PROCESS CHARACTERISTICS IN HIGH-PRECISION LASER METAL DEPOSITION USING WIRE AND POWDER

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Abstract

Meanwhile laser-based Additive Manufacturing (AM) technologies such as Laser Metal Deposition (LMD) have been introduced in various fields of applications. The latter is not only used for the fabrication of complete new parts, but also for the purpose of repair and redesign. Therefore, weld beads with dimensions above 1 mm were mostly used in the past. In some cases, bead widths can even exceed 10 mm or more. However, the build-up of filigree parts by means of sub-millimeter structures has gained interest during the several last years. Fabrication of structures with small dimensions requires different process modifications along the process chain. This includes general process strategies but also adjusted system components. The changed process yields material deposition of varying geometries possibly used in aerospace, space, medical technology as well as micro tooling. Additionally, it can be also used for the repair of worn or damaged micro parts.

Within this paper, the aforementioned process modifications are shown and demonstrated. In addition, high-speed process observations are discussed and, finally, fabricated parts are analyzed. The latter includes non-destructive and also destructive methods. Based on the combination of changed process elements, a stable laser-based AM procedure is presented which is already in production.

Introduction

Initial results have been already published in [10]. However, the present paper is based on further studies not only taking into account powdery filler material, but also wire based filler.

In addition to nozzle-based Laser Additive Manufacturing using powdery material, specific limitations have been reduced at wire-based laser metal deposition during the last years.

In comparison with laser metal deposition with powder, the use of wire offers some significant advantages, e.g. highly effective material utilization, suitable productivity and clean process conditions. As basic principle, the laser beam is split into three separate beams, which are subsequently focused onto a circular focal point. (see Fig. 1). The optical elements are protected by a cross jet stream. To avoid oxidation in the process zone the shielding gas flow supplants the environmental air. Hence, the newly developed laser processing head COAXwire (see Fig. 2) is capable to perform omni-directional movements, but mostly in melt pool dimensions above 1 mm.

Fig. 1: Principle of omni-directional laser metal deposition using wire (top) and powder (bottom) (coaxial laser beams)
It can be used for laser power up to 6 kW. Actually the wire diameter is limited between 0.4 and 1.6 mm. The investigations shown in this paper will allow wire diameters down to 0.2 mm.

Fig. 2: Precise laser cladding equipment: cladding head for wire (left); cladding head for powder (right)

However, latest research projects also focus on the downscaling of mentioned wire-based system to address robust micro processes used for filigree applications. Various system modifications based on high speed observations were applied to show that wire-based LMD is also capable to generate small structures below 1 mm.

High-Precision Laser Cladding / LMD

During previous years the majority of applications, e.g. wear and corrosion resistance in offshore equipment, focused on predominantly large melt pool diameters of approx. 1 mm up to 40 mm and high deposition rates in the range of several kilograms per hour. The latter can be achieved by means of fiber-coupled diode lasers. Especially the combination with inductive energy supply led to deposition rates up to approx. 15 kg/h [1].

However, there was also an increasing need for small structures especially in the field of aviation and medical technology during the last years [2, 3]. To fulfill the requirements needed for the generation of miniaturized dense structures (as can be seen in cross-sectional view in Fig. 3), the laser process had to be modified. In line with the development of brilliant fiber and disc lasers as well as by various modifications of system components, the smallest possible melt pools could be scaled down to dimensions of approx. 30 µm which enables the rapid fabrication of various miniaturized features.

Fig. 3: Cross-section of a miniaturized structure generated by high-precision laser metal deposition with powder

Robustness and high reproducibility

High-precision using powder: Compared to the conventional laser metal deposition process, high-precision laser metal deposition is characterized by a small process window. One challenge is the required precise adjustment of the small powder spot with the narrow laser beam to allow a beneficial interaction of the particles with the radiation. Hence, the use of conventional LMD equipment led to high adjustment effort, unsatisfying reproducibility as well as low process efficiency.

In order to overcome these drawbacks theoretical process analyses have been carried out to identify important process effects including relevant parameters and their tolerances. In this way, influences were identified which haven’t played a major role in conventional laser metal deposition so far. For example, the distance between the powder nozzle and the substrate yields a strong influence on the process result which is comparable to the laser power itself. Another example is the interaction of the powder grain size and the carrier gas velocity which together affect the power distribution between the substrate and the added material [4].

Unknown process influences as well as large parameter tolerances can cause insufficient reproducibility. Based on various process models the parameter tolerances, their propagation and the impact on process results could be understood. As an example, the surface roughness which is an indication for the quality of the deposited weld bead is degraded especially by varying powder mass flow and working distance. In consideration of increased reproducibility thus a reduction of parameter variations, e.g. by precise sensor and actuator equipment, is inevitable.

Generally speaking, the solution for high precision laser metal deposition includes all relevant system components and strategies which had to be further developed to fulfill precise industrial requirements. As
aforementioned the achievable precision is significantly promoted by the integration of single mode fiber or disc lasers. In addition, the accurate adjustment of the nozzle systems but also the possibility to supply fine powdery materials with stabilized small powder flow rates is essential. Suitable process strategies have been especially adjusted to structures in the sub-millimeter range and were integrated into high-precision machine equipment.

**High-precision using wire:** The challenge in case of wire-based LMD is to ensure a stable and precise wire feed without local deviations. The wire has to be always centered in the melt pool. Small deformations which occur due to unavoidable wire processing could cause lateral oscillations of the wire close to the melt pool boundary yielding process disruptions. In the worst case the wire moves out of the laser affected zone and will not be molten up. The smaller the melt pool dimensions / wire diameters the bigger the effect of the mentioned phenomena. Hence, it became obvious that the wire condition as well as the wire supply has to be adapted to the requirements given by high precision laser metal deposition. Additional mechanical wire straightening systems were applied to overcome this drawback. The wire feeding drive of a commercially available feeder system was modified for the feeding of fine wires to improve the stabilization of the melt pool. The complex adjustment of these systems which usually is supported by software tools has to be adapted to the mechanical properties of the wire (e.g. tensile strength, young’s modulus, hardness). Nevertheless, the correct timing between laser operation and the wire feeding is essential to achieve robust process conditions. Process observation using high speed camera systems were carried out, to set up synchronous start/stop procedures.

The waiting time depends on the wire feed rate and distance between the end of the wire and the substrate. Is the waiting time too long, the wire abuts on the substrate and can buckle. Long waiting times can lead to a spherical burnup, called balling (see Fig. 4 left). On the left side of Fig. 5, a stable process is shown. The continuously fed wire penetrates vertically the melt pool and is melted. At the end of a welding seam the wire feed stops and the wire is pulled back out of the melt pool. After the stick out the laser beam is turned off (Fig. 5 right).

![Fig. 4: High speed process observations of laser-wire-melt pool interaction at different wire feed rates (X45CrSi9-3 on S235), left: balling, right: stable process](image)

![Fig. 5: High speed process observations of wire-melt pool interaction by building up a micro wall structure, left: start, middle: running process, right: end](image)

After setting up the start-stop routines it was possible to build up wall structures in an automated procedure. As an example, single tracks were placed on top of each other. By this way a wall was built up with 30 layers. The resulting structure has no cracks or pores and a low level of dilution. In comparison with powder surfaces are obviously smoother. Every single layer is identifiable by the wavy flank surface (see Fig. 6).

![Fig. 6: Micro wall-structure, 30 layers, lateral width below 800 µm, build up at 400W laser power, 1500 mm/min welding speed](image)
Performance of powder-based laser metal deposition used in precise micro applications

In comparison with wire-based high precision laser metal deposition it is possible to add rather small structures (see Fig. 7) on simple and even complex shaped parts while keeping the beneficial process properties of laser metal deposition, e.g. near-net-shape material deposition, low dilution of the base material in the added coating and a strong joint between coating and part [5].

As a result of the system modifications different applications could be already realized. They required the possibility of three-dimensional structuring and combined functionalization of freeform surfaces by precise metallic material deposition. In contrast to other competing methods like etching and subtractive laser structuring [6], each structure element can have a tailored profile and/or can be generated with varying materials.

In medical technology coatings on specific areas can improve, e.g. the wear behaviour of implant components. This can be carried out in a customized way fitted to individual requirements of patients.

Another application is the structuring on gas turbine and jet engine components: Ceramic thermal barrier coatings (TBC) which are used to protect hot engine sections are strongly affected by high working temperatures required for a high efficiency of such systems. The huge thermal load can lead to intolerable failures and delamination of the sprayed TBC. Compared to plain surfaces the filigree structuring of turbine parts improves the clamping conditions between part and TBC and, hence, improve the durability of the coating system as schematically shown in Figure 8. In these cases, the structures work as a strong thermal resistant bonding agent [7].

Surface functionalization by high precision laser metal deposition can also be applied to realize tribological optimized surfaces with well definable geometrical tailored multi-material pit patterns (Fig. 9). Resulting cavities with defined dimensions can be used e. g. for the storage of lubricants.

Latest work concerned about high aspect ratios which require highest robustness as well as reproducibility (see Fig. 10). By means of adjusted blown-powder nozzle components as well as process configurations and suitable build-up strategies, aspect ratios of 20:1 (height 3mm, width 150 µm) could be realized.
More applications can be found in the field of small tools (e.g. design modifications of micro components), labeling/marking (e.g. seals for embossed printing or direct generation of Braille prints) as well as filtering systems.

**Generation of micro parts using wire and powder**

By developing special coating strategies it is now possible to build up vertical near-net-shape pin structures with dimensions of approx. 1 mm diameter using high precision laser metal deposition with wire (see Fig. 11). The IWS COAXwire cladding head was used with an IPG 400W CW fiber laser and a modified DINSE wire feeding system. For the successful production of these small structures many cladding strategies has been investigated.

Today, similar structures are created by subtractive methods like etching, milling or laser ablation. High-precision LMD could be an economical alternative to build up such structures. These pins are used for the production of paper towels and handkerchiefs. The diameter of the current structures are three times bigger than the diameter of the used wire.

An important aspect for mentioned applications is the right adjustment of the right dimensions, a small dilution of substrate material, a requested resulting microstructure and corresponding hardness values in different regions of the build-up. As Fig. 12 exemplarily shows, build-ups meet the expectations related to hardness as well as the density in the upper section of the pin. The reasons for the jump in the hardness trend could be caused by a strong mixing of the substrate and wire material (X45CrSi9-3 on S235) on the one hand as well as different cooling rates depending on the build height on the other hand. In a certain build height the heat conduction processes were changed. This occurs the forming of different phases of the material, which result in different hardness.
There is also the possibility to generate micro volume and geometries by the placement of many neighboring weld bead layers (see Fig. 13 and 14).

Thereby the deposition rate and the achievable precision are strongly dependent on the melt pool size. Also volume build-ups are almost pore-free and can be realized close to the final shape of the part [8, 9]. The low energy input into the work piece reduces its distortion while keeping excellent mechanical properties. Comparable with conventional LMD, it is also possible to build up graded materials by powder mixing during processing.

Fig. 13: Small laser-generated stent-like structure

Fig. 14: Small laser-generated pyramid with edges of 0.5 mm and a height of 1.0 mm

Applications of this miniaturized additive manufacturing technology can be found in the generation of micro implants, e. g. for hearing aids or prostheses. The high-accuracy to build up small details can be used to individually fit bio-compatible parts to requirements of human patients. Other applications can be found in the generation of small tools, e. g. small electrodes. With the same technology different melt pool dimensions from 30 µm up to several millimeters can be realized, and, hence, part dimensions can be continuously adapted to the specific application.

Summary and outlook

The solutions for highly precise systems for very small weld bead dimensions could be added to already existing systems. In this way, precise system setups can support the range of LMD starting with a few grams per minute going up to high deposition rates of about 15 kg metal powder per hour. Next to a huge variation of feasible deposition rates, there is a factor of about three power of ten between the smallest weld bead width (approx. 30 µm) and the biggest one (< 40 mm). This can be reached by means of commercially available equipment and scientific based modifications which are predominantly related to powder delivery components as well as build-up strategies. Initially, the focus on high-precision LMD was initiated by the freeform structuring in the field of aerospace. Meanwhile, also other (potential) applications have been identified going from repair purposes up to the build-up of micro components. The modified system is in line with upcoming trends like customization and miniaturization while guaranteeing high resource efficiency and reproducibility.

References


Meet the Authors

Dr. Frank Brueckner studied automation and control engineering as well as business administration at the Technische Universität Dresden. He finished his PhD about theoretical aspects of laser cladding. Now he is group leader of Additive Manufacturing at the Fraunhofer IWS Dresden. Together with his team, he mainly focuses on nozzle-based as well as powder-bed based processes.

Mirko Riede studied mechatronics at the Technische Universität Dresden. In 2011 he has done his master thesis about high precision laser cladding at the Fraunhofer IWS Dresden. For 5 years he worked on several research projects related to Additive Manufacturing and structuring. Currently he is mainly focused on process analysis, automation and kinematic challenges.

Franz Marquardt studied mechanical engineering with focus on construction at University of Applied Sciences Dresden. At the beginning of 2016 he finished his diploma thesis about the increase of the geometric resolution of laser wire cladding. Currently he is mainly focused on experimental projects related to wire-based laser cladding at the Fraunhofer IWS Dresden.

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