Visualization of the molten pool of the laser beam submerged arc hybrid welding process

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Abstract

Submerged arc welding is currently the predominant industrial welding process for joining various steel grades in the plate thickness range of about 40 mm. A high energy input and the associated component distortion are unavoidable due to the high number of welding layers. By combining the conventional submerged arc welding process with the laser beam welding process to form a common hybrid welding process, this welding task can be mastered in only two welding layers by means of layer-counter-layer technology. This considerably reduces the welding time and thermally induced component distortion to a minimum due to the symmetrical energy input. A characteristic feature of a hybrid welding process is the formation of a common weld pool. In previous studies, the mixing of the molten pool has already been proven using chemical analysis methods. In the context of this paper, the shaping of the hybrid weld pool is also discussed. The molten material is expelled out of the joining zone by means of a gas pressure surge. Subsequently, a light section sensor was used to scan this area and produce a three-dimensional image from the formerly molten weld seam area. This shows that a single contiguous melt pool is produced. Finally, the first one-sided welds with full penetration and backing will be presented and discussed.

Keywords Laser beam welding · Submerged arc welding · Hybrid welding · Thick plate welding

1 Introduction/motivation

Welding structural steel in the field of large plate thicknesses using conventional welding technology is a time-consuming joining task. In the field of wind power plant construction or pipe and pipeline production, such steel grades are joined in the plate thickness range of 40 mm by means of arc welding [1, 2]. The workpieces are prepared with a double-V weld seam preparation, fixed to each other by means of gas metal arc (GMA) welding process and then completely welded by means of submerged arc (SA) welding process. Depending on

the plate thickness, numerous welding layers are necessary [3, 4]. Wage costs and filler metal costs are high. In practice, beam welding processes such as laser beam (LB) or electron beam (EB) welding are often not suitable for accomplishing this joining task due to the required accuracy in weld seam preparation (joint gap, offset). The combination of laser beam and GMA welding process to a common hybrid process shifts the limit of the required tolerances so that also defined joining gaps can be welded [5, 6]. Various studies have shown that the joining of steel plates with a plate thickness of up to 20 mm [7] and even 25 mm [8] can be achieved in only one layer. However, pores prove to be problematic. This weld seam irregularity/error can be observed especially for large weld penetration depths. Due to its high aspect ratio, the molten pool solidifies faster than the gas bubbles which can escape from the depth via the weld surface [9, 10].

Against the background of increasing the solidification interval of the molten pool and thus reducing the porosity, the GMA process was substituted by a SA process. In 2004, initial efforts were made to create a hybrid welding process, submerged arc laser beam hybrid welding (SA-LAHW), from a SA welding process and a CO₂ laser beam [11]. However, the process stability and weld

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Fig. 1 EDX-analysis along the depth of the weld seam (wt.%); $D_{LA} = 24$ mm (a); $D_{LA} = 15$ mm (b) [18]

quality are described as rather low [12, 13]. In later work, the CO_2 laser beam source was replaced by a disk laser and the process stability was drastically increased. The joining of plates with a thickness of 36 mm in layer-counter-layer technology was made possible [14]. However, significantly different weld seam properties were determined over the depth of the weld seam. For example, it was shown that the upper SA dominated weld area has a notched bar impact strength of about only 90 J (Charpy-V; -20°C) while in the LB dominated weld area 220 J (Charpy-V; -20°C) are present [15]. Further investigations have shown that SA-LAHW enables the joining of plate thicknesses of up to 50 mm by using the layer-counter-layer technique [16]. Furthermore, the process stability was increased by adjusting the laser beam to an angle of 15° to the workpiece perpendicular. In addition,

it could be proven that during welding with a process distance (D_{LA}) of 15 mm, alloying elements located exclusively in the filler material are located in the root area of the weld seam, Fig. 1 [17, 18].

Consequently, one common weld pool was formed (characteristic property of a hybrid welding process) and not two melt pools separated by a solidified phase (characteristic property of a serial welding process).

2 Welding setup

The laser beam running forward in the welding direction has an angle of 15° to the workpiece perpendicular in a trailing position. The SA torch has an angle of 5° to the workpiece perpendicular directed away from the weld bead. Between the

Fig. 2 Process zone, schematic (a); process zone, CAD-Model (b); hybrid welding head (c)

Table 1 Metallurgical composition basic material and wire electrode (wt.%; balance: iron)

	Designation	C (%)	Si (%)	Mn (%)	P (%)	Cr (%)	Ni (%)	Cu (%)
Basic material	S355	0.033	0.33	1.52	0.009	0.15	0.013	0.017
Wire electrode	T3Ni1	0.02	0.4	1.9	/	/	0.8	/

two welding processes, there is a separating plate which has the objective of separating the welding flux required for the submerged arc welding process from the effective area of the laser beam. During the welding tests, the process distance (D_{LA}) is varied between 13 and 19 mm. Figure 2a) schematically shows a section through the process zone. Figure 2 also shows both (a) CAD-model of the process zone (b) and the real hybrid welding head (c).

The travel speed for the most welding tests is 0.6 m/min. A wire feed speed of 2.1 m/min is selected in order to achieve a sufficient filling level. The focus position is 8 mm underfocused.

A disk laser with a maximum output power of 16 kW is used as the laser beam source (TruDisk 16,002; Trumpf; beam quality: 8 mm*mrad). With the used optical setup used and the used optical fibre (diameter: 300 μ m), a calculated spot diameter of 0.6 mm is achieved. The laser beam optic used (YW52; Precitec) offers the possibility of one-dimensional deflection of the laser beam across to the weld joint. If the welding tests presented in this paper were performed with an oscillating laser beam, different deflection amplitudes at a constant frequency of 100 Hz were preset.

The diameter of the wire electrode is 4 mm. The welding flux used has a degree of basicity by Boniszewski of 3.2. The base material is S355 with a plate thickness of 40 mm. The joining partners are provided with a double-Y weld seam preparation (depth of root face: 24 mm; total opening angle 70°). The metallurgical composition of the base material and the wire electrode is listed in Table 1.

The liquid molten pool is expelled out of the joining zone by four nozzles. One nozzle is located in the welding direction in front of the separating plate - in the area of the LB process - and three further nozzles in the welding direction behind the separating plate - in the area of the submerged arc welding process. The angle of the nozzles is 50° to the workpiece

perpendicular. The four nozzles use nitrogen at a pressure of 50 bars for a period of 0.5 s while simultaneously switching off the laser beam and the submerged arc welding process, to expel the melt from the joining zone.

After the molten material has been expelled out of the joining zone, the negative image of the weld is scanned line by line with a light section sensor (DIGI-I/S by Servorobot; 104 Hz). Using the corresponding software, a 3-dimensional image of the expelled former molten area can be created in the following.

In this work, welding tests with different process distances are carried out and immediately, at the end of the process, the still liquid molten pool is expelled out of the joining zone. The aim of this is to further substantiate and visually portray the results already presented in the state-of-the-art regarding the shaping of a hybrid melt pool. In addition, the SA-LAHW process will be used for the first time for full penetration welding with and without backing.

3 Results/discussion

On the basis of the state-of-the-art knowledge regarding welding parameters which lead to a hybrid welding process, a series of tests was carried out which describes the transition from a serial process to a hybrid welding process. For the welding tests which aim to visualise the formation of the molten pool at different process distances, a laser beam power of 16 kW and an oscillation of the laser beam of 1.5 mm across to the weld joint are preset. For the full penetration welding trials with and without backing, different amplitudes for the laser beam oscillation were selected. Table 2 summarizes the most important preset welding parameters for the respective welding test.

Table 2 Welding parameters

Welding trial(#)	Welding speed (m/min)	Laser power (kW)	Process distance (mm)	Oscillation amplitude (mm)	Wire feed rate (m/min)
1	0.6	16	19	1.5	2.1
2	0.6	16	17	1.5	2.1
3	0.6	16	15	1.5	2.1
4	0.6	16	13	1.5	2.1
5	0.6	16	15	1.0	2.3
6	0.5	16	15	0.7	1.9

Fig. 3 Macrosections; #1 (left); #2 (middle); and #3 (right)

3.1 Forming of the melt pool at different process distances

In a first series of tests, the process distance was successively reduced from 19 to 15 mm with otherwise unchanged welding parameters. The associated macrosections are summarized in the figure below, Fig. 3.

Number 1 has a welding depth of 15.7 mm. Two clearly separated weld seam areas can be identified - the upper SA-dominated weld seam area and the lower LB-dominated weld seam area. These two areas are separated by the direction of solidification of the dendrites. In addition, there is no optical uniform geometric transition between the two areas. In

addition, a small pore is visible. Number 2 has a welding depth of 18.5 mm, increased by about 3 mm. It can also be seen that the penetration depth of the SA-dominated weld seam area also extends 2.5 mm deeper into the interior of the material. The geometric transition between the two areas is also more uniform. Number 3 has a welding depth of 21.5 mm. This corresponds to an increase of the welding depth of more than 35% compared with the sample #1, achieved by reducing the process distance. Likewise, no sharp transition from the LB- to the SA-dominated weld seam area can be detected. Furthermore, it is noticeable that the lower LB-dominated weld area has significantly widened compared with the samples #1 and #2. Thus, a constant increase of the weld penetration depth can be observed while reducing the process distance with otherwise unchanged welding parameters. Likewise, the SA-dominated weld seam area extends into ever deeper weld seam regions and an optically uniform transition is achieved.

Using the technique described in the “[Welding setup](#)” section, the liquid molten pool was expelled out of the joining

Fig. 4 Longitudinal macrosections; #1 (top); #2 (middle); and #3 (bottom)

Fig. 5 3D-model; #2 (top); #3 (bottom)

Fig. 6 3D-model (left); longitudinal macrosection (right); #4

zone for these welding tests. Subsequently, longitudinal sections of these areas were made, Fig. 4.

In weld seam #1, the upper SA-dominated weld seam area is clearly separated from the lower LB-dominated area. The penetration, as a result of the SA welding process, is about 9.3 mm. Below, a sharp dividing line can be seen and the LB dominated weld area is adjacent. The subsequent SA welding process has only remelted the weld produced by the laser beam. Furthermore, a large number of pores and blow-holes can be seen in the lower weld area.

For samples #2 and #3, a uniform transition from the following SA process to the preceding LB process is always visible. Furthermore, no pores can be detected. The SA process reaches the area melted by the laser beam before it solidifies. The effective areas of both processes increasingly coincide in a common process zone. Both melting baths are mixed and alloying elements introduced by the filler material are transported into the deep LB-dominated weld seam areas, as has already been proven in [18] by chemical analysis methods.

In addition, the areas from which the liquid molten pool was expelled were scanned with a light section sensor, and a 3D-model of the molten area at a certain point in time was generated from the data, Fig. 5.

It can be clearly seen that the contour of the 3D-models has a high correspondence with the real longitudinal grinding, see Fig. 4. The scanning of the area from which the melt was expelled is therefore a suitable method for recording the molten area so that the time-consuming creation of longitudinal sections of 100 mm can be dispensed with.

In a further welding test, the process distance was further reduced to 13 mm. Figure 6 shows the corresponding longitudinal section and 3D-model of the molten area.

Both the longitudinal section and the 3D-model show an almost ideal transition from the area melted by the laser beam to the area melted by the submerged arc process. The welding depth is approximately 22 mm, unchanged from the tests #2 and #3.

A closer look at the 3D-models reveals changes in the LB-dominated weld seam area, Fig. 7.

In test #2, it can be observed that the LB-dominated weld seam area from X-position 20 mm to about X-position 50 mm falls to a depth of about 14 mm (gradient is about 25%). Then, the LB-dominated welding depth remains at a constant depth for a few millimetres and then drops steeply to the deepest point. In test #3, the LB-dominated weld area drops from the X-position 30 to the X-position 50 mm to a depth of 17 mm

Fig. 7 3D-models; LB-dominated weld seam area; #2 (top); #3 (middle); #4 (bottom)

Fig. 8 One-sided welding; no backing; #5

(gradient is about 45%). Then, a plateau of a few millimetres is formed again until the welding depth drops steeply to the lowest point. In test #4, the LB-dominated weld seam area drops uniformly from the X-position of 30 mm to the lowest point. No plateau is formed. The gradient is about 45%.

3.2 Full penetration welding

Up to now, SA-LAHW processes have only been carried out by using layer-counter-layer welding. If full penetration welding is carried out, the supporting effect of the surrounding solid material is eliminated. It is expected that molten material on the root side will simply fall out of the weld seam. Consequently, one-sided full penetration welding tests were carried out on a plate thickness of 22 mm - with an unchanged weld seam preparation - and with and without backing. For the first welding test, the parameter setting of #3 was set (D_{LA} : 15 mm) and no backing was used. Figure 8 shows the macrosection associated with the welding result.

Fig. 9 One-sided welding; backing; #6

It can be seen that a complete penetration of the workpiece has taken place. Sporadically, however, parts of the molten material have fallen out of the weld on the root side. This also means that the welding process can be described as highly uneven. Furthermore, the geometry of the weld seam has changed considerably compared with #3. Whereas for #3, the LB- and the SA-dominated weld seam areas merge optically uniformly into one another, for the one-side weld shown here, made with the same welding parameters, the weld seam areas separated from one another are clearly visible. This indicated that the LB-dominated weld area has already solidified before the submerged arc welding process reaches it. It can be assumed that the solidification interval of the LB-dominated weld area was significantly shortened due to the precipitated weld metal.

In addition, welds were carried out with various backings. Different variants of ceramic and metallic backing bars were tested. In the course of some welding tests, a copper bar with a semi-circular groove of 3 mm diameter proved to be suitable. The macrosections below, Fig. 9, were produced with only slightly different welding parameters compared with the previously discussed one-sided welding. The copper bar was used as backing; the welding feed rate was reduced to 0.5 m/min, and the wire feed rate was adjusted accordingly to 1.9 m/min. The amplitude of the laser beam oscillation was preset to 0.7 mm.

The copper bar efficiently prevents the molten material from falling out. The groove milled into the copper bar forces the root of the weld seam into the geometric shape that can be recognized in the macrosection. Furthermore, a slight weld metal overflow can be detected in the area of the weld root. The transition from the LB- to the SA-dominated weld seam area is uniform as expected.

4 Summary/outlook

In this work, laser beam submerged arc hybrid welds with beam oscillation and at different process distances were presented. Immediately after completion of the welding process, the molten material was expelled out of the joining zone. Later, 3D-models of the weld seam could be derived by means of a light section sensor and verified on the basis of the corresponding longitudinal sections. Thus, it could be shown that at process distances of 19 mm and 17 mm, both welding processes are already working in one process zone, but the transition is not yet completely uniform. As from a process distance of 15 mm and less, both processes merge uniformly.

In addition, one-sided welds were carried out with complete penetration. Without backing, weld seam of sufficient quality could not be produced. Due to the root-side backing of the weld seam by means of a copper bar, weld seams could be produced which had only slight weld metal overflow.

Further experiments aim at modifying the geometric shape of the groove in the copper bar. In this way, a geometrically more notch-favourable shape of the welding root is achieved. Furthermore, different oscillation amplitudes and welding speeds are tested in order to achieve one-sided welds with full penetration and a constantly high weld quality.

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