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Laser metal deposition of bionic aluminum supports: reduction of the energy input for additive manufacturing of a fuselage

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Abstract

Additively manufactured components made of metallic material are subject to special consideration for many R&D departments, since the process control is not yet sufficiently reliable and therefore an extensive quality assurance is necessary. For this reason, few structural components for aviation have been established so far. In this paper, a feasibility study for the use of laser metal deposition (LMD) for the additive manufacturing of a fuselage made of aluminum is carried out. The result is a parameter set with a minimized energy input. However, due to a welding length of 58 m the overall energy input is high and large distortion arises.

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1. Introduction

The applications for various additive manufacturing (AM) technologies are continuously increasing due to a better understanding of the underlying physical and operating principles. Because of the layer-wise part building process, complex three-dimensional structures beyond the limits of conventional machining are now feasible.

For aerospace applications, the AM market is mainly driven by lightweight components made of high-performance materials. However, due to a decrease in machine and material cost of additive manufacturing, more applications with other materials have risen. While the build volume of powder bed based AM machines is still a limiting factor for many applications, nozzle based processes like laser metal deposition (LMD) or wire arc additive manufacturing (WAAM) offer the potential for fabricating larger structures with high volume builds.

In this paper, an airplane fuselage has been analyzed for the potential of being additively manufactured. In aircrafts for civil transportation, the fuselage is reinforced with stiffened shell structures. The support structure consists of frames and stringers, where the frames serve as a support for the exterior fuselage. The stringers are used as longitudinal stiffeners between the frames, thereby achieving a good stiffness to weight ratio, which reduces the weight of the airplane [1, 2]. This can be achieved as well by reinforcing the fuselage with a bionic optimized support structure rather than with standardized frames. FEM can be used to calculate the necessary stiffness of the supports in respect to the load applied on the fuselage [3]. Due to high complexity of those optimized support designs, manufacturing through conventional techniques like milling is challenging or not possible. The layer-wise LMD technology is therefore a promising approach to realize those bionic optimized support structures on thin aluminum sheets.

The fuselage of an aircraft is usually separated into four segments with an individual size of approximately 15 m. One of those segments is analyzed in the present work and scaled to a 1000 x 500 x 4 mm demonstrator.

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Different challenges need to be addressed when fabricating large scale objects like the fuselage compared to single track experiments or small volume builds. The heat transfer from the deposited track to the environment changes significantly with an increasing distance from the baseplate [4, 5]. While the solid to solid heat transfer of the first layers is small to the comparatively large baseplate, at further distances the conductive heat transfer is limited to the area of the horizontal cross section of the manufactured wall. As a result, heterogeneous material properties along the building height can be observed as well as a significant decrease in the geometrical accuracy [6].

The local energy input in combination with the high cooling rates in additive manufacturing, thermal induced residual stresses are formed [7, 8]. For deposition on thin material, the energy input has to be minimized to avoid high distortion and damage to the substrate. In order to additively manufacture a fuselage by laser metal deposition, the energy input minimization is the first step and therefore is the focus of the presented work.

2. Experimental set-up

2.1. System technology for laser metal deposition

The manufacturing of the aluminum supports was executed with a Trumpf TruDisk 6001 cw disk laser with a wavelength of 1030 nm. The spherical powder material is sieved to a fraction of 45 to 90 µm and subsequently transported through a rotational table feeder to the LMD processing head. The hardening alloy AlSi10Mg was used for this feasibility study, but does not match with the real application. The processing head consists of three coaxial nozzles for the powder. Argon gas shields the melt pool and helium serves as a carrier gas.

The experimental set-up consists of an AlMg5 substrate, a 4 mm thick copper sheet for heat transfer and a stainless steel chamber to keep the non-molten powder particles away from the surrounding (Fig. 1). The final structure is welded on a 4 mm thick sheet, which is intended to represent the thin outer skin of the aircraft. Regarding the real application, the thickness of the sheet metal needs to be reduced even further.

Fig. 1. Robot assisted LMD cell with the experimental set-up for single track experiments.

2.2. Abstraction of the fuselage

For the feasibility study, the bionic optimized fuselage was abstracted and projected on a 1000 x 500 mm demonstrator.

Since topology optimization does not take into account the restrictions of the manufacturing process, the model was first adapted to the LMD process. For this purpose, the calculated support structures were thickened by 10% in width and continuous welding paths were defined. Being a feasibility study, recalculation of the adapted structure was not carried out. The necessary support height of 50 mm was also reduced to just 4 mm.

The path planning for the structure was done according to the following welding experiments. The process parameters were initially optimized for minimum energy input. This was followed by experimental investigation of the defined nodes of the fuselage. (Fig. 2).

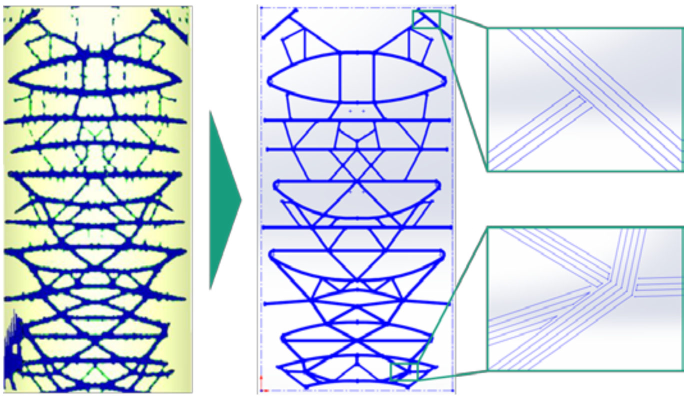

Fig. 2. Result from the topology optimization of the fuselage (left) and adapted LMD support structure (right).

The support structures have a different width (3-5 mm) and therefore a parameter needs to be defined, with which different wall thicknesses can be realized by overlapping several individual welding tracks.

In order to improve the heat transfer out of the aluminum substrate, an equally sized 4 mm thick copper sheet was cut and clamped with the substrate to the table (Fig. 5). Demmeler clamping system with a total of 40 screws were used for as a fixture.

3. Analysis of the energy input

In order to manufacture the demonstrator on a 4 mm thick sheet metal, it was necessary to optimize the process induced energy input.

While most applications aim for a high deposition rate, the optimization criteria for the following experiments were reduced energy input and dilution. The approach is to reduce the laser focus to have a smaller melt pool, which enables the laser metal deposition on thin aluminum sheets as well as supports with different wall thicknesses. These criteria were identified during the abstraction of the bionic optimized fuselage.

The first run of experiments was based on an optimized process parameter set from Fraunhofer IAPT for a high deposition rate of 330 cm^3/h with a focus diameter of 5 mm. The laser focus for the following experiments was reduced to 1.575 mm.

Through an iterative process of single track experiments, the fabrication and evaluation of cross sections of single tracks and adaptation of the parameters, the energy input was gradually reduced. For this purpose, laser power, feed rate and powder mass flow were the identified main influencing variables on the process.

Based on the process parameter for high deposition rate, these three quantities are separately varied to quantify the effect on the dilution. Focus diameter, shielding gas flow and other process variables remain constant throughout the optimization.

During this approach, a conflict of interest arises between the degree of dilution, aspect ratio (ratio between track height and track width) and adhesion of partly melted particles. An increase in the powder mass flow leads to a direct reduction of the dilution, since less laser radiation can be absorbed by the substrate as a result of the increased energy absorption of the dense powder cloud. In this case, no increased porosity or insufficient melting of the additional material was observed, but the aspect ratio raises up to 69% (recommendation 25 % [9]). With such an aspect ratio, due to the steep increase of the material in the tracks when overlapping several tracks, shadowing effects of the laser radiation may occur. This can lead to imperfections between adjacent deposition tracks. Furthermore, adhesion of partly melted particles around the track was noticeable, which can also be an indicator for insufficient bonding (Fig. 3 left).

A successive increase of the velocity leads to an increase of the dilution. This is contrary to the theory of a smaller melt pool with higher welding velocity. In addition, a relationship between the degree of dilution and the aspect ratio is observed. As the velocity increases, the dilution increases and the aspect ratio decreases. However, a reduction of material build-up around the deposition track cannot be achieved.

The adhering particles can be avoided by an increase in laser power. However, this consequently increases the degree of dilution again. This results in the conflict of optimization goals to minimize the energy input with suitable deposition track geometry.

4. Results and discussion

4.1. Preliminary experiments

As described before, minimizing the energy input leads to a conflict of interest. The following figure 3 shows the progress of the optimization from a minimized degree of dilution of 8.4 % to the final parameter without significant particle adhesion. The final parameter is shown in Table 1.

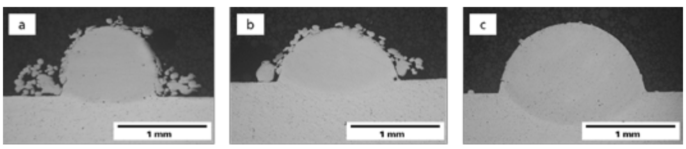

Fig. 3. (a) minimized dilution of 8.4 % but high amount of adhered particles; (b) reduced aspect ratio by increased velocity; (c) cross-section of final parameter.

Table 1. Optimized process parameter for laser metal deposition on thin aluminum sheet material.

	Final parameter
Energy per unit length [J/m]	90225
Powder mass rate [g/min]	4.4
Focus diameter [mm]	1.575

For manufacturing the demonstrator defined nodes were analyzed experimentally as described in 2.2. Walls of three, four and five overlapping single tracks were defined for the three different widths of support. The optimal degree of overlapping with the final parameter set for the individual tracks was found to be 25 % of the track width.

For path planning of individual segments of the demonstrator, a meandering strategy was used. A cross-section in the x-y-plane of two nodes is shown in the following figure 4.

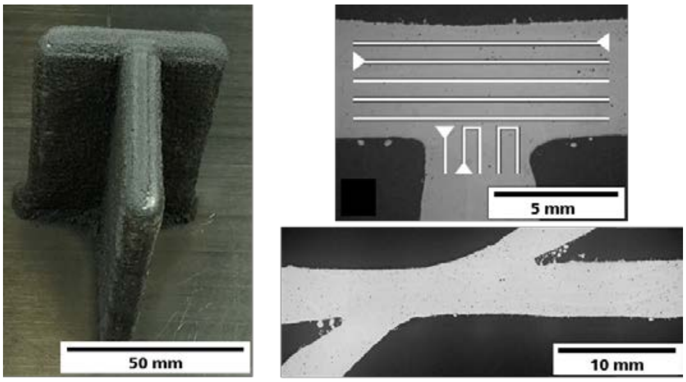

Fig. 4. 60 mm high T-joint with optimized path planning (left) and two cross-sections of different segments from the preliminary experiments (right).

The optimization criterion was the distance between the welding paths, as shown in the T-joint. When the distance becomes too small, a significant material increase of the crossing weld paths occur and accordingly, process instabilities can occur. Vice versa, if the distance is too high, a sufficient connection in the node is no longer guaranteed and the wall width decreases at this point and does not fulfill the desired geometry (see figure 4 top right).

With an increase in number of layers, a change in porosity has been observed. This relationship can be described with the changing thermal boundary conditions in the wall structure. The constant process parameters were not adapted to the thermal conditions of the previous layers and can explain the increase in porosity. Apart from that, considering the individual segments, the resulting heat accumulation is significantly greater than in the final structure because of shorter welding paths. The adaption of process parameters over build height is an ongoing research work.

4.2. Fuselage

With the knowledge gained from the preliminary investigations, the final geometry of the demonstrator can be defined.

By overlaying several individual tracks, the deposition of a single layer of the demonstrator leads to 58 m weld seam length consuming 74 minutes of welding time. A total of 4 layers with a height of 3.7 mm were built. The structure had to be cooled down to room temperature between the layers, due to a very high increase of surrounding temperature after one layer of deposition.

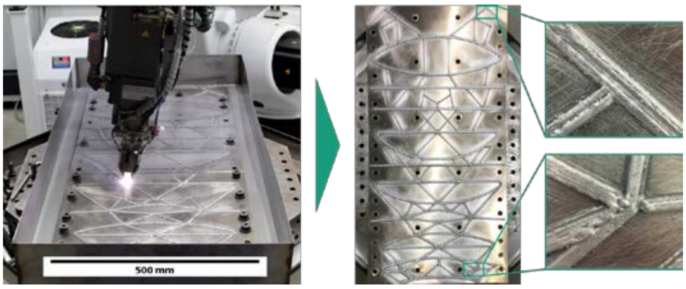

Fig. 5. Laser metal deposition of the fuselage (left) and final build with 3.7 mm high support structures (right).

The following observations were made and analyzed after the welding process:

- The structure which was divided into individual segments, were successively welded. The welding order envisages the shortest distance to the previous segment. This lead to heat accumulation in the lower part of the demonstrator, since this area was welded at the end. This resulted in an unstable melt pool and correspondingly poor weld formation (see Fig. 5, bottom right).
- The chosen thickness of copper plate was not sufficient to dissipate the input energy. Thus, in addition to the copper plate, the table reached an elevated temperature. The demonstrator had to be cooled down between the layers, as preliminary investigations showed that during the LMD process temperatures can be reached that exceed the melting point of aluminum and can cause build failure.
- Additive manufacturing of AlSi10Mg, in general, produces lower residual stress due to the high plasticity of the material compared to higher strength alloys. Nevertheless, large deformations of the demonstrator in the longitudinal direction after removal of the clamping were observed. It is assumed that the cooling between the layers increased that effect.
- The experiments were carried out with a Kuka KR 60 HA robot with a maximum reach of 2233 mm in the x-y plane (with welding head). The furthest point of the demonstrator during the deposition process was approximately 2200 mm away from the A1 rotation axis of the robot. During the acceleration of the processing head that far out, vibration of the process nozzle of several millimeters in the z-direction has been observed. Nevertheless, the geometric accuracy for those sections was dimensionally stable, but imperfections inside the material are expected.

5. Conclusion

The feasibility of manufacturing a bionic optimized support structure on a 4 mm aluminum sheet using LMD has been demonstrated.

In minimizing the energy input of individual tracks a conflict of interest arises between a minimum degree of dilution, the aspect ratio and the adhered partly melted particles. A parameter set for a minimum energy input, resulting in optimum degree of dilution (29.7 %) and aspect ratio (64.22 %) has been developed. It is possible to build very accurate geometries of different size and shape with the developed parameter set.

Longer weld seam length of 58 m over a deposition time of 74 minutes results in a high energy input over time and subsequently large deformation due to the induced stresses.

For further investigations, a process nozzle that ensures a higher absorption of laser radiation by powder rather than the substrate (for example a continuous coaxial powder nozzle) has to be investigated. With this approach, a reduction of partly melted and adhered particles while reducing the overall dilution can be expected.

Furthermore, wire and arc based additive manufacturing processes have to be examined in terms of feasibility for the examined application. With the technology of cold metal transfer (CMT), an even lower thermal load on the substrate can be achieved compared to the LMD process and is part of an ongoing research at Fraunhofer IAPT.

Acknowledgement

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References

[1] Rossow CC, Wolf K, Horst P.: Handbuch der Luftfahrzeugtechnik. München. Carl Hanser Fachbuchverlag; 2014.

[2] Klußmann N, Malik A.: Lexikon der Luftfahrt. 3rd ed. Berlin, Heidelberg: Springer-Verlag. 2012. p. 238.

[3] Klinzmann A.: Optimierung von nicht konventionellen Strukturen als Flugzeugrumpfversteifung. Göttingen: Cuvillier. 2011.

[4] Kelly, S.M., Kampe, S.L.: Microstructural Evolution in Laser-Deposited MultilayerTi-6Al-4V Builds: Part I. Microstructural Characterization, Metallurgical and materials transactions Vol. 35A, June 2004 – 1861

[5] Heilemann, M., , Möller, M., Emmelmann, C., Burkhardt, I., Riekehr, S., Ventzke, V., Kashaev, N., Enz, J.: Laser Metal Deposition of Ti-6Al-4V Strcutures: Analysis of the Build Height Dependent Microstructure and Mechanical Properties. MS&T 2017

[6] Moeller M., Ewald, A., Weber, J., Heilemann, M., Herzog, D., Emmelmann, C.: Characterization of the Anisotropic Properties for Laser Metal Deposition Ti-6Al-4V, ICALEO 2016

[7] Meiners, W.: Direktes Selektives Laser Sintern einkomponentiger metallischer Werkstoffe. Dissertation RWTH Aachen, Shaker, Aachen 1999

[8] Buchbinder, D., Schilling, G., Meiners, W., Pirch, N., Wissenbach, K.: Untersuchung zur Reduzierung des Verzugs durch Vorwärmung bei der Herstellung von Aluminiumbauteilen mittels SLM. RTejournal 2011

[9] Witzel, Johannes F. M. (2015): Qualifizierung des Laserstrahl-Auftragschweißens zur generativen Fertigung von Luftfahrtkomponenten. Dissertation. Rheinisch-Westfälische Technische Hochschule, Aachen.