part of the weld is only conditionally realizable. The alloying elements of the filler wire could not be verified in the weld root, due to the inhomogeneous distribution of the filler wire through the weld depth. Such inhomogeneity becomes especially evident at single-pass hybrid welds with a penetration depth of more than 14 mm as reported by Gook et al., 2014. To overcome this problem, a technique with a combination of the hybrid laser-arc welding and cut-wire process was developed by Wahba et al., 2016. The gap between the workpieces was filled with cut-wires before welding. This method resulted in a greater uniformity of the element distribution in the joint. Straße et al., 2020 use a coating of the edge to be welded by the laser metal deposition process before welding. So, the filler material was distributed homogeneous over the entire seam thickness.

The goal of this study is the determine the influence of the heat input on the thermal cycles, the hardness and the Charpy impact toughness of the welded joints over the entire depth. Previous studies showed that the Charpy impact toughness for single-pass HLAW 25 mm thick plates made of S355J2 is decreased up to 60 % in the root, the so-called laser-dominated zone as reported by Üstündag et al., 2019. Therefore, hybrid laser-arc welded specimens with electromagnetic weld pool support were conducted, to eliminate the gravity drop-out with a contactless bath support and to extend the process window to find an optimal range of the welding parameters, where the required mechanical properties can be reached.

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 in pulse mode with a 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 set to 0.5 m min^{-1} and 0.9 m min^{-1} so that the heat input was changed from 1.8 kJ mm^{-1} and 3.2 kJ mm^{-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 2.5 kW ± 100 W. The temperature measurements during welding were performed with help of two two-color pyrometers, which were focused on two collimators with a numerical aperture (NA) of 0.25 and for wavelengths of 1050 nm to 1600 nm. One optical fibre with a core diameter of 550 µm, NA of 0.22 for wavelengths of 400 nm to 2200 nm were fixed each to the collimator. The optical fibers were put in the material, which were prefabricated with holes, to measure the cooling time during welding in the material middle and the root part. Fig. 2 demonstrates the experimental setup of a HLAW welding process with electromagnetic weld pool support.

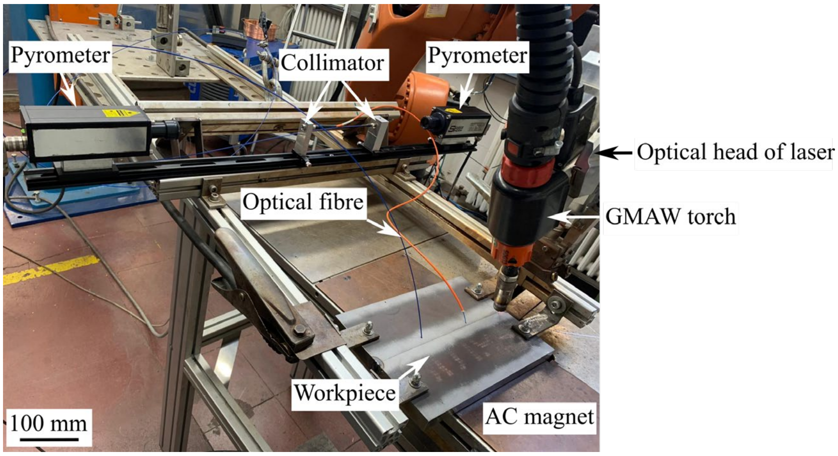

Fig. 2. Experimental setup during HLAW of 25 mm structural steel plate with electromagnetic weld pool support and measurement of the cooling time with two-color pyrometer

For the tests, structural steel S355J2 with a material thickness of 25 mm was used. All welds were butt-joint welded in a single-pass. G3Ni1 according to EN ISO 14341 with a diameter of 1.2 mm was used as filler wire. 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.

The samples were welded with two different welding parameters and resulting different heat inputs to evaluate the influence of the heat input on the mechanical properties. The welding parameters were selected as follows:

Table 2. Welding parameters

Case	Welding speed in m min^{-1}	Laser power in kW	Wire feed speed in m min^{-1}	focal position in mm	AC frequency in Hz	AC power in kW	Heat input in kJ mm^{-1}
Case 1	0.5	18.1	10	-7	1200	2.4	3.2
Case 2	0.9	20.4				2.6	2

3. Results & discussion

Plates with a thickness of 25 mm in square groove butt joint configuration could be welded in a single-pass without sagging and gravity drop-out. With an AC power of 2.5 kW ± 100 W 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 penetrated welds of 25 mm thick structural steel S355J2. According to EN ISO 12932, which defines the quality levels for imperfections for HLAW of steels, the welded 25 mm thick plates can be classified in the highest evaluation group B related to the seam root quality. The welded seams and cross-sections are shown in Fig. 3. It is evident, that the root is ideally compensated over the entire seam length. The width of the fusion zone and heat-affected-zone increases with increasing heat input as expected.

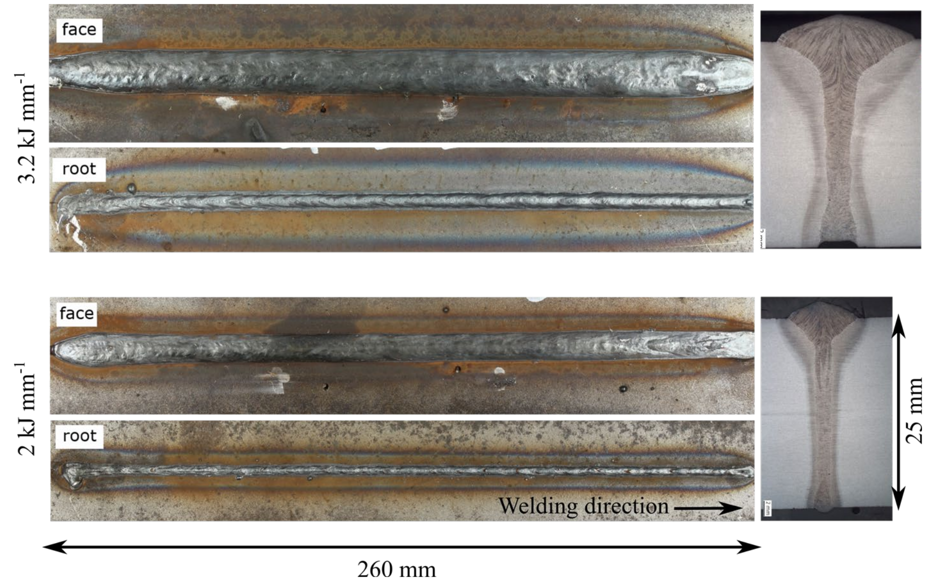

Fig. 3. The face and the root of the single-pass hybrid laser arc welded 25 mm thick joints with electromagnetic weld pool support technique: Case 1 (top); Case 2 (bottom).

Fig. 4 shows the X-ray images of the welded samples. No internal defects such as pores and cracks could be detected in the seams. The holes for the temperature measurements can be clearly identified.

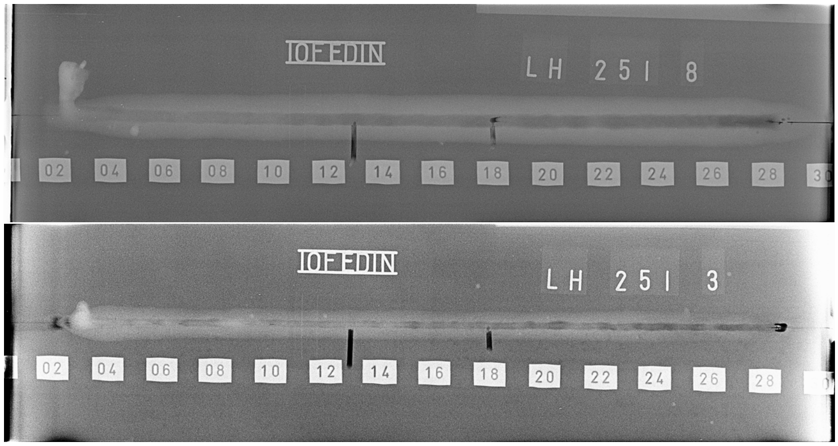

Fig. 4. X-ray images of the single-pass HLAW samples: Case 1 (top); Case 2 (bottom).

The cooling times from 800 °C to 500 °C, the so-called $t_{8/5}$-time, were measured on the top of the workpiece, in the middle with a horizontal distance of 2 mm to the edge and in the root with a distance of 2 mm each to the edge end to the bottom of the workpiece. The $t_{8/5}$-time for the Case 1 with the higher heat input is decreased from 19.3 s on the top to 15.8 s and 14.1 s in the middle and the top, respectively. It can be recognized that the cooling time decreases over the thickness. The additional heat input from the arc welding process has a low impact to the root, which can be limitational factor for single-pass HLAW of thick plates. Nevertheless, the heat balance over the thickness is more uniform for lower welding speeds in comparison to the welds with higher welding speeds and resulting lower heat inputs, such as in Case 2. The measured $t_{8/5}$-times for Case 2 were 9.2 s in the top, 8 s in the middle and 3.2 s in the root part. It can be recognized that the cooling time is decreased up to 65 % in the root (laser-dominated zone) in respect to the colling time on the top side (arc-dominated zone). Exemplarily, the course of the $t_{8/5}$-times for Case 2 are shown in Fig. 5.

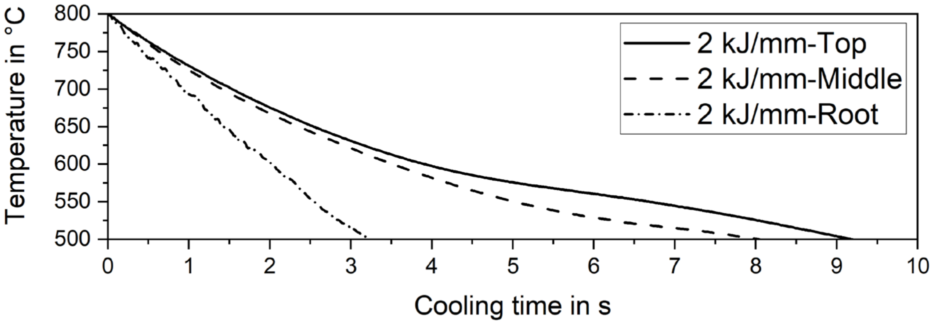

Fig. 5. Measured $t_{8/5}$-times via pyrometer and optical fibre on the top, the middle and the root for Case 2.

Charpy impact specimens with undersized dimensions of 10 mm x 7.5 mm x 55 mm were extracted in three different levels of the single-pass welded samples. The tests were carried out at a testing temperature of -20 °C. The average Charpy impact strength on the top was 49 J ± 4 J, for Case 1. The impact strength decreases to 31 J ± 21 J in the middle and 21 J ± 7 J in the root respectively. The Charpy impact toughness in the root is 35 J cm^{-2} ± 12 J cm^{-2}. The minimum requirement of the Charpy impact toughness for S355J2 of 34 J cm^{-2} was not reached for some Charpy impact samples tested, in Case 1. This is due to the fact, that the $t_{8/5}$-time was too high and there was no effect in the root of the additional filler wire due to the inhomogeneous distribution of it in contrast to the top and the middle. With decreasing heat input in Case 2 the Charpy impact strength increases to 51 J ± 1 J in the top, 88 J ± 49 J in the middle part and 123 J ± 66 J in the root part, respectively and all samples tested corresponds to the minimum requirements of 27 J for welded S355J2 samples. A high heat input and high cooling time is not recommended for welding of fine-grained steels such as S355J2, due to the grain coarsening. If in addition, there is no influence through the filler wire such as in Case 1 (bottom) the requirements regarding the Charpy impact toughness cannot be fulfilled. Table 3 shows the results of the Charpy impact tests. Since, the samples tested were undersized, the impact toughness is also shown in the Table 3. Exemplarily, one of each Charpy impact sample tested with a high impact toughness with a ductile fracture and low impact toughness with a brittle fracture are shown in Fig. 6.

Table 3. Results of the Charpy impact testing

Case	Heat input in kJ mm^{-1}	$t_{8/5}$-time top in s	KV top in J	αk top in J cm^{-2}	$t_{8/5}$-time middle in s	KV middle in J	αk middle in J cm^{-2}	$t_{8/5}$-time root in s	KV root in J	αk root in J cm^{-2}
1	3.2	19.3	49 ± 4	82 ± 7	15.8	31 ± 12	52 ± 20	14.1	21 ± 7	35 ± 12
2	2	9.2	51 ± 1	85 ± 2	8	88 ± 49	147 ± 82	3.2	123 ± 66	205 ± 110

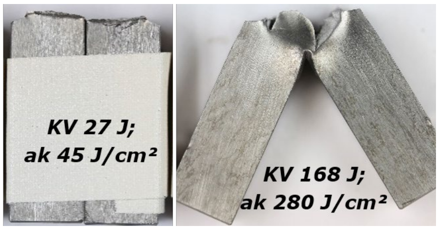

Fig. 6. Charpy impact samples tested: brittle fracture (left) and ductile fracture (right).

4. Conclusion

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 welds carried out in this study can be classified in the highest evaluation group B according to EN ISO 12932 in regard to the external and internal weld imperfections. In addition, the influence of the welding parameters on the heat input, the cooling time and the Charpy impact toughness was discussed. It could be recognized that a high heat input results in deterioration of the impact toughness especially in the root part. Reasons for that are the grain coarsening at the high cooling times, the so-called $t_{8/5}$-time. The samples tested fulfill the minimum requirements regarding the Charpy impact toughness due to the effect of the additional filler wire (Case 1). For lower heat inputs such as in Case 2, the impact toughness of the welds fulfills the minimum requirements of 27 J and 34 J cm^{-2} in all depths. It could be shown that the impact strength can vary over the entire weld depth. This phenomenon may depend on different factors such as the cooling time, the grain size distribution and the influence of the additional filler wire. A cooling time of approx. 3 s is recommended for HLAW of the studied structural steel made of S355J2.

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