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Influence on the bead geometry in Laser Metal Deposition with wire

Tizia Charlotte Weidemann[a], Mohammad Abuabiah [b,c,*] , Bahaa Shaqour[c], Robin Day[a], Thomas Bergs[a,d], Peter Plapper[b]

[a]*Process Technology, Fraunhofer Institute for Production Technology, Steinbachstraße 17, 52074 Aachen, Germany*
[b]*Department of Engineering, University of Luxembourg, 6, Rue-Kalergi, L-1359 Luxembourg, Luxembourg*
[c]*Mechatronics Engineering Department, Faculty of Engineering and Information Technology, An-Najah National University, P.O. Box 7, Nabulus, Palestine*
[d]*Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Campus-Boulevard 30, 52074 Aachen, Germany*

Abstract

Laser metal deposition with wire (LMD-w) is a promising additive manufacturing technology, which attracts interest due to the low waste of material, the flexible application possibilities along the production chain and the improved metallurgical properties compared to powder-based processes. However, the complex handling of the technology and the resulting low process stability inhibit the broad industrial application. In particular, the varying bead geometry prevents automation and series production. To improve the geometric accuracy, it is necessary to understand influencing parameters. For this purpose, a parameter study is carried out in the present work. Different combinations of laser power, wire feed rate, traverse speed and welding angle are set, and the deposited beads are evaluated in terms of height and width. A factorial design experiment with the Box-Behnken was used to analyse and understand the interaction of these parameters on the deposited beads.

Keywords: laser metal deposition with wire; bead geometry; parameter study

1. Introduction

Laser metal deposition with wire (LMD-w), also known as laser wire-feed metal additive manufacturing, is an additive manufacturing technology that utilizes a laser beam to melt a metallic wire as it is deposited onto a substrate. It involves the continuous feeding of wire material, such as metal alloy, into the laser beam's focal point. The heat generated by the laser causes the wire to melt, creating a melt pool between the wire and the substrate plate. Through the continuous flow of wire material into the melt pool, the wire is precisely deposited onto the target surface, see e.g., (Craeghs et al., 2010; Akbari et al., 2017; Abadi et al., 2023; Mbodj et al., 2023).

To provide a comprehensive understanding of the LMD-w technology, (Abuabiah *et al.*, 2023) emphasize the importance of key aspects of LMD-w, including parametric modelling, monitoring systems, control algorithms, and path-planning approaches. LMD-w offers several advantages over traditional manufacturing processes, it enables minimal material waste, provides versatile application possibilities, and exhibits improved metallurgical properties (Ding *et al.*, 2015; Xia *et al.*, 2020).

Despite these benefits, the broad industrial implementation of LMD-w faces challenges stemming from its complex nature and inherent process instability, particularly concerning the inconsistent bead geometry (Du *et al.*, 2019; Mbodj *et al.*, 2022; Roberts, Xia and Kennedy, 2022; Zhu *et al.*, 2022; Abadi *et al.*, 2023). To overcome this limitation and achieve higher geometric precision, extensive parameter studies have been conducted in recent years within the directed energy deposition (DED) domain. These studies aim to identify the key influencing parameters and optimize their combinations to enhance bead geometry control and stability, thereby facilitating automation and series production.

*Corresponding author. Tel.: 00352-661967207.
E-mail address: mohammad.abuabiah@uni.lu.

(Dinovitzer et al., 2019) investigate the impact of process parameters on TIG-based Wire Arc Additive Manufacturing (WAAM) using Hastelloy X welding wire and stainless-steel 304 plates as the substrate. The study employs the Taguchi method and ANOVA to analyze the effects of travel speed, wire feed rate, current, and argon flow rate on various responses, such as bead shape, size, roughness, oxidation levels, melt-through depth, and microstructure. Travel speed and current were identified as the most influential factors. Furthermore, the research explores different printing strategies involving multiple layers and concludes that there is no significant difference between printing layers in the same direction or alternating directions. (Huang et al., 2021) investigated the deposition of Al alloy 5A06 wire with a laser beam by producing single and multi-layered tracks. ANOVA analysis was used to determine the significance of the main process parameters (laser power, traverse speed, and wire feed rate) on the geometry characteristics of the deposited material. The study found that the wire feeding direction and angle had a significant effect on the weight and dimension of the deposited single tracks.

Furthermore, (Liu et al., 2022) examined the process parameters (laser power, scanning speed, wire feeding speed) and bead characteristics (width, height) using DOE and ANOVA. The study categorized bead types and analyzed wire transfer behaviors through high-speed camera footage. The results show that lower scanning speed resulted in coarser microstructure and decreased microhardness. (Moradi et al., 2021) explore parameters influences of powder direct laser metal deposition of Inconel 718 using a full factorial design. Laser speed, powder feed rate, and scanning strategies are studied as input variables, while geometrical dimensions, microhardness deviation, and wall stability are process responses. ANOVA is employed to analyze the impact of process parameters on response variations. Optimum process conditions are determined as a scanning speed of 2.5 mm/s, powder feed rate of 28.52 g/min, and unidirectional scanning pattern. While, (Ayed et al., 2021) highlight the significance of first-order process parameters in the laser-wire deposition: wire feed speed, travel speed, and laser power. Titanium deposits were achieved with power levels up to 5 kW and wire feed speeds of 5 m/min, ensuring process repeatability. Starting the deposits sequentially, with laser first and then wire feed, led to issues, including molten titanium drops forming at the wire's end and rising by capillarity, causing fusion with the contact tube. Laser powers above 3 kW resulted in contact tube melting due to beam reflection, preventing wire deposition.

On the other hand, (Mbodj et al., 2021) introduce a machine-learning regression algorithm to predict the layer geometry in LMD-w. The influence of deposition parameters on bead geometry is studied using a neural network. Findings show efficient prediction of bead height, width, and ratio, and examine the influence of laser power, wire-feed rate, and travel speed. Furthermore, a machine learning-based material design framework was also proposed by (Liu, Brice and Zhang, 2022), utilizing experimental data from LMD-w Ti-6Al-4V. The dataset covers various process variables and output characteristics, including bead quality, shape, and microstructures. Data-driven machine learning models capture the process-geometry-microstructure relations, visualized through a 3D contour map. Finally, (Zapata et al., 2022) focus on the development of coaxial LMD-w using both aluminum and stainless-steel wire materials. By employing regression analysis, the study investigates the influence of process parameters on bead height and width. The results show that a linear model is suitable for describing the correlation between the process parameters and the dimensions of the beads. Specifically, the energy per unit length and speed ratio proportion are identified as critical factors for achieving defect-free processes.

The mentioned literature provides valuable insights into the influence of various process parameters on bead geometry in LMD-w. However, a research gap still exists regarding the combined effects of laser power, wire feed rate, traverse speed, and welding angle on deposited beads. Existing studies primarily focus on individual or limited combinations of process parameters, with a limited investigation into the relationship between these parameters and critical bead characteristics like height and width. Addressing this gap, this manuscript builds upon previous research by investigating the influence of the aforementioned parameters on the bead geometry in LMD-w. Thus, this study aims to determine the relationship between these parameters and deposited bead characteristics. To achieve that, this research proposes a factorial design experiment with the Box-Behnken method, systematically varying and analysing parameter interactions. By considering a wide range of parameter combinations, a comprehensive insight into their combined effects on deposited bead geometry will be discussed. This research will contribute to understanding the LMD-w process and provide valuable information for optimizing parameters to achieve desired bead geometry in various applications of metal additive manufacturing.

The remaining sections of the paper are outlined as follows: Section 2 discusses the methodology and presents the experimental setup employed for the study. Section 3 is dedicated to presenting the results obtained from the experiments and a discussion of these findings. Finally, Section 4 offers a concise conclusion that emphasizes the key insights drawn from the study.

2. Materials and methods

Achieving a stable deposition process is crucial for successful welding operations. The consistency and uniformity of the deposited part's geometry play a vital role in ensuring reliable outcomes. In this study, our primary objective is to analyze the impact of various parameters on the bead geometry during Laser Metal Deposition with wire (LMD-w). To accomplish this goal, we conducted welding experiments, focusing on the deposition of single beads. During these experiments, we systematically altered the welding parameters for each bead and thoroughly examined their resulting geometry.

By carefully manipulating the parameters, we aimed to gain insights into their influence on the bead geometry. This investigation provides valuable knowledge about how different settings can affect the quality and consistency of the deposited material. Analyzing and understanding the relationship between these parameters and bead geometry is crucial for optimizing the LMD-w process and achieving desirable outcomes.

2.1. Selection of parameters

The selected parameters in this study were four parameters, namely, laser power (PWR), wire feed rate (Wf), traverse speed (Ts), and welding head angle (HA). Laser power, wire feed rate and traverse speed are common parameters which are often investigated because of their large effect on the process. The laser power directly impacts the heat input during the process and therefore affects the melt pool geometry and consequently the bead geometry. The wire feed rate and the traverse speed are strongly connected to the laser power, as no parameter can be changed without altering the other. The wire feed rate and the traverse speed determine the volume of the deposited wire hence affecting the bead geometry. Unlike the aforementioned parameters, the welding head angle or incident angle is almost not studied in LMD-w yet. The incident angle must be differentiated from the wire feeding angle. The latter describes the angle between the wire and the substrate plate, whereas the incident angle can be defined as the angle between the laser and the substrate plate, as shown in Figure 1. In the set-up used in this work, the laser and the wire cannot be rotated independently as they are mounted together in a welding head. So, by shifting the angle of the welding head the incident angle as well as the wire feeding angle is changed. Therefore, the angle will be called the welding head angle in the following. As the welding head angle impacts the heat flow it can be assumed that solidification and therefore the geometry can be controlled with it.

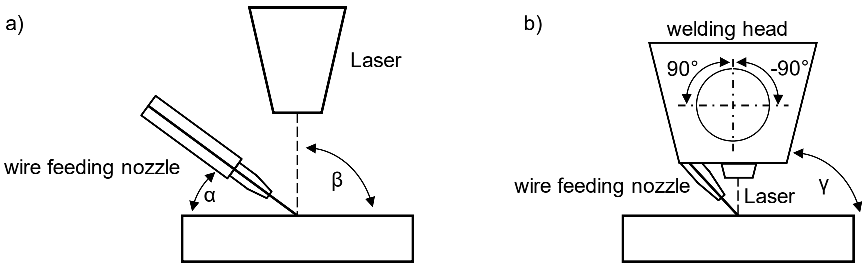

Fig. 1. (a) Definition of wire feeding angle α and incident angle β; (b) Experimental setup showing welding head angle γ.

2.2. Experimental design

The methodology employed in this study aimed to thoroughly investigate the effects of the four different parameters on the final product deposition. To achieve comprehensive results with a limited number of experiments, a factorial design experiment was chosen. This design is known for its efficiency in complex experimental setups, allowing researchers to assess multiple variables and their interactions simultaneously.

Specifically, the Box-Behnken design was adopted for this experiment. This design approach offers a two-level design with centre points, allowing for a balanced exploration of the parameter space. The centre points were run three times to ensure a more uniform estimate of the prediction variance across the entire design space. By incorporating centre points, it becomes possible to detect potential curvature in the response surface and assess the influence of interactions between the parameters.

To minimize the impact of unmeasured and uncontrolled disturbances on the system's response, the actual experiments were conducted in random order. This randomized order of experiments was achieved using the Fisher-Yates algorithm, ensuring that any potential biases or confounding effects were evenly distributed.

Since we are studying four parameters in this experiment, the factorial design employed yields a total of 27 experiments. This calculation considers the combinations of parameter settings across the two levels of each parameter, resulting in 16 factorial points. Additionally, the three runs of the centre point are included, bringing the total number of experiments to 27. By systematically varying the parameter settings in these experiments, we can effectively explore and analyse the individual effects of each parameter as well as their potential interactions on the final product deposition. This comprehensive approach allows for a thorough understanding of how each parameter contributes to the observed outcomes.

The general strategy for the determination of the parameter values is to choose the low, medium, and high values of normal operation. In this case, we use Inconel 718 as wire material, which gives a range from 1600 W to 2000 W for the laser power. As a medium value, 1800 W was chosen. The high and low values of the wire feed rate and the traverse speed were set to 1200 mm/min and 1600 mm/min with a medium value of 1400 mm/min. As a low value of the welding head angle, 0° was chosen. This corresponds to the usual experimental setup with no change in the angle. Since the effect of the welding head angle on the process is not known, it was decided to vary the angle only to a small extent. This ensured that the process still worked. The high value was set to 5° and the medium value to 2.5°.

Statistical analysis was conducted using Minitab 21.4. A response surface design of experiment analysis was used to set up the experiment. The software was used to set up a Box-Behnken DOE with a randomized experiment as shown in Table 1. After conducting the experiments and analysing the produced samples, the values of the bead height (H) and width (W) for each sample were then fed to the software. A full quadratic response surface regression analysis was performed on the values of height and width.

Table 1. Parameter list of the welding experiments.

Experiment	Order of Experiments	Input parameters				Output parameters	
		Laser Power (W)	Traverse speed (mm/min)	Wire feed rate (mm/min)	Head Angle (deg.)	Width (W) (mm)	Height (H) mm
1	5	1600	1200	1400	2.50	2.24	0.67
2	4	1600	1600	1400	2.50	2.24	0.65
3	16	2000	1200	1400	2.50	2.38	0.76
4	2	2000	1600	1400	2.50	2.22	0.67
5	10	1800	1400	1200	0.00	2.20	0.80
6	11	1800	1400	1200	5.00	2.20	0.77
7	12	1800	1400	1600	0.00	2.13	0.61
8	6	1800	1400	1600	5.00	2.19	0.73
9	19	1600	1400	1400	0.00	2.26	0.46
10	25	1600	1400	1400	5.00	2.30	0.60
11	18	2000	1400	1400	0.00	2.23	0.67
12	13	2000	1400	1400	5.00	2.44	0.82
13	17	1800	1200	1200	2.50	2.29	0.67
14	22	1800	1200	1600	2.50	2.28	0.84
15	15	1800	1600	1200	2.50	2.06	0.55
16	8	1800	1600	1600	2.50	2.66	0.77
17	9	1600	1400	1200	2.50	2.21	0.76
18	14	1600	1400	1600	2.50	2.64	0.64
19	21	2000	1400	1200	2.50	2.24	0.65
20	3	2000	1400	1600	2.50	2.54	0.73
21	24	1800	1200	1400	0.00	2.38	0.56
22	20	1800	1200	1400	5.00	2.20	0.84
23	27	1800	1600	1400	0.00	2.45	0.65
24	7	1800	1600	1400	5.00	2.48	0.81
25	1	1800	1400	1400	2.50	2.27	0.66
26	23	1800	1400	1400	2.50	2.41	0.67
27	26	1800	1400	1400	2.50	2.38	0.60

2.3. LMD-w Experiment Setup

The deposition experiments were carried out on a 6-axis industrial robot of the type IRB 6660 from ABB. The robot is equipped with a welding head, which was constructed at the Fraunhofer IPT. The welding head contains the optical system of the laser, the supply of the shielding gas, and the lateral wire feeding. The wire is positioned at an angle of 20° with respect to the optical axis. As wire feeder serves the Master-Feeder-System MFS-V3 from Abicor Binzel. The shielding gas is Argon, which is fed to the process through a nozzle next to the optical system. The diode laser LDF 4500-40 VGP from Laserline with 4500 W output power is used as a laser source.

2.4. Experimental Procedure

In this study, Inconel 718 wire material with a diameter of 1.2 mm was utilized. The beads were deposited on a substrate plate made of 1.0570 steel. Each parameter set involved the deposition of a single bead with a length of 6 cm. Figure 2.a provides an optical observation of multiple individual deposits generated by the LMD-w Laser, with a laser spot diameter set at 2.1 mm.

For the subsequent metallographic examination, the beads were separated from one another, and a cross-section measuring 25 x 20 x 15 mm was precisely cut out from the middle of each bead. Following the cut, the specimens underwent grinding, and polishing, and were etched using 3% nitric acid to reveal the heat-affected zone within the substrate plate. Photographs were taken of the cross-sections, which were thoroughly examined to assess the bead's geometry. To measure the height and width of each specimen, the "ImageJ" program was employed, as depicted in Figure 2.b.

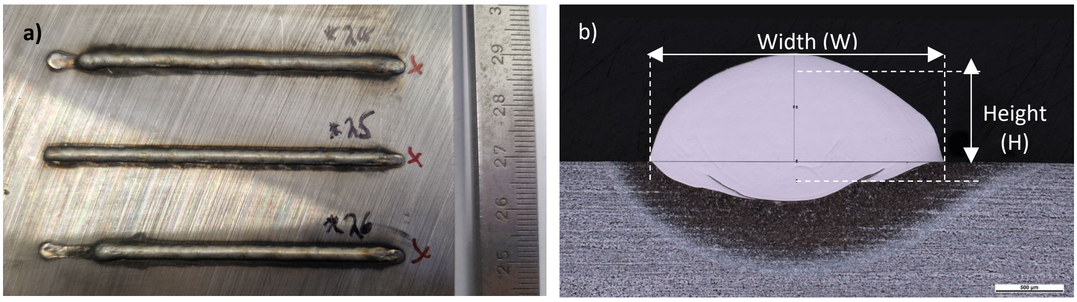

Fig. 2. (a) Optical observation of a few single deposits;(b) Metallographic examination.

3. Results and Discussion

A response surface design with full quadratic terms (i.e.: linear, squares and interactions) was conducted using Minitab software for the responses measured in Table 1 (width and height). The initial model showed several statistically insignificant factors. To improve the model, squares and interactions with statistically insignificant (P>0.05) factors were removed (Ghorbani, Li and Srivastava, 2020). The resulting regression equation for width (Equation 1) and for height (Equation 2) is shown below,

$$W = -10.48 + 0.00476\,PWR + 0.00445\,Ts + 0.00699\,Wf + 0.322\,HA - 0.000002\,Wf^2 - 0.000003\,PWR * Ts - 0.000194\,PWR * HA \quad (1)$$

$$H = 0.587 - 0.000023\,PWR - 0.000378\,Ts + 0.000481\,Wf - 0.00062\,HA \quad (2)$$

As shown in Equation 1, PWR, Ts, Wf and HA were included in the model as linear factors and only the Wf was included as a square factor. Moreover, the PWR*Ts and PWR*HA were included as interaction factors. Other factors showed statistically insignificant contributions to the model. On the other hand, only linear factors were included for the height model and square and interactions factors were removed as they showed statistically insignificant contributions.

The main effects plot (Figure 3) shows that with the increase of laser power the width increases. Traverse speed and head angle show a negative proportional relation with the width. Moreover, the wire feed rate shows a first increase in the width up to the middle limit and a decrease in the width afterwards. On the other hand, the main effects plot (Figure 4) shows that both laser power and head angle have a minimal effect on height. While the traverse speed and wire feed rate have an opposite relation with the height, the latter is positively proportional to the height.

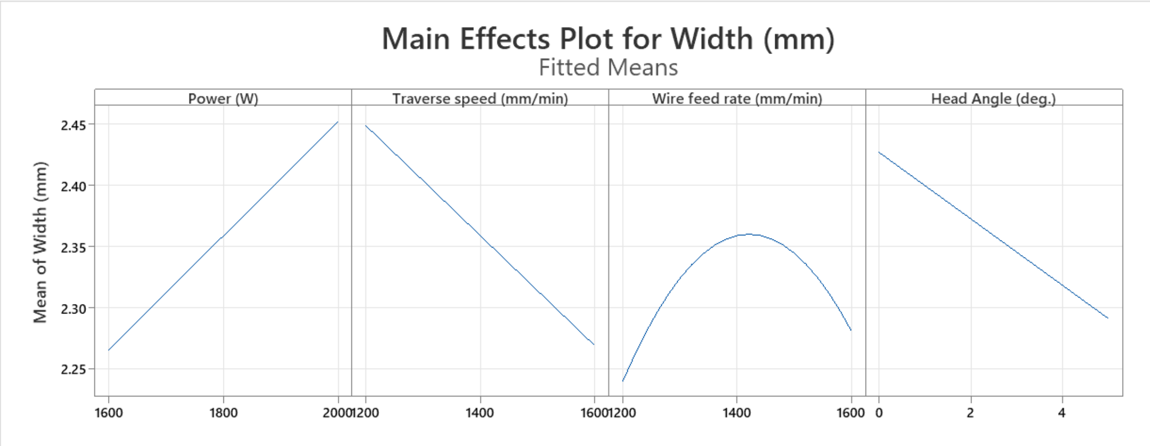

Fig. 3. Main effect plot for bead width.

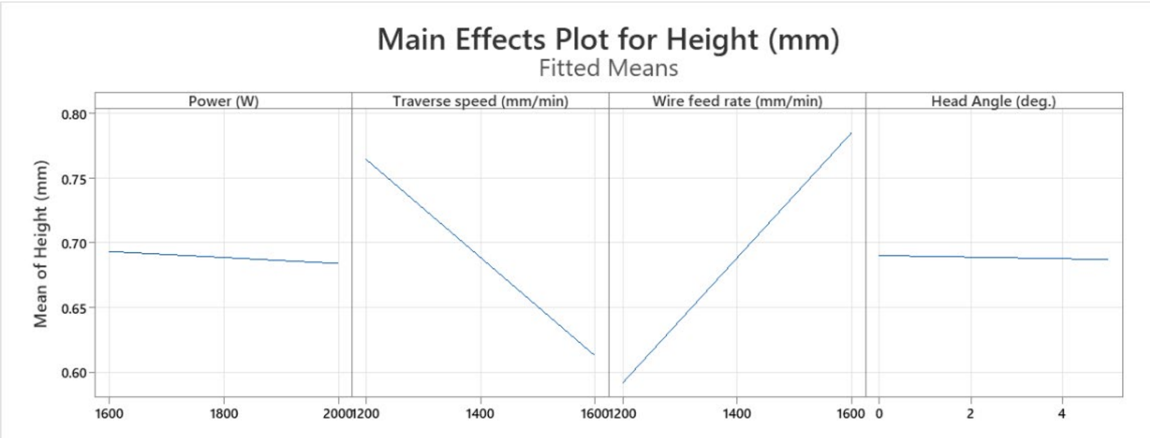

Fig. 4. Main effect plot for bead height.

4. Conclusion.

This paper presents the results of a comprehensive parameter study investigating the influence of laser power (PWR), wire feed rate (Wf), traverse speed (Ts), and head angle (HA) on the bead geometry in Laser Metal Deposition with Wire (LMD-w). Understanding the intricate relationship between these parameters and bead geometry is critical for optimizing the LMD-w process and achieving desirable outcomes in additive manufacturing. To analyze the width and height of the deposited beads, a factorial design experiment with the Box-Behnken design was employed. The findings revealed significant effects of factors such as PWR, Ts, Wf, and HA on the bead width. Additionally, the square of Wf was also found to have a notable influence on bead width. Similarly, factors including PWR, Ts, and HA, along with the square of Wf, were identified as influential in determining bead height.

These results highlight the importance of carefully selecting and controlling the aforementioned parameters to achieve desired bead geometries in LMD-w. By optimizing these parameters, manufacturers can enhance the quality, consistency, and efficiency of the additive manufacturing process. Finally, based on the outcomes of this study, further research is recommended to improve process stability and support series production in LMD-w. Such advancements will contribute to the broader adoption and implementation of LMD-w in various industrial applications.

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