Lasers in Manufacturing Conference 2019

Laser deposition welding with centric material feed and circular direct diode modules

Guepner, M.[a*], Ulrich, S.[b], Bliedtner, J.[a], Schnick, M.[c], Brocke, N.[c]

[a]*Ernst-Abbe-Hochschule Jena University of Applied Sciences, Carl-Zeiß-Promenade 2, 07745 Jena, Germany*
[b]*Guenter Koehler Institute of Joining and Material Testing, Otto-Schott-Straße 13, 07745 Jena, Germany*
[c]*Oscar PLT GmbH, Hamburger Ring 11, 01665 Klipphausen, Germany*

Abstract

The central subject of this paper is a new hybrid, cost-effective deposition welding system for the industrial user. The basis for this is an innovative machining head, in which for the first time the beam source is integrated directly into the machining head. This is made possible by implementing a direct diode laser. This leads to a significant saving in space and footprint. The arrangement of the diode stacks allows a simple, coaxial, centric supply of the filler material. One of the key advantages is the coaxial feeding and processing of wire or powdered filler material. Due to the mentioned variety of technological advantages of the coaxial deposition welding system, diverse tasks in the field of deposition welding can be mastered. In this paper, the coaxial deposition welding system is presented and fundamentally characterized. This is done both from a system engineering and from a process engineering point of view.

Keywords: hybrid laser metal deposition system; laser metal deposition; powder; wire; direct diode laser

1. Introduction

Laser metal deposition (LMD) is a well-established generative manufacturing process for fabrication and repair of toolmaking components. Tools which have been manufactured conventionally, for example by machining semi-finished parts, are usually entirely made of expensive, hardened and tempered, highly alloyed tool steels. With laser deposition welding however, tools can be designed by applying functional layers locally, specifically aimed at the interaction zone of the tool. This type of coating can be applied on inexpensive, easily weldable substrate material.

A second huge industrial application is the LMD based repair welding. Cost intensive worn parts like moulds or tools can be repaired and reused, instead of being disposed. The defects must be identified and removed using subtractive processes like milling or grinding. New volume is locally, in the defect area,

* Corresponding author. Tel.: +49-3641-205-964;
E-mail address: Michael.Guepner@eah-jena.de .

added. The last step is a milling or grinding finishing process, to bring the part back to its original shape. In the same way, geometrical deviations or production faults can be compensated.

A third application of LMD is the 3d-geneartion of structures or parts. LMD shows advantages, when thin walled parts with a big aspect ratio like housings or turbine blades have to be manufactured. Producing such parts by subtractive manufacturing processes leads to a low material efficiency, due to the high share of wastage. Creating thin walled parts with LMD, the generated structures are close to the final geometry of the part and only functional surfaces must be finished.

In this paper, the coaxial deposition welding system is presented and fundamentally characterized. This is done from system engineering and from a process engineering point of view.

2. State of the art in laser metal deposition machines

In principle, build-up welding systems consist of a beam source and a machine unit for realizing the relative movement between the laser beam and the workpiece. The machine unit (axis system or industrial robot) contains the processing optics, by means of which the beam shaping, necessary for processing, is realized. Beam source and processing optics are usually arranged spatially separated. Therefore, a beam guide between the beam source and processing optics must be realized. This is done traditionally by the use of reflective fixed optics or by, the preferred in industrial everyday use, optical fibers for guiding the laser beam. In comparison with fixed optics, these enable the safe, uncomplicated conduction of laser radiation to the destination over long distances [Hügel and Graf, 2009].

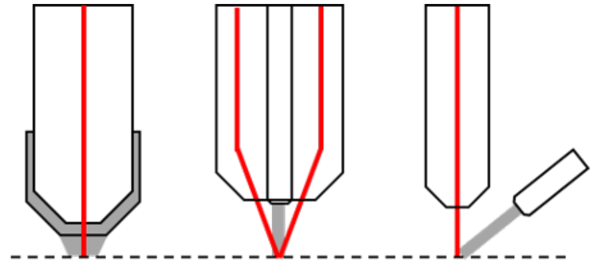


Fig. 1. LMD head configurations: (a) fibre guided system with coaxial powder nozzle (b); inverted arrangement system with centric material feed and (c); conventional welding head with lateral material feed

However, the use of such transport fibers comes along with immanent limitations and risks. Transport fibers are expensive to buy and only to a very limited extent mechanically durable. Therefore, costly protective measures such as strain relief and drag chains are to be integrated into the system structure. The permanent entrainment of the transport fiber additionally limits the flexibility of the machining process. Furthermore, there is the risk of thermal destruction of the transport fiber by laser radiation that is reflected by the workpiece. The safe handling of transport fiber and the fiber laser additionally requires specially trained operating personnel.

To ensure flexible, direction-independent machining, the supply of the filler metal is preferably arranged coaxially to the optical axis of the laser beam (Fig. 1a). Typically, an annular gap nozzle or a multi-jet nozzle is used.

Wire-shaped filler metal is commonly fed laterally to the propagation direction of the laser beam. This results in a simpler system design with straightforward nozzle concepts. However, the lateral arrangement of the welding wire feed leads to a direction-dependent processing and to a limited component accessibility (Fig. 1c).

Systems with inverse arrangement have increasingly been developed in recent years [Kelbassa et al., 2018; Ocylok et al., 2016; Govekar et al., 2018; Schulz et al., 2018]. As shown in Fig. 1b, the supply of filler metal is centric so that in addition to powder, even wire can be coaxially provided. However, this requires a complex optical system to generate annual beam shapes or partial beams arrangements and furthermore ensure homogeneous and direction independent intensity profile on the workpiece. All commercially available systems use an externally arranged beam source.

3. New system for LMD with direct diode laser and centric material feed

This publication focuses on the innovative, patented build-up welding system ProFocus1000 from OSCAR PLT GmbH (Fig. 2). The beam source is integrated directly into the machining head and the beam source used is a direct diode laser. Diode lasers are among the cheapest sources for laser material processing in terms of running costs and investment costs. This is due to the low production costs and the high electro-optical efficiency of the beam source [Bliedtner et al., 2013]. Furthermore, the integration of the beam source in the machining head leads to a significant saving in space and footprint regarding the overall system. Furthermore, the innovative optical design of the system saves costly optical peripherals (e.g. transport fiber including beam injection).

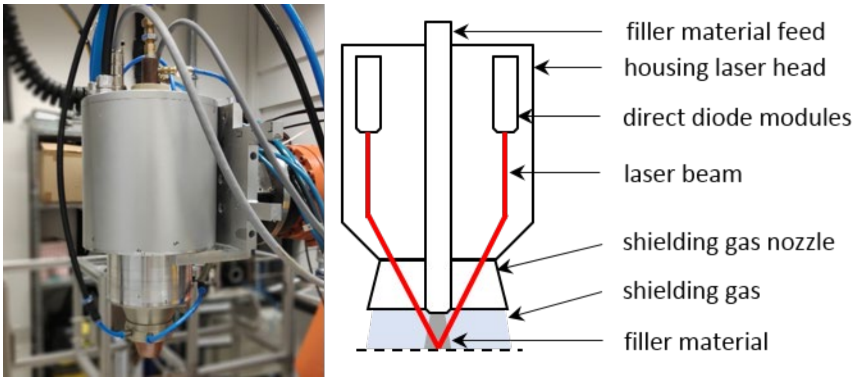


Fig. 2. New LMD head ProFocus1000 with integrated direct-diode laser and centric material feed

From a process engineering point of view, the radial arrangement of five or six diode stacks (emitting 1 kW of power) leads to many advantages. The arrangement of the diode stacks allows a simple, coaxial, centric feed of the filler metal (Fig. 2). The individual beams are conducted parallel to the conveying unit of the filler metal and combined only in the working plane below the outlet opening of the welding filler to form a complete laser beam. Therefore, modular and simple feed units can be integrated into the build-up welding head.

Both wire and powder conveying units can be coupled without problems. The modular design therefore allows the flexible change between powder and wire-shaped filler materials using one application welding head. The coaxial supply of laser beam and filler metal is always possible. This leads to an extremely flexible, direction-independent machining process, which can be ensured in everyday industrial life currently dominated by only powder filler metal.

As a result of the centric arrangement of the welding filler material supply, the beam guidance concept of the laser radiation can be used on a simple, easier-to-control, lower-cost, single-jet powder nozzles. This eliminates the need for conventional coaxial feed concepts, necessary to split the powder flow into partial streams with the subsequent reunification in the powder focus. Consequently, the need for the characteristic powder focus to be accurately set during processing is also eliminated, since the single-jet nozzle concept produces a low divergence emission cone (Fig. 2).

Another advantage of the novel deposition welding system is the separate arrangement of protective and carrier gas in powder applications. Since the carrier gas is fed through a separate nozzle of large diameter to the joint, it creates a much larger-scale gas shielding by the greatly enlarged flow cross section. This provides much better shielding gas coverage, as well as more effective shielding of the carrier gas flow from the surrounding atmosphere in powder applications.

Figure 3 shows selected results of the analysis of the focused laser radiation. The waist of the radiation field shows a Gaussian, homogeneous intensity distribution and a low ellipticity perpendicular to the beam propagation direction (Fig. 3a). The focus diameter is 1 mm.

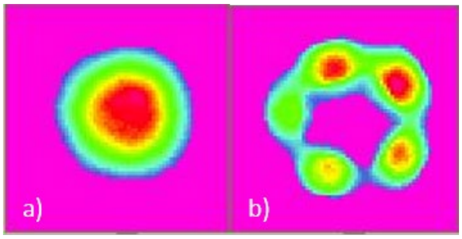


Fig. 3. Intensity distributions for different working distances [a) smallest diameter of 1 mm for small structures using powder; (b) diameter of 2 mm with adapted intensity profile for processing wire

If the beam waist is positioned 2.5 mm below the workpiece surface, the beam diameter can be increased up to 2 mm, which increases the seam width (Fig. 3b). At the same time, the working distance decreases, which further reduces the diameter of the mass flow in the working plane. Both circumstances increase the degree of powder utilization.

By separating the five partial radiation fields, a donut-like intensity profile is formed. This focus position is particularly suitable for processing the wire-shaped material, since the wire can be fed in concentrically arranged intensity minimum, whereby premature melting of the wire can be counteracted. The outer, high-intensity areas form the molten pool around the wire.

4. Basics and approach

The energy input per unit length E_L is an indicator of the thermal stress of a part. The energy input per unit length increment can be calculated from the ratio of the supplied laser power P_B to the feed rate v:

$$E = \frac{P_B}{v} \qquad (1)$$

The higher the amount of energy per unit length, the higher is the thermal stress acting on the workpiece. Therefore, to reduce the part distortion the energy input per unit length should be reduced. In contrast to conventional welding methods, laser metal deposition additionally requires considerations regarding the mass per unit length m_L:

$$m_L = \frac{\dot{m}}{v} \tag{2}$$

The mass per unit length characterizes the mass applied per unit length increment and is obtained by the ratio of the powder mass flow $\dot{m}$ to the feed rate v. The amount of mass per unit length is directly proportional to the process efficiency and provides an independent comparative value for assessing the metal deposition result [Hügel and Graf, 2009].

$$AG = \frac{A_2}{A_1 + A_2} \tag{3}$$

The degree of dilution (*AG*) provides another parameter of the quality of the deposited track. It characterizes the degree by which the filler metal dilutes with the substrate material (Eq. 3).

The purpose of coatings, applied by LMD with similar material, is to obtain a systematic increase in volume. Therefore, the cross-sectional area on the substrate A_1 has to be maximized, while the cross-sectional area in the substrate A_2 has to be minimized. Accordingly, laser metal deposition of high quality and efficiency has a low degree of dilution.

The motivation for the experimental investigation using powder is the manufacturing of tools by applying functional layers locally, specifically aimed at the interaction zone of the tool. An unalloyed, easily weldable substrate material with the material number 1.0330 was chosen. To create the hard layer, the filler material EuTroLoy 16606 04 A by the company Castolin GmbH was applied on the substrate. This powder is a hard-to-weld, highly alloyed high-speed steel with the material number 1.3342.

The motivation of the experiments using wire is located in the field of repairing worn tools or molds. Therefore, typical tool steel with the material number 1.2343 was chosen as wire and substrate material.

5. Experimental setup and system characterization

A 6-axis articulated robot was responsible for the relative movement between LMD head and workpiece. For the powder based experiments, a powder feeder from the company GTV GmbH was used.

Figure 4 shows the experimental setup for the wire applications. The wire storage, the straightening unit, the wire feed unit FD100LS were supplied by the company Dinse GmbH and the flexible tube for guiding the wire into the LMD head was arranged on top of the robot.

Two- and three-dimensional geometries were produced by overlaps of several individual cladding tracks side by side or by superimposition. Consequently, the individual track is always the basic geometrical element in coating, repairing or the generative manufacturing of 3-dimensional parts. It is therefore useful to characterize the basic correlations based on individual weld tracks. To reduce the number of variables, a single weld track with a length of 40 mm was deposited centrally to square substrates of the edge length of 50 mm. The additional mass of filler material was weighed and the characteristic weld geometry (track width, height, penetration depth and cross-sectional areas) was recorded from micro cross-sections. Substrates of 4 mm thickness were examined.

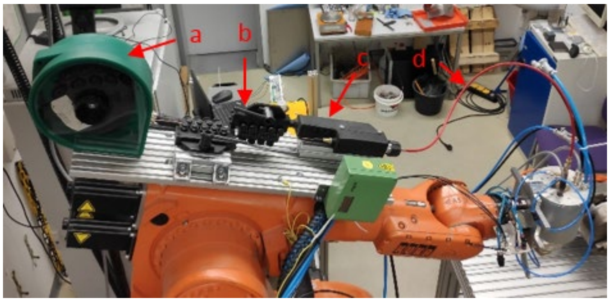


Fig. 4. Setup for processing wire a) wire storage, b) straightening unit, c) wire feed unit and d) flexible tube for wire guide

After characterizing the individual tracks, parameter sets for wire and powder were selected and applied to 3 dimensional cubes with an edge length of 20 mm. Therefore, 14 deposition tracks were placed side by side with 30% overlap. 30 layers were built up on substrates with a thickness of 10 mm.

Fig. 5. Imaging of powder stream (a) experimental setup; (b) raw data; (c) software for brightness selection; (d) measured picture

In a next step to characterize the build-up welding system, the divergence angle and the diameter of the powder mass flow were determined. Photographs of the powder mass flow (Fig. 5a and b) were taken in a darkened environment. Subsequently, a defined brightness range was selected via image processing (Fig. 5c). The software processing of the image material enabled the reproducible measurement of the powder flow. The determined divergence angles were on average 20° (full opening angle). The diameter in the interaction zone was, depending on the focal position, in the range of 2 to 3.5 mm.

Aperture tests were conducted with the aim to further qualify a correlation between the width of the meld pool and powder utilization efficiency by means of a suitable test stand. The melt pool was simulated by a hole in a film and irradiated statically with the powder mass flow. The volume delivered over one minute was collected in a vessel, weighted and compared with the previously measured mass flow without aperture.

To simplify positioning, adjustment and testing, a customized device was designed (Figure 6a). The various holes were placed in a steel foil. This is positioned on a support plate via pins and clamped by hold-downs. The device allows easy movement of the film to get from aperture to aperture. Aperture diameters of 0.5 to 5 mm (step width 0.5 mm) were studied.

Figure 6b shows the percentage of the supported (transmitted) powder as a function of the aperture diameter. With a diameter of 2 mm, which corresponds approximately to the usual melt pool widths, about 70% of the powder can be used. If the diameter is increased to 2.5 mm, very good values of over 90% powder utilization are achieved.

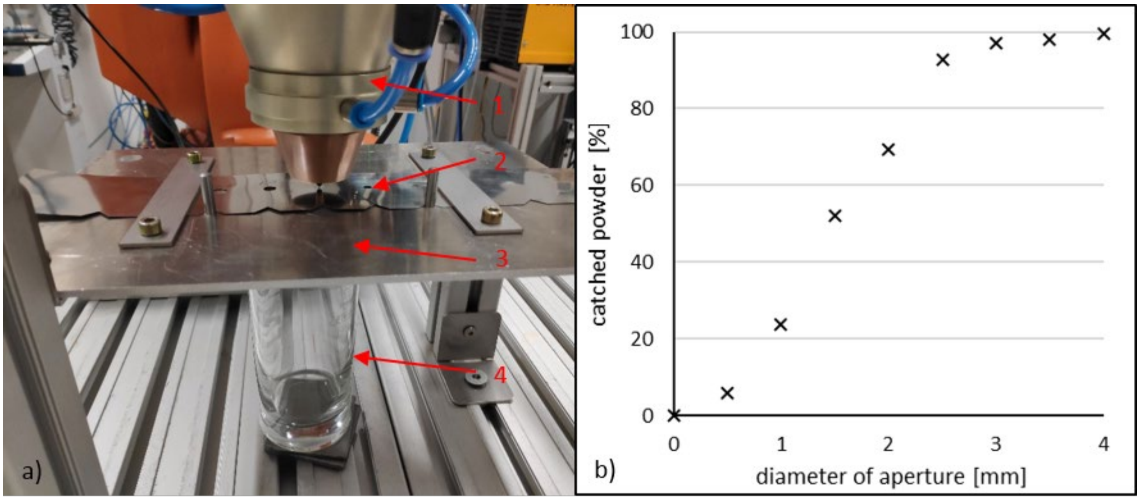


Fig. 6. (a) Experimental setup for aperture tests 1) LMD head, 2) thin foil with different aperture diameters, 3) Clamping device for thin foil and 4) glass tub; (b) catchment efficiency as a function of the aperture diameter at a constant powder mass flow

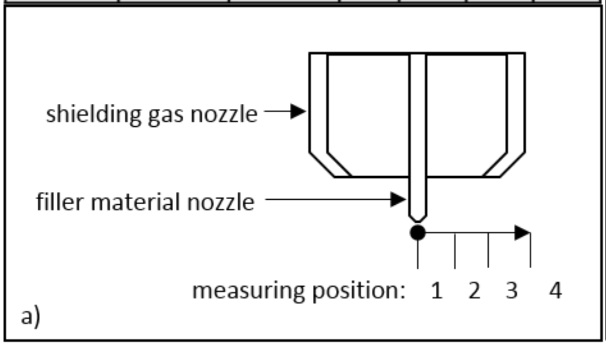
The measuring device SWM200T of the company Zirox was used to assess the quality of the protective gas shield by measuring the residual oxygen content below the protective gas nozzles. Three protective gas nozzles for the ProFocus system as well as an industry-typical three-jet coaxial nozzle as a reference object were investigated. All measurements were carried out at a protective gas flow of 18 l/min. Four positions perpendicular to the flow direction were measured (see Fig. 7). These four positions were defined relative to the outlet opening of the respective protective gas nozzle (centric in the middle of the outlet opening, half-way between the center and edge of the nozzle opening, inner edge of the nozzle opening and 5 mm adjacent the outer edge of the outlet opening).

Figure 7a illustrates the measurement strategy graphically. The variation in distance is causes by the different diameters of the individual protective gas nozzles. Powder and carrier gas were not supported during the measurement. The oxygen content was measured over the duration of 1 min. Shown are mean values calculated from approx. 70 measured values during this period (Figure 7b).

The measured values of the industrial reference nozzle show considerable higher oxygen contents at all measuring positions. A limiting factor is the very small shielding gas nozzle diameter of 7 mm and the relatively high separation distance of 16 mm, as well as the functionally integrated concept of shielding gas and powder nozzle. The size of the centrically arranged shielding gas nozzle is conceptually limited by the outer, radially arranged shielding gas nozzles. From measurement position 1 to 3, the oxygen content in the protective gas cover increases significantly from 70 to 2324 ppm.

The protective gas nozzles of the ProFocus system always show an oxygen content of less than 10 ppm at measuring positions 1 to 3. Only at measuring position 4, 5 mm outside the nozzle diameter, does the oxygen content increase up to 2088 ppm. Due to the inverse arrangement of laser radiation and the supply of the filler material, compared to the reference system, a much more effective and larger-scale shielding gas coverage can be realized with nozzle diameters up to 35 mm. At this point, the concept of the ProFocus shows considerable advantages compared to the industrially established reference system.

Shielding gas nozzle	Nozzle diameter [mm]	Working distance [mm]	Distances for measuring positions [mm]			
			1	2	3	4
ProFocus	12.2	6.8	0	3.1	6	12.8
	22.5	9.9	0	5.5	11	18.5
	35	6.9	0	8.7	17.4	24.1
Reference	7	16	0	1.7	3.4	9.4



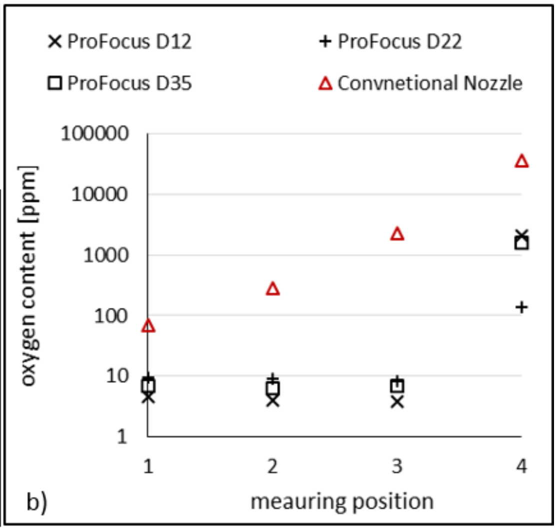


Fig. 7. (a) Measuring strategy for the evaluation of the oxygen content of the shielding gas coverage; (b) Comparison of the shielding gas coverage for the new LMD head and a conventional coaxial powder nozzle

6. Results and discussion

6.1. Characterization of powder based LMD

Fig. 8 shows the track width as a function of the energy per unit length at a constant power level of 930 W. All parameter sets which are included in Fig. 8 were performed with a beam diameter of approximately 2 mm, at a constant beam intensity.

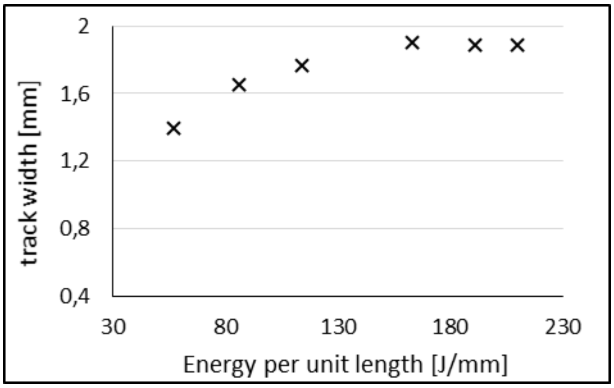


Fig. 8. Track width as a function of the energy per unit length at a constant power level

The energy per unit length shows an influence on the track width and is adapted, using the travel speed of the robot. Decreasing the travel speed is raising the track width between line energy levels of 60 up to 180 J/mm on a maximum value of nearly 2 mm. The surplus of coupled energy can be used to create wider tracks. At higher values for the energy per unit length, the track with is kept constant, because the beam diameter is defining the maximum achievable track width.

All investigated parameter sets showed really small degrees of dilution between 1 and 10%. The energy surplus which causes the extended track width does not contribute to an increase in track height. The box plots, which are marked in brown (Fig. 9a), are representing different line energy and power levels. All three boxplots are showing nearly the same heights, because the whisker of the boxplots are overlapping each other. The variation of the mass per unit length at a constant power level is affecting the track height. The mass per unit length is the main influencing variable to adapt the track height.

The increase of the mass per unit length from 4 up to 13 g/m at a constant power level (930 W) leads to an approximately linear growth of the track height. The whisker of the boxplots, which are marked in blue, green, grey and orange, are not overlapping. Consequently, the mass per unit length is one of the main influencing variables to adapt the track height. The track height can be varied in a flexible way between 0.3 and 1 mm.

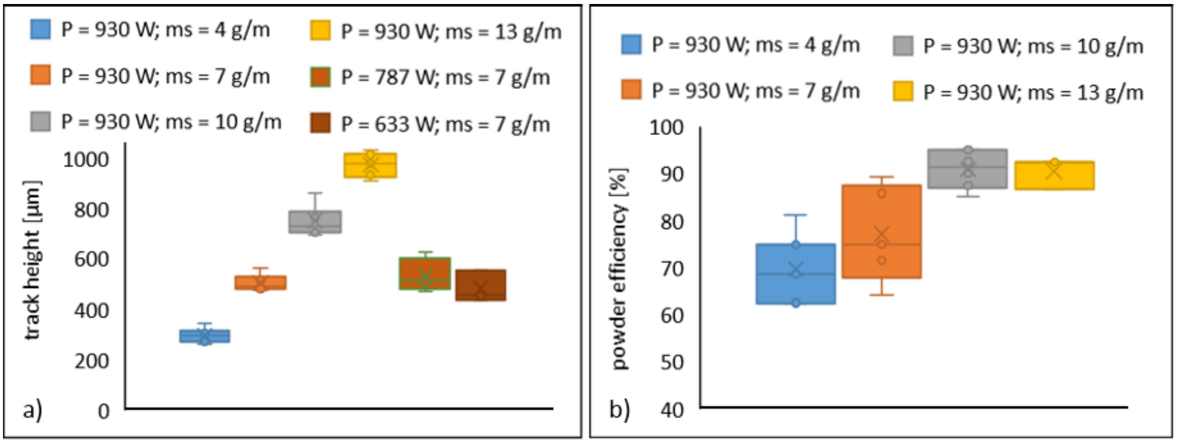


Fig. 9. (a) Powder efficiency for different mass per unit lengths at a constant power level; (b) track height for different powder levels and mass per unit lengths

Fig. 9b illustrates the powder efficiency for different mass per unit lengths at a constant power level of 930 W and a beam diameter of 2 mm. The previously presented results around the aperture tests are indicating a powder efficiency around 70% at a seam width or melt pool size of 2 mm. This value is achieved at the welding experiments, by applying the smallest mass per unit length of 4 g/m into the melt pool. The seam width is equal to the melt pool size and is one of the main influencing factors on the powder efficiency. The mass per unit length is the second main influencing factor beside the melt pool size, which can be seen in Fig. 9b. The box plots are showing an increased powder efficiency with really good maximum values larger than 90% with raised mass per unit length. The surplus of the supplied powder is guided into the melt pool and is used to increase the track height. The aspect ratio, which is defined by the ratio of the track width and the track height, is increased too. If the aspect ratio is getting to large, the contact angle of the deposition track is getting to huge. This can cause defects in 2-d or 3-d applications, when multiple tracks and layers are needed.

The single deposition tracks, which are generated with the new LMD head, are showing a homogeneous, spherical shape. Inside the substrate, a very small molten area can be observed, which is an indicator for very small values of dilution. One representative example is presented in Fig. 10. The high powder efficiency leads to a smooth surface with fewer powder particle deposits on top.

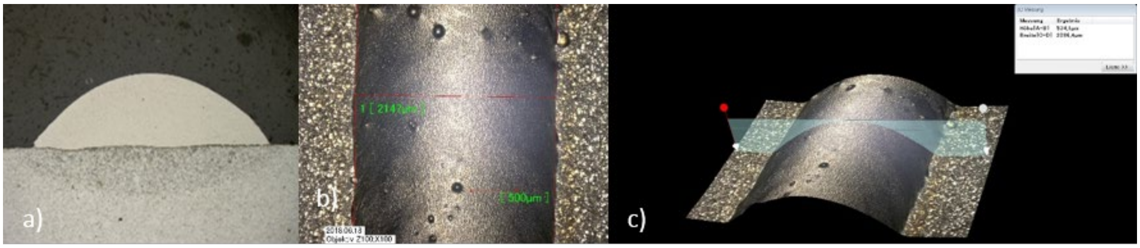


Fig. 10. Chosen parameter set for 3-d generation *(P*=930 W, m_L=7 g/m, *v*=10 mm/s) (a) cross-section image; (b) top view on deposition track; (c) 3-d image

The specimen illustrated in Fig. 10 is representing the parameter set, which was used for the 3d volume generation (P = 930 W, m_L = 7 g/m, v = 10 mm/s, d = 2 mm).

6.2. Characterization of wire based LMD

The generated results using powder as filler material are the basis for the wire experiments. The change from powder to wire can be done easily. Only the straight powder tube must be removed from the cladding head and must be replaced by the flexible wire tube.

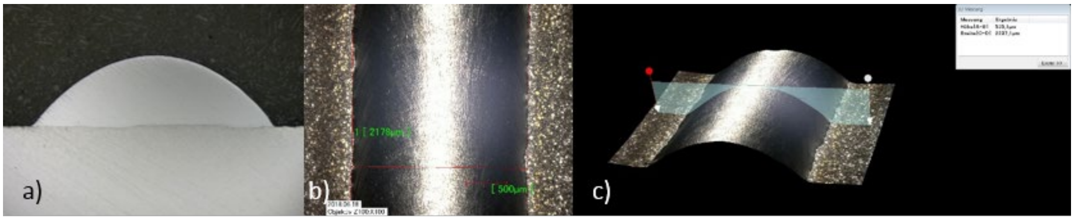


Fig. 11. Chosen parameter set for 3-d generation (*P*=930 W, wire feed rate 0,6 m/min, *v*=10 mm/s) (a) cross-section image; (b) top view on deposition track; (c) 3-d image

A wire with a diameter of 1 mm, which was made of a tooling steel, was chosen for the experiments. The previously presented, for the wire application adapted, intensity profile was used (Fig. 3b). The energy per unit length of 90 J/mm was suitable for the wire application. Approximately the same values for the seam width and the track height were achieved. Therefore, the wire feed rate was adapted in the range of the travel speed of the robot. Furthermore, it was possible to transfer the excellent values for the degree of dilution from the powder to the wire application. The deposition tracked looked basically similar to powder-based specimens (Fig. 11) and the surface quality was even better in terms of roughness and smoothness.

The shielding gas coverage seemed to be even better wire application. In contrast to the powder application, no carrier gas was needed. Because of that the shielding gas coverage is more effective, because there is no dilution of powder, carrier gas and shielding gas.

6.3. Generation of 3-d structures for powder and wire

The generated results using powder as filler material are the basis for the wire experiments. The change from powder to wire can be done easily. Only the straight powder tube must be removed from the cladding head and must be replaced by the flexible wire tube.

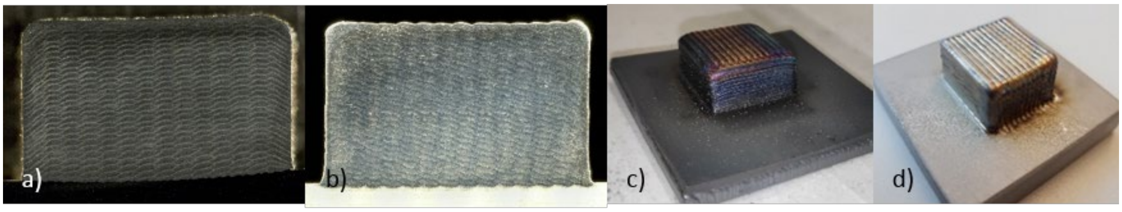


Fig. 12. Generation of 3-d structures (a) & (c) powder; (b) & (d) wire

Fig. 12 is illustrating the generated structures and the related cross-sections. The wire-based specimen shows a better geometrical accuracy in the cross-sectional image. Due to the material combination of the powder-based specimens, the substrate must be preheated to avoid cold cracks. The wire-based specimen has fewer annealing colors because no preheating is needed and the shielding gas coverage is more efficient.

7. Conclusion

The characterization of the new LMD head ProFocus1000 showed many conceptual advantages. The beam source is integrated directly into the machining head, which leads to significant advantages in beam profiling, shield gas protection and flexibility. The innovative optical design creates an adapted intensity distribution for the processing of wire applications. The arrangement of the diode stacks allows a simple, coaxial, centric supply of wire and powder as filler materials. Both kinds of filler material can be fed coaxially and independent from the direction of the movement. The inverted arrangement of the laser beam and the material feed allows an effective and large-scaled shielding gas coverage with an oxygen content below 10 ppm. The single nozzle for the powder supply creates a powder stream with a small divergence angle. Consequently, powder efficiencies up to 90 % are achievable. Deposition tracks with a homogenous surface and small dilutions between 1 and 10 % can be generated.

Acknowledgements

The project was supported by the Federal Ministry of Economy and Energy under grant number MF160095, following a decision of the German Bundestag for which the authors are very grateful. Furthermore, we want to thank the Oscar PLT GmbH for borrowing the LMD head and supporting the project as an associated partner. Thanks go to DINSE GmbH for the possibility to use the wire feeder for the research project.

References

Bliedtner J., Müller H. and Barz, A., 2013. Lasermaterialbearbeitung – Grundlagen – Verfahren – Anwendungen – Beispiele (Laser material processing – Processes - Basics – Applications – Examples), Carl Hanser Verlag, Munich.

Govekar E., Jeromen A., Kuznetsov A., Leny G. and Fujishima M., 2018. “Study of an annular laser beam based axially-fed powder cladding process”, CIRP Annals – Manufacturing Technology 67, pp 241 – 244.

Hügel H. and Graf T., 2009. „Laser in der Fertigung: Grundlagen der Strahlquellen, Systeme, Fertigungsverfahren (Laser in manufacturing: fundamentals in beam sources, systems, manufacturing processes)“, 2th Edition, Springer Vieweg, Wiesbaden, 306pp.

Kelbassa, J., Gasser A., Bremer J., Pütsch O., Poprawe R. and Schleifenbaum J., 2018. “Equipment and process window for laser metal deposition with coaxial wire feeding”, Proc. of ICALEO, 37th int. Cong. on Applications of Lasers and Electro-Optics, Orlando, USA, Paper #802.

Ocylok S., Leichnitz M., Thieme S. and Nowotny S., 2016. “Investigations on laser metal deposition of stainless steel 316L with coaxial wire feeding”, Proc. of LANE, 9th int. Conf on Photonic Technologies, Fürth.

Schulz M., Klocke F., Riepe J., Klingbeil N. and Arntz C., 2018. “Process Optimization of Wire Based Laser Metal Deposition of Titanium”, Proc. ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition, Oslo.