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Influence of the laser position in laser-assisted WAAM process on weld bead shape and surface properties

Kai Biester[a,*], Marius Lammers[a], Jörg Hermsdorf[a], Stefan Kaierle[a,b]

[a]*Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany*
[b]*Leibniz University Hannover, Institute of Transport and Automation Technology, An der Universität 2, 30823 Garbsen, Germany*

* Corresponding author. Tel.: +49 511 2788-378; fax: +49 511 2788-100. *E-mail address:* k.biester@lzh.de

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Abstract

The lateral use of the laser in laser-assisted WAAM processes, resulting in a directional dependence, can influence the bead shape and the bead surface. The influence of the laser position on the weld bead is investigated. Beads with different laser positions are applied and the height and width as well as the waviness of the beads are evaluated. In addition, claddings are welded and the waviness is measured. The waviness along the beads ranges from 8.77 to 34.66 µm, and no significant correlation with the welding direction could be determined. For the bead shape, the differences in height range from 3.54 to 3.90 mm and in width from 8.20 to 8.89 mm. Based on the results, a dependence on the laser position for surface properties and weld bead shape becomes clear.

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1. Introduction

Wire Arc Additive Manufacturing (WAAM) is a commonly used, economical process for creating, cladding and repairing three-dimensional metal components. In WAAM processes, the wire is in most cases coaxially fed into the process zone, from which a directional independence of the welding process is derived. The use of laser radiation can improve the process speed and the surface properties of the weld bead. In addition, the application rate can be increased. The laser is arranged laterally, resulting in a directional dependence. This dependence leads to the investigation of the influence of the position of the laser spot in the process on the weld bead geometry and the surface properties.

2. State-of-the-art

Steen [1] was the first to combine a laser beam and a welding arc with the aim of increasing the power of a Tungsten Inert Gas (TIG) process with low-power CO_2 laser radiation. It was found that synergy effects occur when the two heat sources are combined. He determined that the laser beam was capable of stabilizing the TIG arc and that the feed rate for penetration welds could be increased. These results provided the basis for numerous experimental and theoretical works to explain these effects.

Further research on the interaction of CO_2 laser radiation with a plasma arc and steel materials was carried out by Cui [2]. It was found that a plasma was induced by the laser radiation, which focused the arc. In addition, there was a decrease in the arc voltage.

Investigations by Seyffarth and Krivtsun [3] with a CO_2 laser and a gas metal arc welding (GMAW) process on aluminum showed that the laser radiation increased the temperature below or inside the arc. This effect was attributed to a higher degree of ionization and thus improved conductivity.

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Investigations by Schnick et al. [4] could not confirm this effect. Experimental investigations and simulations, on the other hand, showed a decrease in temperature.

Further effects that were investigated are mentioned in Kling et al. [5]. These effects are the photoelectric effect, the inverse bremsstrahlung, the optogalvanic effect, the laser induced plasma and the laser induced radiation. The dominating mechanisms could be identified depending on the operating mode of the laser. In pulsed mode, the laser induced plasma dominates. Due to the high energy, metal particles are vaporized, which leads to an improved conductivity of the arc. In the continuous wave mode, the optogalvanic effect was identified as dominant.

To date, there is no definitive clarity on the dominant effect for stabilization, also due to the fact that a wide variety of process variants of laser and welding process combinations exist.

Barroi et al. [6] stabilized the arc in a GMAW process by supporting the arc with laser radiation from a diode laser emitting a maximum power of 500 W. In the setup, the laser radiation was perpendicular to the substrate and the welding torch was arranged at an angle of 30° to the laser radiation in the pushing direction. A hardfacing material (1.8401) was used for the investigation of the generated claddings. By supporting the process with laser radiation, it was possible to increase the welding speed and thus minimize the distortion of the component [7].

In a later study, Barroi et al. created a 3D structure with a continuous weld bead using the laser-assisted WAAM (LA WAAM) process. The material used was a mild steel in the form of a G3Si1 welding wire. In this process, the welding torch is oriented perpendicular to the substrate and the laser radiation was introduced laterally and directed to the base of the arc. A diode laser with a wavelength of 1025 nm with a power of 425 W was used. The structure could be fabricated with a good surface roughness, a low number of shape defects and no pores inside. [8]

Näsström, Brueckner and Kaplan have found higher geometric accuracy and better melt pool stability in structures they have fabricated using a hybrid process that uses energy for process control from the laser beam as well as from the arc to melt the electrode and substrate, compared to the WAAM process. In the experiments, the welding torch was perpendicular to the substrate and the laser beam was at a 30° angle to the torch. They studied the influence of the pushing and the dragging laser arrangement on the weld bead. The structures were created using a 316L stainless steel wire. The laser beam source was a fiber laser with a wavelength of 1070 ± 5 nm and a maximum power of 3.5 kW. The pushing laser beam leads to a topological improvement in the capabilities of the WAAM process. The dragging laser beam leads to a deteriorated topological accuracy. However, in combination with the cold metal transfer process, a synergistic effect occurs which can be used for a higher deposition rate. [9]

In addition, there are other studies dealing with the LA WAAM process and the use of materials such as Ti-6Al-4 V, aluminum-zinc alloys such as 2219 and 2319, or AlMg6 [10,11,12].

The investigations presented have shown that different approaches to the process are being pursued. On the one hand with relatively low laser power at approx. 400 W with the LA WAAM process and on the other hand with a laser power of 3.5 kW, i.e. a hybrid process. The dependence of the bead on the delivery direction of the laser at high laser power has already been demonstrated for the dragging and pushing positions. For powers in the range of 400 W and for the lateral positions, no results are known. For this reason, the aim of this study is to investigate the directional dependence for lateral delivery of the laser radiation in the LA WAAM process. For this purpose, the following question is addressed:

How does the delivery direction of the laser radiation influence the weld bead in terms of

- height
- width
- waviness of the surface in the welding direction?

3. Materials and methods

In this paper, the influence of the position of the laser spot in a LA WAAM process on the bead shape and surface properties of weld beads is investigated. Beads with the laser spot at eight different positions are welded and the geometry is evaluated. In addition, the surface of a cladding is analyzed.

3.1. Experimental setup

The experiments are carried out with a TruDisk 16002 disk laser from TRUMPF GmbH + Co. KG with a maximum power of 16 kW and a wavelength of 1070 nm in continuous wave mode. The optical beam path consists of a fiber with a diameter of 300 µm, a collimator with a focal length of 200 mm and a focusing lens with a focal length of 300 mm. An alpha Q 552 RC PULS from EWM AG is used as the welding power source. The setting for the process variant is the ColdArc process. The shielding gas coverage is ensured with a gas mixture of 82% argon and 18% CO_2. The welding process is performed with a wire with a diameter of 1.2 mm. An overview of the process parameters is provided in Table 1.

Table 1. Process parameters for the LA WAAM process

Process parameters	Unit	Values
Laser power	W	400
Welding speed	mm/min	250
Welding current	A	163
Wire feed rate	m/min	4.6
Welding voltage	V	16.6
Shielding gas flow rate	l/min	19
Stickout length	mm	10

The laser beam is arranged at an angle of 30° to the welding torch, which is aligned perpendicular to the substrate. The laser spot on the substrate surface has an elliptical shape due to the angle between the laser beam and the torch. The laser beam is positioned so that its center is on an axis with the center of the

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wire in the welding direction, so that the laser beam is tangent to the position of the wire (see Figure 1).

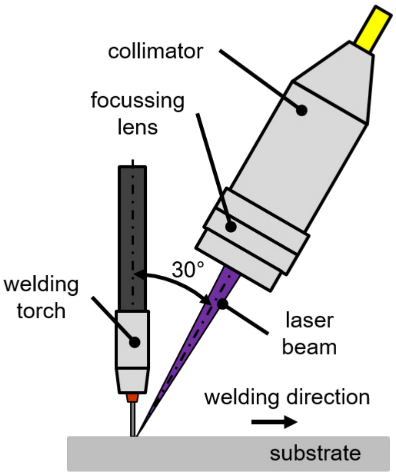

Fig. 1. Experimental arrangement of the laser beam and the welding torch.

3.2. Materials

For large-scale structures in maritime shipbuilding that are not exposed to direct sea atmosphere, low-alloy steel is often used for economic reasons. Therefore, the investigation is carried out using a structural steel substrate with a thickness of 15 mm made of S355J2 and G3Si1 as wire material coated with copper. The chemical compositions of the wire and the substrate material are given in Table 2.

Table 2. Chemical composition in wt.% of S355J2 and G3Si1

Element	S355J2 (1.0577)	G3Si1 (1.5125)
Fe	bal.	bal.
C	0.15 – 0.20	0.06 – 0.15
Si	< 0.30	0.80 – 1.15
Mn	< 1.60	1.40 – 1.85
S	< 0.025	-
Cu	< 0.015	< 0.50

3.3. Methods

For the study, weld beads with a length of 100 mm are welded in the directions 0° to 315° at 45° degree intervals as shown in Figure 2.

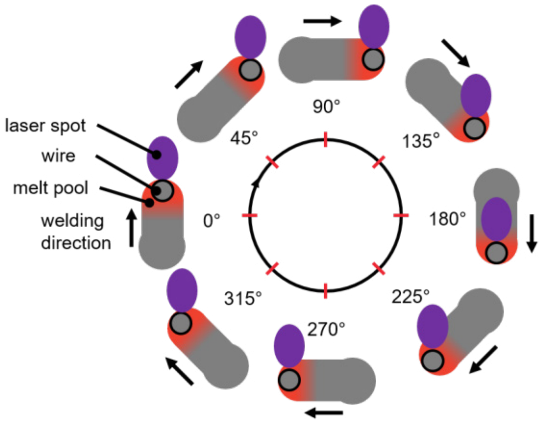

Fig. 2. Welding directions.

The figure shows the top view of the substrate and the position of the laser spot in relation to the wire and the melt pool. Before welding, the substrate is sandblasted and then cleaned with isopropanol. Three weld beads are applied for each welding direction. In addition, two claddings consisting of five adjacent circles are welded. The first cladding is welded with the start position at 0° and the second with the start position at 90°. The spacing of the beads of the cladding welded was 4,4 mm. The study was conducted on the basis of Design of Experiment with a randomized experimental design.

3.4. Analysis

For the evaluation, sections of the surface of the weld beads are measured with a VK-X 1100 laser scanning microscope from Keyence GmbH. Subsequently, the evaluation is carried out with the MultiFileAnalyzer software. Based on the data, the width and height of the respective beads can be determined. Likewise, the waviness along the bead can be determined with the software. The cutoff wavelength used to separate the roughness from the waviness is λ = 0.8 mm. Furthermore, the waviness of the claddings orthogonal to the welding direction is determined at the positions of the examined welding directions. A measured cladding is shown in Figure 3.

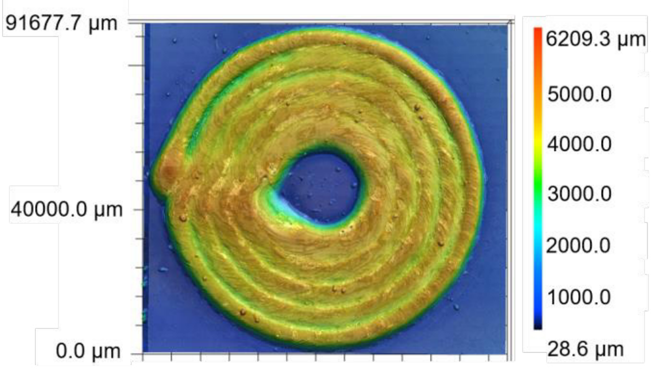

Fig. 3. Measurement data of the cladding with the start position at 0°.

4. Results and discussion

An example of the welded structures, bead and cladding are shown in Figure 4. The evaluation of the structures is presented below.

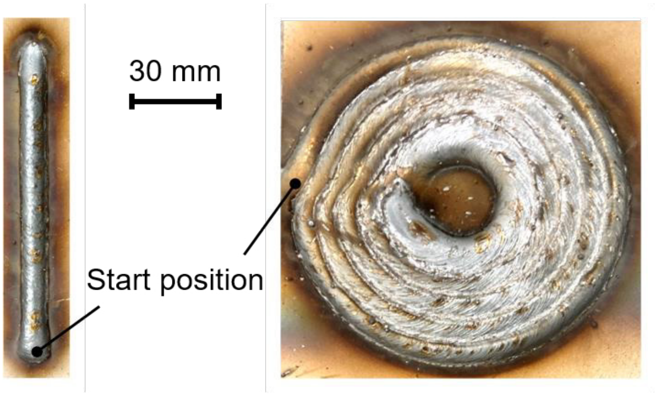

Fig. 4. Welded structures, weld bead in the welding direction 0° (left), cladding with start position at 0° (right)

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4.1. Single weld bead results

The height and width of each weld bead is measured at three positions at approximately the half of the travel distance based on the 3D measurement data. The mean values with the associated standard deviations of the nine determined measured values per welding direction, are plotted in a graph which is shown in Figure 5. The values for height were determined in a range from 3.46 to 3.90 mm. The highest bead was measured at a welding direction of 0° and the lowest at 315°. Width values were found to range from 8.12 to 8.89 mm, with the narrowest bead found at a weld direction of 270° and the widest at 45°. An ANOVA (Analysis of Variance) test was performed to verify the dependence of the height and width on the welding direction. For the analysis, a significance level of $\alpha = 0.05$ is used. The dependence of the height and also the width of the beads on the welding direction are significant with P values of 0.001 in each case.

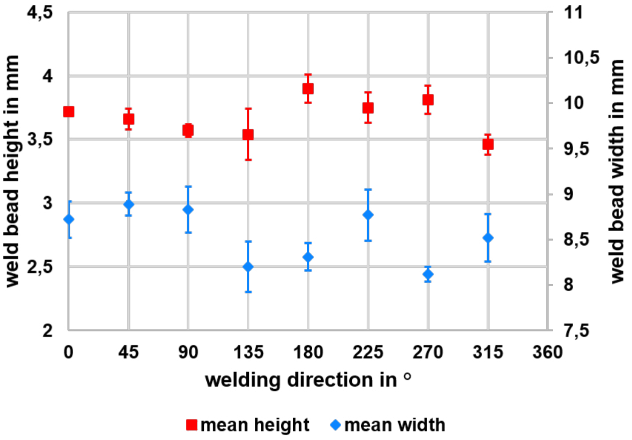

Fig. 5. Mean height and mean width of the weld beads welded in the different welding directions

A cross-section of a weld bead was made for each welding direction. These sections are shown in Figure 6. The cross-section shows the bead looking in the direction against the direction of welding.

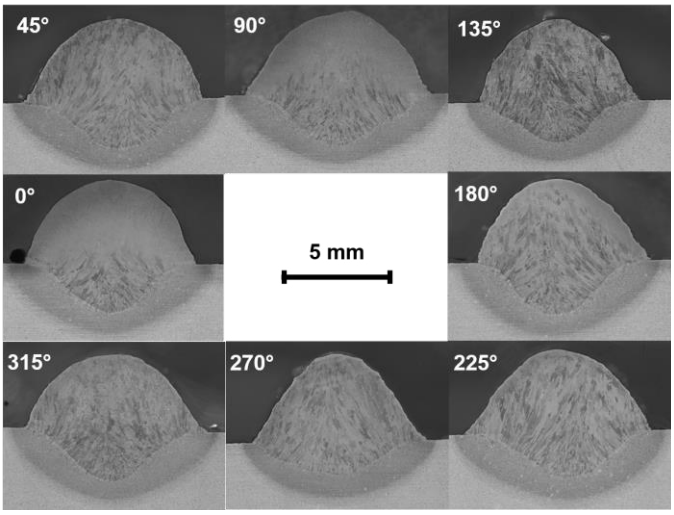

Fig. 6. Cross-sections of the welded beads at the different welding directions

It is noticeable that the shape of the bead differs depending on the direction. The beads at 0°, 90° and 270° are relatively uniform and have approximately equal flank angles, whereas the beads at 45°, 135°, 180°, 225° and 315° have different flank angles on the left and right side of the bead. The different flank angles can be explained in part by the fact that the laser radiation deflects the arc laterally, which causes the asymmetry.

The waviness Wa along the welded beads ranges from 8.77 to 34.66 µm. The graph of the mean values of the waviness is shown in Figure 7. The lowest waviness occurs at a welding direction of 315°. The largest waviness was measured at a welding direction of 180°. The ANOVA test with a P value of 0.134 shows that there is no significance in the dependence of the waviness on the welding direction.

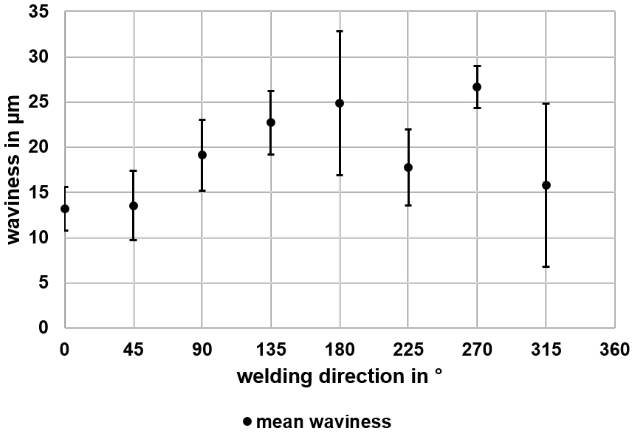

Fig. 7. Graph of the mean waviness of the single weld beads for the different welding directions

Figure 7 shows that the waviness along the weld bead increases steadily from the 0° direction to the 180° direction. From the 180° direction to the 315° direction, a trend of steady decrease can be seen, whereby the 270° direction with the highest waviness within the investigation does not correspond to the expectation for the single seams. The values similar to the 90° welding direction are expected. The greater waviness with increasing welding direction up to the 180° direction can be explained by the changing arrangement of the laser beam in relation to the weld bead. The laser radiation impinges on the welded bead and thus the stabilizing effect of the radiation on the arc is reduced or even prevented. For the welding direction 180°, the laser radiation impinges on the welded bead with an average height of 3.9 mm, which means that the laser radiation can no longer interact with the arc at the base point of the arc. In this case, the distance between the base of the arc and the point of impact of the radiation is too large. Figure 8 shows this symbolically for the welding directions 0° and 180°. Since for the welding directions 45°, 90° and 135° the radiation of the laser is partially shadowed by the welding bead, the stabilizing effect of the arc by the radiation probably occurs to a reduced extent. The same effect can be expected in reverse order from 180° to 315°.

Barroi et al. [8] applied a three-dimensional structure with a continuous seam using the laser-stabilizing GMAW process without reorienting the laser beam. No directional dependence on shape deviations or surface conditions was observed. The

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seam height was much lower compared to the beads created here, which leads to the assumption that the directional dependence is related to the weld bead height and the resulting influence on the stabilization of the arc.

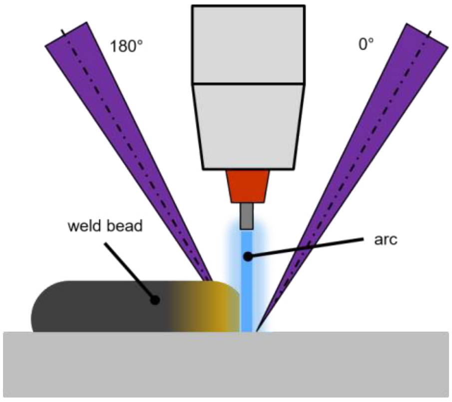

Fig. 8. Incident point of the laser beam and its distance from the base point of the arc for welding directions 180° (left laser beam) and 0° (right laser beam)

The waviness increases with increasing angle of the welding direction up to 180°, whereby the laser radiation hits the applied bead, resulting in less radiation reaching the process zone. This may result in a loss of energy in the process zone, which means that the temperature in the process is lower. This can lead to faster solidification of the melt zone, which results in higher waviness because the melt has less time to flow.

As the results of Seyffarth and Krivtsun [3] and Schnick et al. [4] show, the influence of the laser beam on the arc temperature has not been clearly clarified. As the arc temperature changes, so does the temperature that results on the workpiece. Due to these unclear conditions, no statement can be made about the influence of the temperature, which may be introduced or withdrawn by the laser radiation, on the formation of the weld beads in the present investigation. In addition, no conclusion can be drawn about temperature effects on the basis of the micrographs produced. The micrographs only provide an overview of the geometric characteristics of the weld beads and their connection to the substrate.

4.2. Claddings

The waviness Wa of the claddings are measured orthogonally to the welding direction, which is why the determined values are much higher than the previously determined values along the beads. The determined values at the starting points are not taken into account, which is why only one value is available for 0° and 90°. The values determined are shown in the graph in Figure 9.

The waviness of the claddings is in a range from 693 to 1,789 µm. It is noticeable that the values for the waviness for 0°, 90°, 180° and 270° are clearly below the values of the other directions. In addition, the lowest waviness is obtained for a welding direction of 270° with a value of Wa = 693 µm.

The waviness of the cladding depends significantly on the welding direction, with a P value of 0.008.

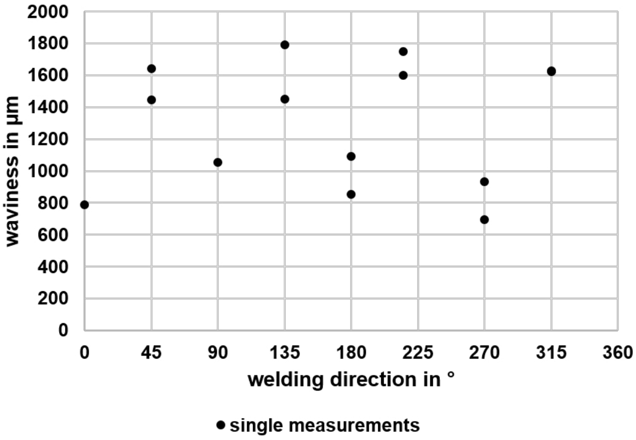

Fig. 9. Mean waviness of the claddings measured orthogonally to the welding direction

5. Conclusion

The welded beads show no significant correlation between the welding direction and the waviness along the beads. Due to the achieved seam heights of 3.46 to 3.9 mm, a part of the radiation is shielded for all welding directions except 0°. Here, an influence on the effect of stabilization is suspected, which becomes noticeable in increasing values of waviness with decreasing irradiation of the base point of the arc. For this reason, the influence of the seam height on the directional dependence must be investigated with a considerably increased sample size in further investigations.

For the claddings, the lowest waviness orthogonal to the welding direction was measured at a direction of 270°, with the next highest waviness found at 0°. The weld bead at 0° exhibits equal flank angles and the lowest waviness along the bead. From this, it can be concluded that the best surface properties can be achieved with the welding direction 0°, i.e. with a dragging laser position. The other welding directions have less good properties in terms of waviness or flank angles, resulting in deviation of the bead shape.

The laser position has a significant influence on the width and height of the bead. When looking at the average height values for the different welding directions, it is noticeable that a difference of up to 0.44 mm occurs. When this difference is added up during the welding of a few layers, the resulting deviation can already lead to the process becoming unstable. For this reason, the deviation in height during welding in different directions should be taken into account and eliminated or minimized by suitable measures. In order to create a geometry that meets the requirements for the shape and the surface properties, welding should be performed with the welding direction 0°. This results in the need to rotate the part, or turn the head, so that the laser beam is always oriented in a dragging position. Another approach is to adjust the process parameters. This approach can be investigated in further investigations. Another approach for investigation is to look at the temperature in the process zone and how it is affected by the laser radiation and the different welding positions.

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