Cladding and Additive Layer Manufacturing with a laser supported arc process

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Abstract

This paper describes the potential of a new process, combining the geometrical precision of a laser technique and the deposition rates of GMA cladding. Dilutions as low as 3 % can be achieved, leading to a high purity, in the first layer. Different material combinations like mild steel with X45CrSi9-3 are presented. Microsections for penetration depth determination show the high quality of the deposition layers. A hardness of the coatings of 63 HRC is reached. Hardfacing of shafts serve as an application example. The low heat input enables the process to build up structures. This results in a process variant for additive layer manufacturing which is also presented. The production of macro-sized structures is shown and discussed.

Introduction

Metal deposition techniques are used for cladding and form fabrication. Both applications deposit in layers, which are formed by single seams that are welded to the underlying surface. In cladding these seams are welded directly next to each other with a slight overlap. This forms an even surface. In Additive Layer Manufacturing (ALM) more complex geometries need to be handled and the process requires higher controllability. This controllability relates to switching the process on and off. A gap in the component can be produced when the process is switched off and a deposit is made when switched on. Using this method a component is built on a substrate. The substrate material can be the same as the deposition material, especially if the substrate is part of the component. If not it can be a cheap, easy to weld material which is removed afterwards. In cladding, where functional coatings are applied to workpieces, the materials differ. Another distinction of metal deposition techniques is the size of the components. In this work a new technique will be presented. It is suited for cladding and has the potential for fabrication, in both cases in the macro regime.

Macro sized claddings and fabrications are presently done by various techniques. Plasma Transferred Arc for example is a process which provides extremely high deposition rates, but has rather high dilutions of 5-20 % [1]. Another technique is laser cladding, where high precision and almost no dilution are reached. The major drawback is the need for high-power laser systems and the accompanying high costs. An approach to reduce these costs is Plasma Augmented Laser Cladding. Here, plasma is used to heat the deposition powder just below its melting temperature. A setback is the rather low deposition rate [2].

Form fabrication experiments with gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) have been performed by Almeida et al. They were conducted with a titanium alloy as fabrication material. Applying the GTAW process, 1000 x 200 mm structures were built. The setback is the low deposition rate and a high heat input. Due to this heat input, the workpiece has to cool down to room temperature after each layer, resulting in a slow process. Cold Metal Transfer (CMT), a GMAW process with less heat input, has also been tested. The process uses a controlled current and a forward/backward oscillation of wire which is superimposing the wire feed. Despite this control the results with CMT show high penetration depth of around 2 mm [3]. To overcome this setback a laser enhanced cold GMAW process is used. The presented technique involves a GMA welding machine and a diode laser. The laser radiation is used for stabilization and guidance of the electric arc. Therefore, it is tuned to a wavelength of 811 nm by means of diode temperature control [4,5,6].

Experimental

The setup is composed of a Merkle welding machine with ColdMIG technology. The torch is at an angle of 60° in the pushing direction. A 500 W direct-diode laser, with the beam inciding perpendicular to the workpiece (Fig. 1, 2), is used in order to stabilize the arc plasma. The laser is pointing in front of the wire tip, with a slight overlap, to ensure that the laser radiation can interact with the plasma without melting the wire.

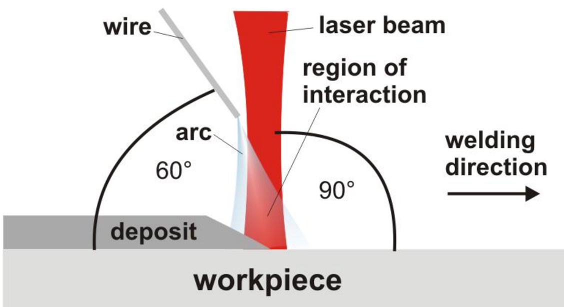

Fig. 1: *Sketch of setup alignment*

Fig. 2: *Setup realization*

Cladding of Layers

For the cladding experiments, two different material combinations are used. *Combination A* consists of structural or mild steel as base material and 1.8401, a wear resistant steel, as deposition material. In *combination B*, 1.4718 hardfacing steel is used as deposition material and mild steel as substrate.

Experiments with material *combination A* are performed on sheet metal. Therefore, an axis system is used to move the welding torch and the laser over the workpiece. After each seam, the welding head is moved back and aside by an offset s_v in order to create a layer (Fig. 3). The seam offset is fitted to the track width b_r in order to achieve an even surface.

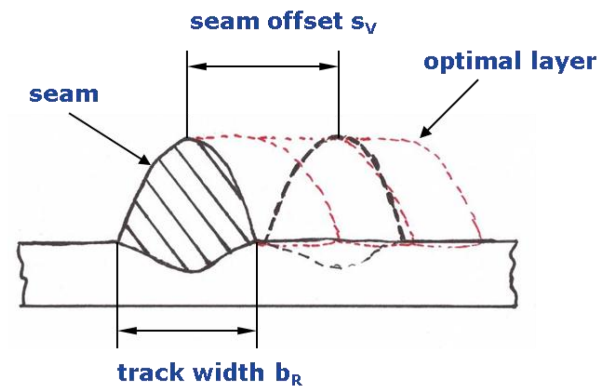

Fig. 3: *Geometrical layer parameters*

The same principle is used for the hardfacing of shafts. A combination of a rotational axis and a linear axis is used to apply the deposition material as a single, helix type seam. The speed of the linear axis is matched to the rotation so that after each full turn the desired seam offset s_v is reached.

The important process parameters are the base current I_g, the lower limit current I_a and the average voltage U which the welding machine tries to maintain. Furthermore, the ratio of the wire feed rate WFR and the feed rate of the axis system FR determine the height and the width of the seam. In all experiments a mixture of Argon and 18 % CO_2 has been used as shielding gas.

Additive Layer Manufacturing

In the ALM or form creation experiments, bar-like structures are produced using the 1.8401 steel. The mild steel substrate is not meant to be a part of the component in our tests. Its function is to carry the generated structure. The seam offsets in these experiments are perpendicular to the sheet plane and are determined by the thickness of the previous layer. They describe how much the welding head is lifted after a layer is welded. Therefore, in the first experiments, the height of the structure is measured after each layer.

Experimental Results

The experiments show promising results in the cladding and the ALM process. With the same setup, it is possible to create protective coatings and to fabricate simple structures.

Results of Cladding

The cladding experiments are performed in order to create a functional coating on a substrate with as little mixture of the materials and as low heat input as possible. For the material *combination A*, low currents together with a high welding speed show very little dilution.

Table 1: *Parameters for sheet coating*

parameter	I_g	I_a	U	WFR	FR	s_v
value	50 A	20 A	17 V	3 m/min	1.1 m/min	1.3 mm

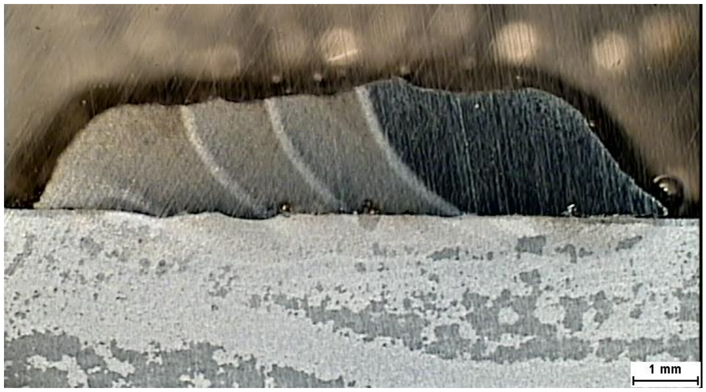

Fig. 4: *Low dilution of base and deposition material*

Fig. 4 shows a cross section of a layer produced by these parameters (Table 2). Due to the low penetration depth of 0 mm to 0.17 mm, the dilution is very low and partly there is no welded bond. The high purity of the coating leads to a hardness of around 370 HV (approx. 38 HRC).

An extreme pushing angle of the GMA torch shows good results. Fig. 5 depicts a cross section of a layer obtained by this parameter set (Table 2). For a good welding quality at that torch angle, more power in the electric arc is needed. The progression of the penetration depth in the cross section shows a wavy behavior. This leads to pores on the substrate coating boundary at the interface of the welding seams. The coating does not show pores in the volume. The reached dilution of about 10 % is higher compared to the previous shown results, but the surface has a better quality.

Table 2: *Parameters with extreme pushing angle of GMA torch*

parameter	I_g	I_a	U	WFR	FR	s_v	torch angle
value	80 A	40 A	11 V	3 m/min	1.5 m/min	1.25 mm	30 °

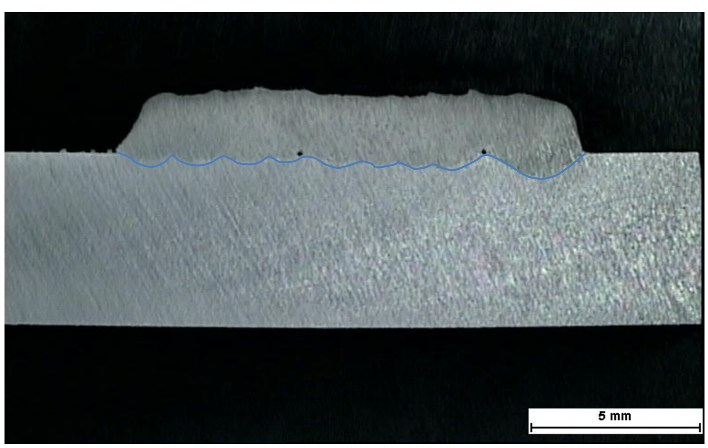

Fig. 5: *Low dilution and even surface with material combination A*

Experiments with the parameter set in Table 3, using material *combination B*, result in a coating that is properly welded to the substrate, but has some pores between the seams at the substrate boundary (Fig. 6). The welding speed for the first seam was raised to lower the penetration depth. Despite this measure, it is still higher compared to the following seams. The dilution of the coating is as low as 3 %, with about 9 % dilution in the region of the first seam and less than 2 % in the rest of the coating. This high purity of the layer leads to a hardness with an average of 63 HRC.

Table 3: *Hardfacing parameters for material combination B on sheet metal*

parameter	I_g	I_a	U	WFR	s_v	FR, first seam	FR, following seams
value	85 A	60 A	19.5 V	2.9 m/min	2.5 mm	0.6 m/min	0.4 m/min

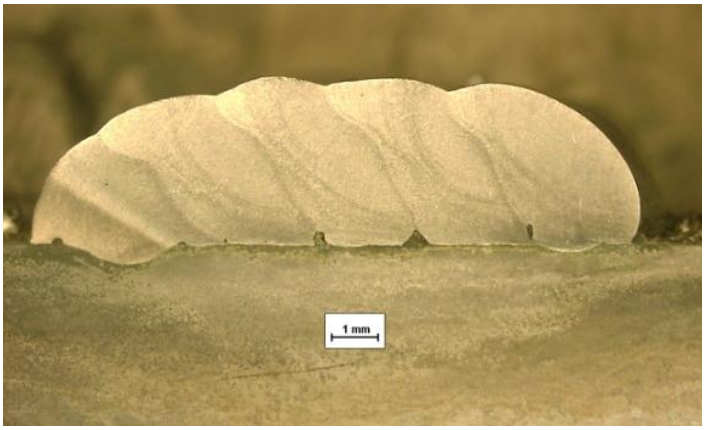

Fig. 6: *Cross section of material combination B*

A transfer of the results from sheet metals to shafts is reached with nearly the same parameters (Table 4). A decrease of the voltage and the seam offset in addition to a slower feed rate of 0.4 m/min leads to an even surface (Fig. 7) and a properly welded deposit (Fig. 8). The hardness of the coating is high at an average of 63 HRC which provides excellent wear protection.

Table 4: *Parameters for shaft cladding*

parameter	I_g	I_a	U	WFR	s_v	FR
value	85 A	60 A	17.2 V	2.9 m/min	2.25 mm	0.4 m/min

Fig. 7: *Seam helix with even surface*

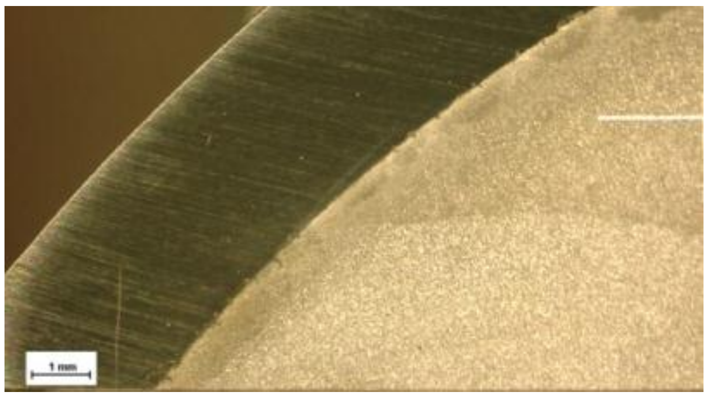

Fig. 8: *Cross section of shaft cladding*

Results for ALM

The ALM experiments are performed with the wear-protective wire material 1.8401. First results show that it is possible to build up structures by laying single seams on top of each other (Fig. 9).

Fig. 9: *Structure 90 x 27 x 6 mm, build by stacking single seams*

In these first tests it was already possible to reach an aspect ratio of the structure of 4:1. The results do not indicate a limitation for increasing this ratio. The heat flow from the welding area on top of the structure towards the substrate does not seem to decrease below a critical amount with the height of the fabricated component.

The laser improves the process significantly. Fig. 10 shows a comparison of two structures. The structure on the left has been produced without laser stabilization and the structure on the right with laser stabilization. A significant misalignment of the seams results from this lack of stabilization. An evenly erected layer-system is produced with the laser enhanced process. We assume that the laser helps to maintain the melting pool in the middle of the seam. Therefore, the melting is distributed evenly and does not flow exceedingly to one side.

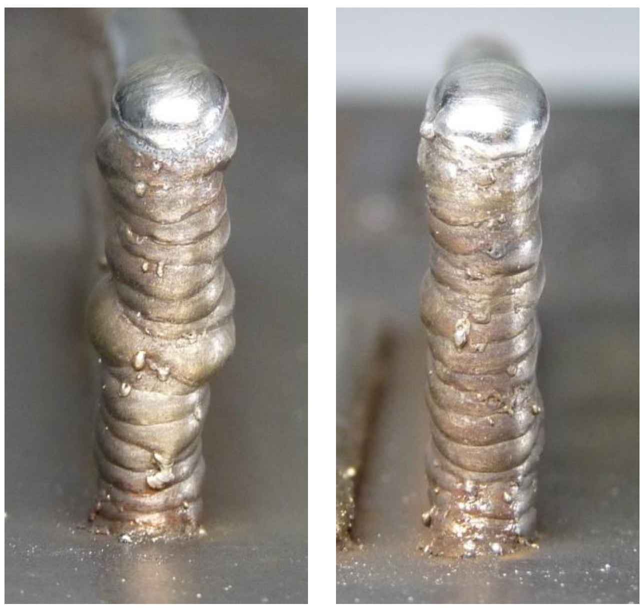

Fig. 10: *Comparison of structures built with laser stabilization (right) and without (left)*

To build this structure we measured the height after welding each layer. This information is used to determine the correct height offset of the welding head for the next layer. To overcome the additional time needed for this measuring step we have analyzed the progression of the height of the structure with each layer. A linear fit to the resulting graph Fig. 11 shows very little deviation. Therefore, a fixed height offset was tested in later experiments.

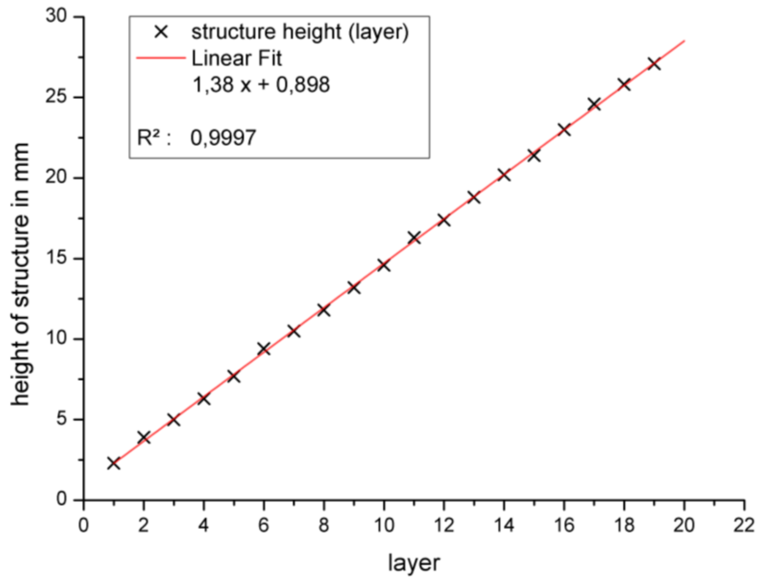

Fig. 11: *Linear progression of the structural height with each layer*

As can be seen in Fig. 12 problems arise at the beginning and the end of the structure when welding in only one, here pushing, direction. The middle of the structure shows a constant height, but since there is too much material at the beginning a build-up accumulates. The opposite is happening at the end of the welds. Not enough material is deposited and leads to a downward ramp that grows towards the middle of the structure with each layer.

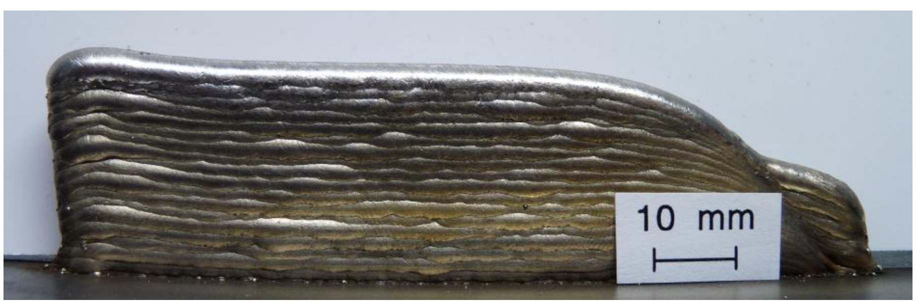

Fig. 12: *Deposit build-up at beginning and lack of material at end of structure*

The simplest way to correct for the volume issue at the beginning and the end of the structure is to weld bi-directionally. One problem is the non-symmetrical setup of the GMA torch. In previous experiments the change of the seam quality depending on the welding direction has been shown [7]. These tests have been repeated with at a slower welding speed. In Fig. 13, the seam quality, related to the welding direction, is compared. The dragging direction shows a distorted surface, whereas the surface in the pushing direction is smooth.

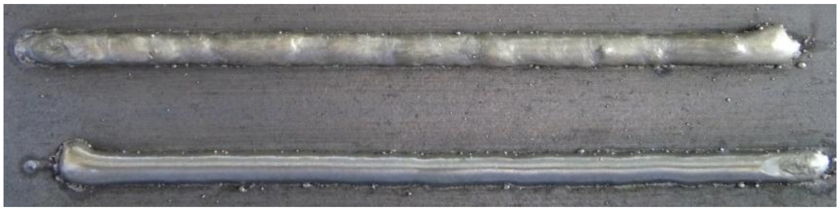

Fig. 13: *Comparison of welding directions dragging (top) and pushing (bottom) direction*

Since the bi-directional welding solution has such an appealing simplicity, we conducted further tests in two-layer systems. Two tests are performed, each without turning off the arc: a) welding in pushing direction, lifting the welding head and welding in dragging direction b) welding in dragging direction, lifting the welding head and welding pushing direction. The seams pictured in Fig. 14 both show smooth surfaces and have less volume issues at the beginning and the end of the structure.

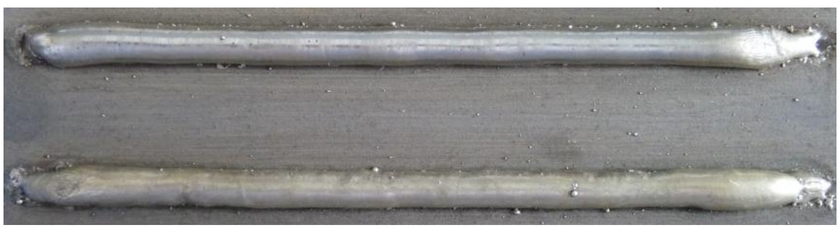

Fig. 14: *Comparison of two-layer systems: a) first dragging, then pushing (top) b) first pushing, then dragging (bottom)*

The structure in Fig. 15 was fabricated with bi-directional welding. The bi-directional welding was done in one step with 3 min delay afterwards for cooling. No height measurement was needed. Due to the consistent layer thickness, an offset of 1.4 mm per layer could be applied. There is no build-up or lack of material at the ends of the structure.

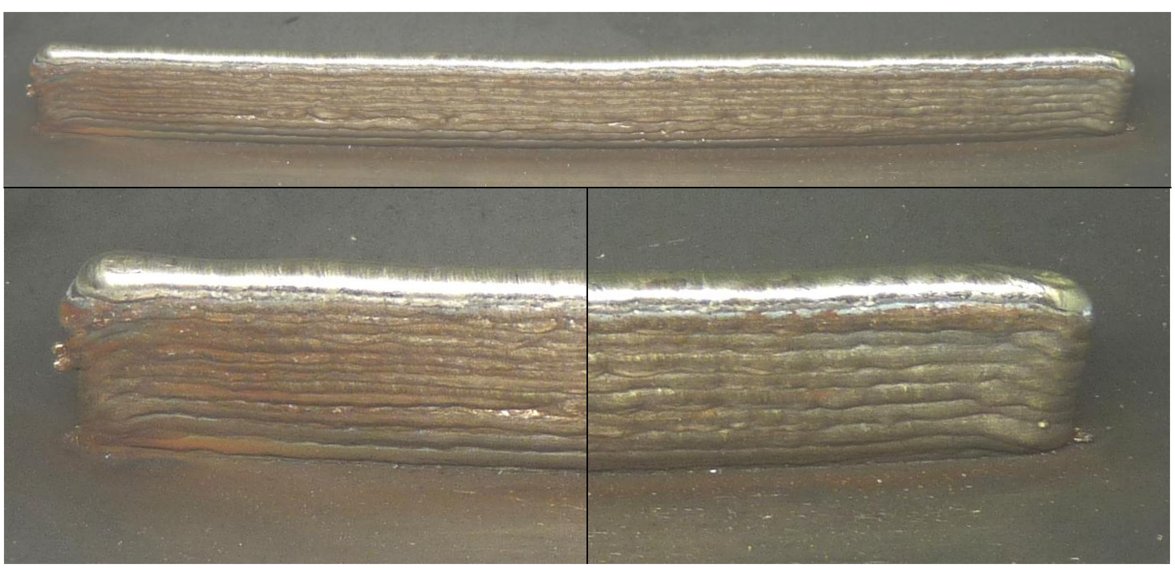

Fig. 15: *Bi-directional welded structure with fixed height offset with a size of 260 x 26 x 6 mm (top) Ends of the structure without build-up or lack of material (bottom)*

Conclusion and Outlook

We have shown that the laser assisted process can be applied in cladding and also has the potential to be used in ALM. In cladding, it is possible to weld at high speed and low power. This results in a low dilution, little heat input and a high hardness, due to the purity of the deposit.

First tests have been performed in order to reduce the penetration depth and therefore the dilution to a minimum. The penetration depth is lowered that far, that there is almost no dilution with the parameters shown in Table 1. An average hardness of 370 HV (approx. 38 HRC) was reached in the coating. The setback with these parameters is the bonding. In the middle of each seam, the materials are welded but in between there is no strong bond.

Tests with an extreme pushing angle (Fig. 5) lead to an even surface of the coating. The dilution is around 10 % due to the higher current that has been used. The few pores on the substrate coating boundary are small and should not have a negative influence on the quality of the layer, due to the properly welded bond. A setback of the extreme pushing angle is that it limits the setup's use in automated cladding of 3D contours due to a reduced free angle between workpiece and process head.

The experiments with material *combination B* are performed with adjusted parameters (Table 3). There is a welded bond of the deposit and the substrate. Only in the seam-to-seam interface are there pores at the substrate boundary level. These will be far away from the surface after the finishing of the coating with grinding. The hardness of the deposit is measured with an average of 63 HRC providing a strong wear protection. A high purity of the layer is reached due to the dilution of only about 3 %. The first welded seam on the right side of the cross section (Fig. 6) shows a higher penetration depth. This is typical for starting seams and is already reduced by a 50 % higher welding speed as compared to the welds done previously. Therefore, the dilution in this region is higher at about 9 %, whereas the dilution of the following seams is less than 2 %. With slightly adjusted parameters (Table 4), it is possible to hardface shafts with helix type welding seam, reaching similar results as on the sheet metal.

The achieved coatings are highly pure, so one layer will be sufficient where often, with conventional processes, two or more layers were needed. No pre-heating of the substrate is needed and the deposit reaches very high hardness for excellent wear protection.

Future steps will be to investigate the 3D ability of the process. Therefore, experiments in different welding positions need to be performed. Furthermore, a laser based adaption of the power distribution in the arc could lead to an evenly penetration depth, elimination of pores at the intersection of the seams and the substrate boundary.

The ALM experiments show that the laser enhancement has advantages in the generation of structures. We assume that the laser helps to keep the melting pool in the middle of the structure. Therefore, the melting is distributed evenly and does not flow exceedingly to one side. Experiments with high-speed cameras will give information about this behavior. We have shown that structures with a high aspect ratio are possible. The 4:1 ratio achieved was only a first test. There is no indication that the ratio is limited by means of the process. The linearity of the structural height with the layers allows a good prediction of the needed height offset per layer, so no measurement needs to be done as an additional process step. Problems of uneven build-up at the ends of the structures have been overcome by bi-directional welding.

The process has shown great potential for ALM but further research has to be performed. As a next step, layers with more seams in a cuboid form will be welded. The process ignition and stopping has to be optimized. Furthermore, seam height and thickness control by welding speed and wire feed rate have to be studied. In order to control the heat distortion the heat management for the workpiece needs to be optimized.

Acknowledgments

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