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Ability of miniaturization of single tracks using laser metal deposition with wire

J. Saffer[a*], K. Hofmann[a], M. Breitwieser[a], K. Schaumberger[a], J. Ermer[a], F. Kaufmann[a], S. Roth[a,c], M. Schmidt[a,b,c]

[a]*Bayerisches Laserzentrum GmbH, Konrad-Zuse-Straße 2-6, 91052 Erlangen, Germany*
[b]*Lehrstuhl für Photonische Technologien, Friedrich-Alexander Universität Erlangen-Nürnberg, Konrad-Zuse-Straße 3/5, 91052 Erlangen, Germany*
[c]*SAOT – Erlangen graduate school in advanced optical technologies, Paul-Gordan-Str. 6, 91052 Erlangen, Germany*

Abstract

Repair of capital goods by wire-based laser metal deposition has the main advantages of higher material utilization and lower costs compared to powder. However, previous publications contradict the influence of the process parameters on the seam geometry. Therefore this study investigates the influence of laser parameters such as laser power, oscillation amplitude and frequency on the track dimensions. The objective is generating single tracks with a smaller width than the wire diameter (d = 0.4 mm). A 1 kW fiber laser was used to deposit tracks by wire (material: 1.3348) on samples of WP7V. The dimensions of the seam, i.e. height, width and remelt depth, were measured from cross-sections. It was proven that laser power has the greatest effect on the track width. Moreover a reduction of the oscillation amplitude results in a decrease of the width. Compared to linear welding the track width constancy is higher when using oscillation. With this knowledge a track width smaller than the wire diameter could be achieved.

Keywords: wire-based laser metal deposition; additive manufacturing; high carbon steel

1. Introduction

Besides very high material, utilization additive manufacturing processes offer the possibility to manufacture complex components. For deposition of metals selective laser melting and powder or rather

* Corresponding author. Tel.: +49 9131/97790-25; fax: +49 9131/97790-11.
E-mail address: j.saffer@blz.org.

wire based laser metal deposition (LMD) are used. The main advantages of laser metal deposition with wire are high deposition rate as well as lower costs compared to powder. However, both the restricted feasible complexity of the components and the low accuracy that can be achieved up to now are disadvantageously. Consequently, an effort needs to be made to further minimize dimension and generate very narrow tracks. Therefore, a high understanding of the process is essential.

For powder based LMD, studies have been made to determine the connection between track geometry and laser power, feed rate and mass per unit, respectively. However, some of the results are contradictory. For example, (Lusquiños et al., 2009) reported an increasing track height with increasing laser power, (Graf et al., 2013) identified no influence of the laser power on the height and (Riveiro et al., 2014) as well as (Zhong et al., 2015) a decreasing height with increasing power. Furthermore, the main influencing parameters on the track dimensions are still unclear. (Graf et al., 2013) reported that the track width is mainly dependent on laser power and the height on feed rate as well as powder mass flux. (Riveiro et al., 2014), on the other hand, concluded that feed rate is the most relevant parameter to adjust seam width and height.

According to (Kaierle et al., 2012), the minimal seam width depends on laser spot size, beam caustic and particle size or rather wire diameter. Due to the possibility of more accurate material application powder based LMD offers higher potential for miniaturization compared to wire based LMD. However, linear downsizing of the process is difficult because of the change in ratios of the process variables and boundary conditions. Using a powder with an average particle size of 4.7 µm, (Jambor, 2012) reported track widths of 25 µm and heights of 6 µm. The possibility of miniaturization of wire based LMD could be proofed by (Demir, 2018), though, the generated track dimensions are, compared to powder based LMD, more than 20 times larger regarding seam width and approximately 50 times larger regarding seam height, respectively. Using wire diameter of 0.5 mm, spot diameter of 850 µm and generating multilayer structures, aspect ratios of circa 20 with a width between 700 µm and 800 µm could be achieved. The heights of each track vary from 300 µm to 375 µm.

A possibility to improve the LMD process is beam oscillation which is an overlay of the feed motion of the processing head or the workpiece and a laser spot motion implemented by galvanometer scanner. Usually it is used for laser welding to control the width and dynamic of the melt bath (Müller et al., 2014). Furthermore, better gap bridging and weld strength is achievable by influencing the structure and weld geometry (Schweier, 2015). In conjunction with LMD, beam oscillation can be used to change the beam-material-interaction area which influences the seam width and therefore improves flexibility regarding generated deposition structure. Due to the fast movement of the laser spot over the surface high local intensities are generated but a lower energy input occurs in total (Pekkarinen, 2015). The reduction of energy input offers an advantage compared to further processes because less of the substrate material is melted. As a result, a low mixture between substrate and additional material is generated that is often desired when using LMD processes. Moreover, with less energy input smaller areas can be treated and less distortion is expected (Klocke et al., 2012). Beam oscillation in combination with wire based LMD was already studied but only with fixed values for the oscillation parameters (Barroi et al.), (Klocke et al., 2012) so that no influence of the oscillation parameters could be identified.

Due to inconsistency of previous studies regarding influence of process parameters on the seam dimensions this study investigates and clarifies the influences of main process parameters such as power and mass per unit for LMD using high carbon steel wire. Furthermore, the effect of beam oscillation on the track geometry and the process stability is analyzed and an approach of generating narrow tracks smaller than the wire diameter is presented.

2. Experimental details

2.1. Material

Both substrate and wire material are tool steels. Table 1 shows the nominal chemical composition of the two alloys. WP7V is a secondary hardenable special material with a very high tensile strength, good compressive strength and a high wear resistance. The plate of the substrate material has a thickness of 10 mm and an area of 80 mm x 50 mm. The high-speed steel 1.3348 offers high wear resistance as well and additionally high toughness and carbon content. This material is used for deposition welding to repair tools. The material is used as a copper-plated wire with a diameter of 0.4 mm.

Table 1. Nominal chemical composition of the substrate (Dörrenberg Edelstahl GmbH) and wire material (Wegst and Wegst, 2016)

wt%	C	Si	Mn	Cr	Mo	V	W	Fe
1.2367	0.35 -0.40	0.30 -0.50	0.30 -0.50	4.80 -5.20	2.70 -3.20	0.40 -0.60	-	Bal.
1.3348	0.95 -1.05	≤ 0.70	≤ 0.40	3.50 -4.50	8.20 -9.20	1.70 -2.20	1.50-2.10	Bal.

2.2. Experimental setup and characterization

For the LMD process a diode-pumped Yb-YAG fiber laser (YLR 1000-SM by IPG Laser GmbH) at the wavelength of 1070 nm and with a nominal output power of 1 kW is used. The laser source generates a high beam quality with a Rayleigh length of about 600 µm and a focal diameter of 32 µm. The laser beam can be moved with a 2-axis deflection unit "Superscan 20" by Raylase GmbH and a f-theta lens over an area of about 70 mm x 70 mm. The feed during the process is implemented by linear motor axes (Aerotech GmbH). The connected x- and y-axis (PRO280LM) handle the specimens in one plane. For adjustment of the working distance, the optical system is moved by a z-axis (PRO165). The wire is positioned on the substrate surface and guided into the process zone using a feeding unit FDE-PB 100 L (Dinse GmbH), which controls the feeding velocity. The inert gas Argon 4.6 is supplied by a nozzle with a round cross section. Fig. 1 a) shows the schematic experimental setup of the laser metal deposition process.

The characterization of the single beads was made by abrasive saw cutting and subsequent grinding, polishing and etching with a V2A-etching solution to reveal the microstructure. The measured values are shown in Fig. 1 b).

3. Results and discussion

The results are structured in two main parts: first, the influences of different process parameters on the seam dimensions are presented and then, the possibility of the reduction of the seam width is discussed.

3.1. Influence of oscillation amplitude

Due to beam oscillation there is a surface distribution of the energy that is introduced in the work piece. The oscillation amplitude is thereby a significant factor of this energy distribution and consequently of the process control. In the left of Fig. 2 the influence of the oscillation amplitude on the track geometry is shown.

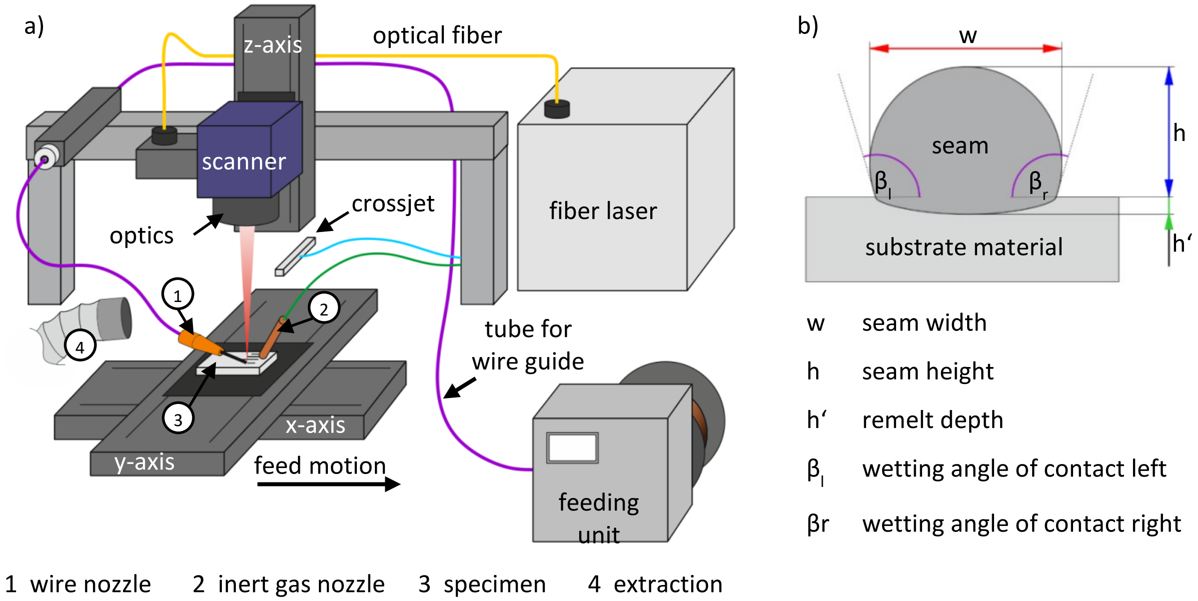


Fig. 1. a) Schematic illustration of the laser metal deposition process, b) Labeling of bead dimensions

Oscillation frequency, laser power and mass per unit stay constant. With regard to generate seam width smaller than wire diameter, the investigated oscillation amplitudes are chosen to be smaller than 0.4 mm.

The parameters that are influenced most are seam width and wetting angle of contact. The seam width decreases when the oscillation amplitude decreases as well. At high amplitudes the highest change in seam width is observed and at lower amplitudes the width approximates a threshold. This seems to be plausible because no amplitude (A = 0 mm) results in the lowest distribution of the introduced energy and a high amplitude in an increase of the energy input area. Consequently, a higher wetting of the substrate is encouraged due to increased temperatures. With greater oscillation amplitudes, the expansion of the seam width and better wetting lead inevitable to a reduction of the seam height by reason of a constant mass per unit. The amplitudes of A = 0.1 mm and 0.05 mm are very small compared to the wire diameter of 0.4 mm as well as the seam width of about 0.37 mm. The difference between these amplitudes is correspondingly low whereas the higher amplitudes are closer to the process dimensions. Contrary to the width, rising amplitude leads to a decreasing wetting angle of contact. A possible cause for the high standard deviation of the wetting angle are asymmetrical tracks that are occurring due to the wire’s curvature. The curvature can vary during the process which can lead to a divergent position of the wire regarding the laser beam position.

Regarding efficiency it is preferable to obtain high deposition rates despite a reduction of the track width. Therefore, high aspect ratios are required. The right of Fig. 2 shows the aspect ratio depending on the oscillation amplitude. Because of the already described reduction of the track width and simultaneous increase of the height by decrease of the oscillation amplitude the aspect ratio rises from approximately 0.43 (A = 0.3 mm) to 0.67 (A = 0.1 mm). Therefore, thinner tracks can be generated using smaller amplitudes.

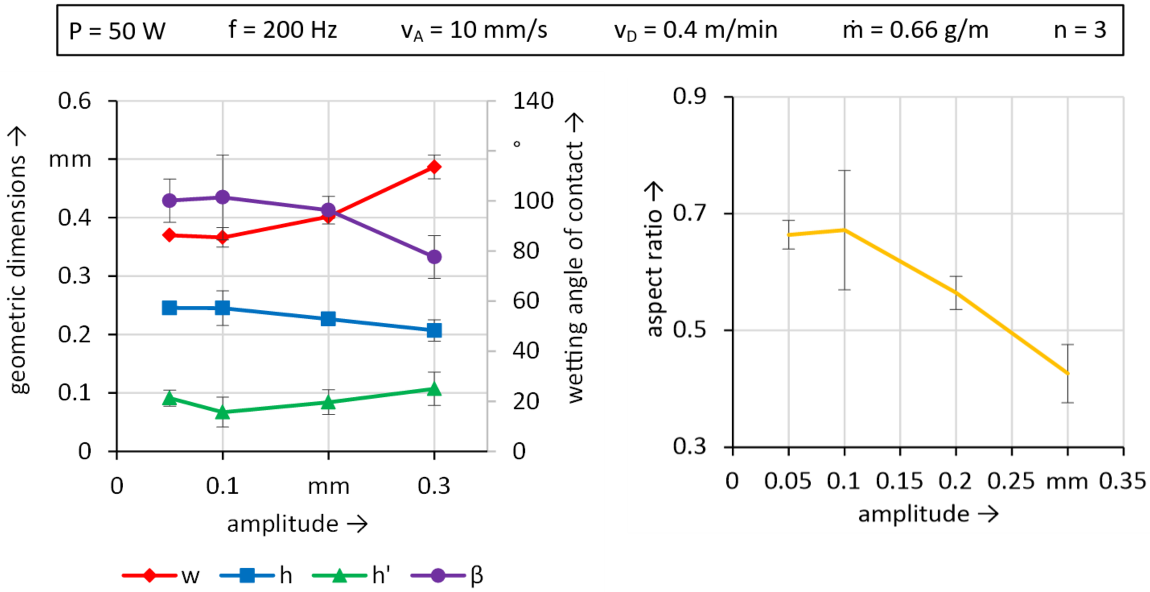


Fig. 2. Influence of the oscillation amplitude both on the track dimensions (seam width w, seam height h, remelt depth h’ and wetting angle of contact β) and the aspect ratio at constant laser power, oscillation frequency and mass per unit

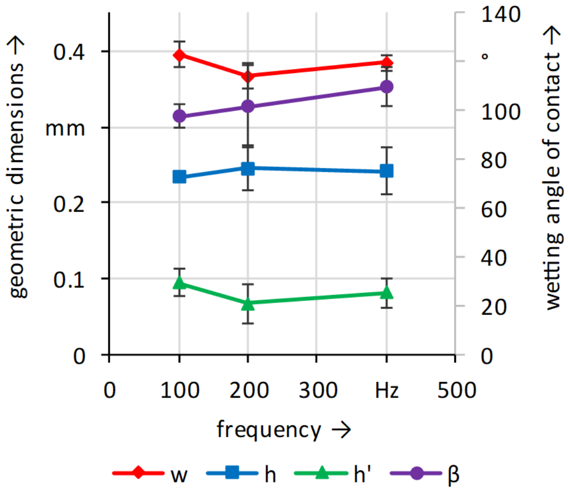
3.2. Influence of oscillation frequency

The oscillation frequency determines velocity of the laser spot, depending on oscillation amplitude and geometry. Thus, it can affect the local energy distribution. The influence of the oscillation frequency on the track geometry is illustrated in Fig. 3.

Unlike the clear influence of the oscillation amplitude, the oscillation frequency seems to have no impact on the track geometry. Low fluctuations of seam width, height, remelt depth and wetting angle of contact are located in the range of the standard deviations. The frequency influences the local energy distribution in a given area due to the spot’s velocity: With increasing oscillation frequency the local energy input is first reduced because the velocity of the oscillation is increased; but simultaneously the time to the next energy input is reduced. Insofar, with lower frequencies the local temperatures and temperature gradient are greater compared to higher frequencies so that a more homogeneous temperature distribution can be achieved. In contrast to a variation of the amplitude the oscillation frequency has no impact on the influenced area and on the local energy input. Consequently there are no significant changes in track dimensions apparent when changing the frequency.

3.3. Influence of mass per unit

The amount of additional material that is introduced in the process can be described by the mass per unit. This value is defined by the relation between wire speed and feed rate. In Fig. 4 the effect of mass per unit on the seam geometry is depicted. The variation of mass per unit is made by change in feed rate. With reduction of the mass per unit by rise of the feed rate the linear energy per unit at constant laser power is reduced.



P = 50 W
A = 0.1 mm
v_A = 10 mm/s
v_D = 0.4 m/min
$\dot{m}$ = 0.66 g/m
n = 3

Fig. 3. Influence of the oscillation frequency on the track dimensions (seam width w, seam height h, remelt depth h' and wetting angle of contact β)

According to Fig. 4, there is a slight influence of the mass per unit on the seam width: with rising mass per unit the seam width is reduced. Regarding remelt depth it can be seen that there is first an approximately constant depth with rising mass per unit and at about 0.6 g/m the progression is decreasing but with comparatively high standard deviation. Both seam height and wetting angle of contact are rising with increasing mass per unit and have a clearer and pronounced relation.

This behavior was expected because with an increase of mass per unit more wire material is available. For this reason, the energy input in the substrate declines, less substrate material is molten and the quality of the connection between wire material and substrate material is decreasing. The molten wire material strives due to its surface tension for the most energetically favorable state. Because of the lower energy input in the substrate the track passes from a wide and flat seam to a circular one with low width and greater wetting angles. This effects higher tracks due to constant volume. In combination with the additional amount of wire material at higher masses per unit the high increase of the height can be explained. The somewhat reduced remelt depth can be attributed to the lower energy input in the substrate with rising mass per unit. The partly constant curve progression of the remelt depth as a function of the mass per unit is possibly based on the change in the linear energy per unit by change of the feed rate.

When varying the mass per unit by changing the feed rate the energy input in the substrate is influenced. Therefore the energy per unit is increasing when the mass per unit is increased due to a lower feed rate whereas the seam width is reduced. The lower width is contrary to the increased mass per unit because a widening of the track was expected. It can be assumed that the influence of the added material is predominant over the gain of the introduced energy. Hence, tighter and higher tracks are generated, as the aspect ratio in Fig. 4 shows.

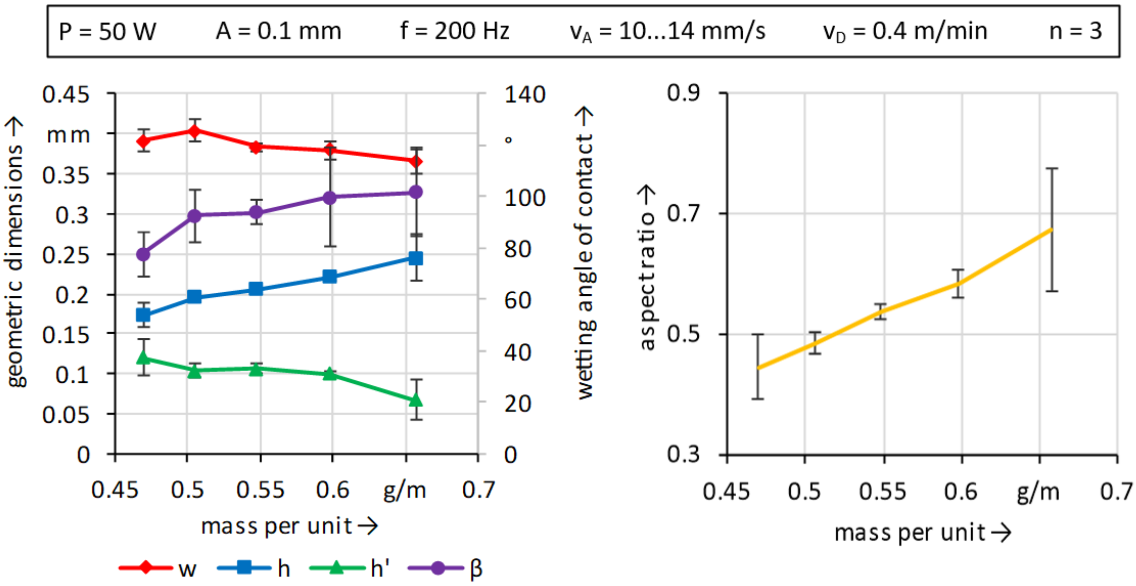


Fig. 4. Influence of the mass per unit both on the track geometry (seam width w, seam height h, remelt depth h' and wetting angle of contact β) and the aspect ratio at constant power, oscillation amplitude and frequency

A linear relation between mass per unit and aspect ratio is shown. It has been considered that the seam width cannot be reduced arbitrary by an increase of the mass per unit. With rise of the mass per unit and a further increase of the aspect ratio the track geometry of the molten material will be approximated to a circular cross section due to surface tension. At a certain point no connection can be generated between track and substrate material. Due to this, the mass per unit has to be reduced to obtain a width as small as possible.

3.4. Influence of laser power

During the laser metal deposition process enough energy has to be provided by the laser to ensure a complete fusing of the wire material and a joining to the substrate. The influence of the laser power on the track geometry is shown at constant mass per unit and constant oscillation parameters in Fig. 5.

In the left diagram of Fig. 5 a reduction of the seam width at decreasing laser power can be identified. Simultaneously an increase of the seam height accompanies by reduction of the laser power. Analogous to the influence of the oscillation amplitude and in contrary to mass per unit, a stronger influence of the laser power on the seam width compared to the seam height persists. Moreover a significant increase of the wetting angle of contact and a decreasing remelt depth is connected with reduction of laser power.

The cross sections in Fig. 6 show a considerable influence of the laser power, especially on the seam width and the remelt depth. Whereas there is no fusion with the substrate at P = 45 W, there already is a great molten area in the substrate at P = 55 W. Using LMD, a fusion as low as possible is striven. However, in this case problems regarding track width constancy exist. Towards higher laser power the track with P = 45 W exhibits a significant discontinuous seam width (Fig. 6, top left). There is not enough energy input available for a stable process and no continuous material deposition is achievable due to the small process zone width and low wetting.

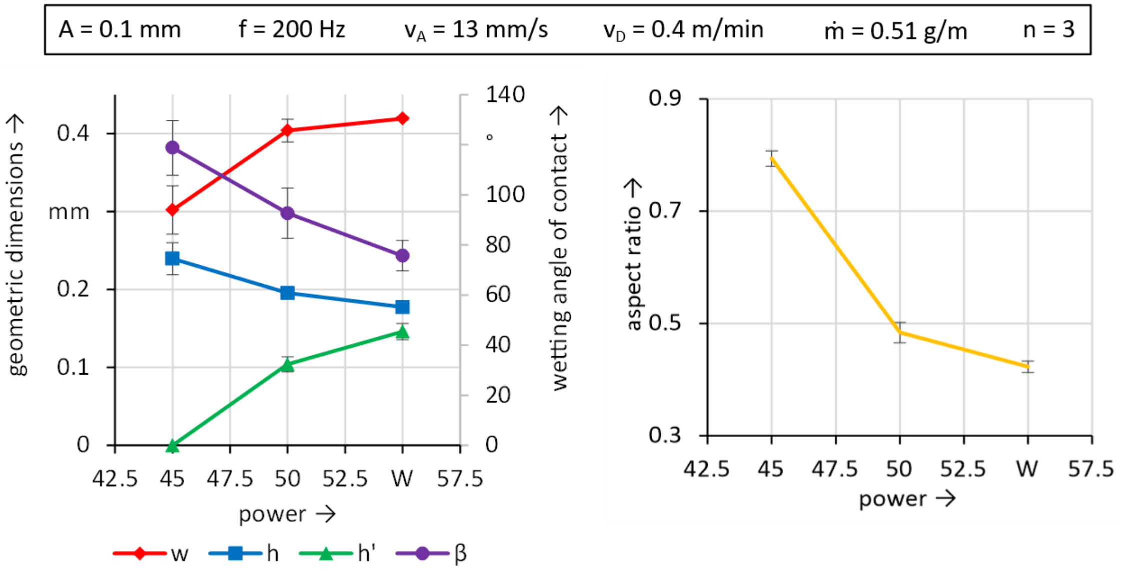


Fig. 5. Influence of the laser power both on the track geometry (seam width w, seam height h, remelt depth h' and wetting angle of contact β) and the aspect ratio at constant mass per unit, oscillation amplitude and frequency

By increasing the laser power, a greater melt pool and greater heated area in the substrate is generated as a result of the higher energy input. This leads to a better wetting of the substrate by the molten wire material. Due to this effect the wetting angles of contact decrease and the seam widths increase. By reason of constant volume of the introduced wire a reduction of the seam height results. Besides higher laser power that generally increases the remelt depth, also decreasing seam heights encourage a higher remelt depth because of the lower amount of wire material between laser and substrate.

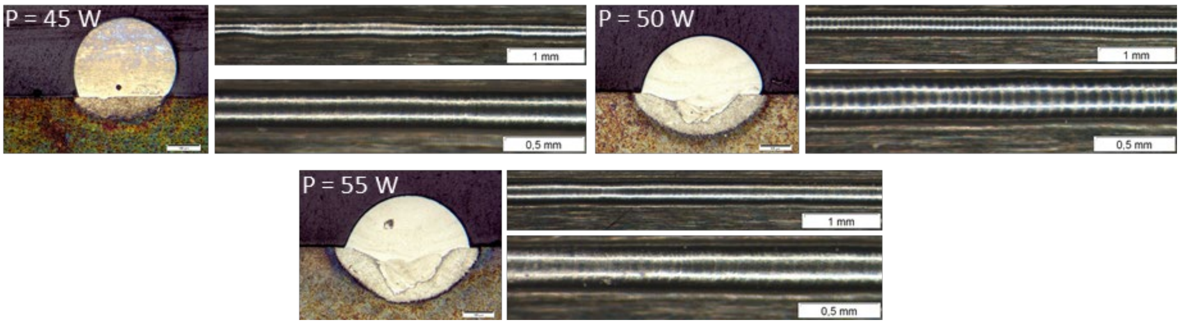


Fig. 6. Cross-sections and top views of different laser powers (constant parameters: v_A = 13 mm/s; v_D = 0.4 m/min; ṁ = 0.51 g/m; A = 0.1 mm; f = 200 Hz)

The aspect ratios, resulting from seam width and height, depending on the laser power are depicted in Fig. 5 right. An approximately doubling of the aspect ratio can be reached by reducing the laser power from P = 55 W to 45 W. The laser power presents a relevant influence factor on the track geometry. Regarding reduction of the achievable seam width, the process stability must be ensured.

3.5. Possibility of seam width reduction

According to the results from sub-points 3.1 to 3.4 that are summarized in Table 2 a miniaturization of the seam width can be achieved by reducing laser power and oscillation amplitude with the lowest possible mass per unit that still results in a stable process. A minimization of relevant process values leads to an approach to the process limits. Nevertheless, process stability must be ensured to generate consistent track of constant width. The influences on the process stability regarding interaction between laser power, oscillation amplitude and mass per unit are presented in the following.

Table 2. Change of geometric parameters of the track when varying procedural parameters

		w	**h**	**h‘**	**β**
P	↑	↑	↓	↑	↓
ṁ	↑	↓	↑	↓	↑
A	↑	↑	↓	(↑)	↓
f	↑	-	-	-	-

The track width can be reduced by applying lower amplitudes. Therefore, the minimal seam width is expected at A = 0 mm (linear beam guiding). This could be confirmed. Independent of laser power, a smaller seam width is generated by linear beam guiding compared to an oscillation with A = 0.1 mm and the difference is about 40 µm. Due to the more narrow distribution of the introduced energy at lower amplitudes, the smallest area of energy input exists at linear beam guiding. Subsequently, the wetting of the substrate material is possible only in a small area which reduces seam width but also process stability. Tracks of A = 0 mm show smaller width of fusion area because of the lower energy distribution. Therefore, larger wetting angles and more narrow tracks result.

At laser powers P = 50 W and 47 W tracks of very constant width can be generated, both at A = 0 mm and A = 0.1 mm. When the power is reduced to 45 W, a deterioration of the width constancy can be noted for both amplitudes. In case of A = 0.1 mm the deviation in seam width is minor whereas clear fluctuations occur at linear beam guiding, on the one hand in constancy of track width and on the other hand in linearity of the track. To minimize the track width and preserve the seam width constancy a compromise needs to be made between an amplitude as low as possible to reduce the width and an amplitude as high as necessary to maintain a sufficient width constancy. To find a suitable value, mass per unit and laser power have to be taken into consideration. Laser powers of P = 45 W or 38 W represent the lower process limit regarding power for a constant mass per unit. The insufficient constancy of the seam width at low laser powers shows in the form of repeated widening and narrowing of the seam. The highest width constancy can be achieved at various masses per unit at various amplitudes.

4. Conclusion

On the basis of the results it can be stated that different geometric parameters of the track are interdependent. An opposite behavior of seam width and height can be identified for all the process variables that influence the track dimensions – laser power, mass per unit and oscillation amplitude – due to constant wire volume.

With regard to seam width as most important target figure, laser power is the decisive actuating variable to influence the width. On the one hand laser power itself has a considerable influence on the resulting track widths. On the other hand, the influences of mass per unit and oscillation amplitude are attributed to the change of the local energy input in the substrate material that relates to laser power.

To reduce the seam width the following conditions should be met: Low oscillation amplitude or linear beam guiding and low mass per unit. However, process stability has to be guaranteed to reduce seam width.

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References

Barroi, A., Hermsdorf, J., Kaierle, S., Overmeyer, L. Influence of Scan Width and Wire Feed Speed on Seam Geometry and the Substrate Surface in Laser Wire Cladding. Proceedings of Icaleo 2016.

Demir, A.G., 2018. Micro laser metal wire deposition for additive manufacturing of thin-walled structures. Optics and Lasers in Engineering 100, 9–17.

Dörrenberg Edelstahl GmbH. Werkstoffdatenblatt WP7V. http://www.dorrenberg.es/download/aceros/DOE/WP7V_deu.pdf. Accessed 16 April 2019.

Graf, B., Ammer, S., Gumenyuk, A., Rethmeier, M., 2013. Design of Experiments for Laser Metal Deposition in Maintenance, Repair and Overhaul Applications. Procedia CIRP 11, 245–248.

Jambor, T., 2012. Funktionalisierung von Bauteiloberflächen durch Mikro-Laserauftragschweißen, 162 pp.

Kaierle, S., Barroi, A., Noelke, C., Hermsdorf, J., Overmeyer, L., Haferkamp, H., 2012. Review on Laser Deposition Welding: From Micro to Macro. Physics Procedia 39, 336–345.

Klocke, F., Brecher, C., Wegener, M., Heinen, D., Fischer, B., Do-Khac, D., 2012. Scanner-based Laser Cladding. Physics Procedia 39, 346–353.

Lusquiños, F., Comesaña, R., Riveiro, A., Quintero, F., Pou, J., 2009. Fibre laser micro-cladding of Co-based alloys on stainless steel. Surface and Coatings Technology 203 (14), 1933–1940.

Müller, A., Goecke, S.-F., Sievi, P., Albert, F., Rethmeier, M., 2014. Laser Beam Oscillation Strategies for Fillet Welds in Lap Joints. Physics Procedia 56, 458–466.

Pekkarinen, J., 2015. Scanning Optics Enabled Possibilities and Challenges in Laser Cladding. Physics Procedia 78, 285–295.

Riveiro, A., Mejías, A., Lusquiños, F., del Val, J., Comesaña, R., Pardo, J., Pou, J., 2014. Laser cladding of aluminium on AISI 304 stainless steel with high-power diode lasers. Surface and Coatings Technology 253, 214–220.

Schweier, M., 2015. Simulative und experimentelle Untersuchungen zum Laserstrahlschweißen mit überlagerter Strahloszillation.

Wegst, M., Wegst, C.W., 2016. Stahlschlüssel-Taschenbuch: Wissenswertes über Stähle, 24. Auflage ed. Stahlschlüssel, Marbach am Neckar, 203 pp.

Zhong, C., Biermann, T., Gasser, A., Poprawe, R., 2015. Experimental study of effects of main process parameters on porosity, track geometry, deposition rate, and powder efficiency for high deposition rate laser metal deposition. Journal of Laser Applications 27 (4), 42003.