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Design recommendations for laser metal deposition of thin wall structures in Ti-Al6-V4

Hannes Zapf[a,*], Niels Bendig[a], Mauritz Möller[a], Claus Emmelmann[a]

[a]Laser Zentrum Nord GmbH, Am Schleusengraben 14, 21029 Hamburg, Germany

Abstract

Today, the use of laser metal deposition (LMD) for industrial applications is increasing tremendously. Due to a high freedom in design, it offers a superior potential for weight saving in lightweight applications with higher build-up rates in comparison to the powder bed technology. However, most design engineers are used to design parts for conventional manufacturing methods, such as milling and casting, and often only have limited experience in designing products for a metal deposition process. The absence of comprehensive design guidelines is therefore limiting the further usage and distribution of LMD. In this paper, experimental investigations on the influence of thin walls and varied process strategies are presented. Thin walls have been identified as typical basic shapes used in lightweight design and were built in LMD at different orientations and overhanging angles to determine the process limits. Additionally, their geometrical accuracy is measured by laser triangulations to compare the wall's shape to the target geometry. From the results of the experiments, an outlook on design guidelines for laser metal deposition is given. For selected structures a recommendation for an optimized building strategy is shown and the underlying process restrictions are mentioned.

Keywords: Laser metal deposition; Ti-Al6-V4; design recommendations; thin walls; tilted walls

1. Introduction

Nowadays the importance of environmental and economic factors incrementally exceeds the importance of resource efficiency. The trend turns towards customized products and shows an increase in the usage of high performance materials. For example titanium is classified as such a high performance material as it is responding to lightweight design demands. An emerging manufacturing technology for customizing products

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* Corresponding author. Tel.: Tel.: +4940-484010-626; fax: +4940-484010-999.
E-mail address: hannes.zapf@lzn-hamburg.de.

is the Laser Metal Deposition (LMD) (Herzog et al., 2016), which generates components in a layer-by-layer manufacturing process (Emmelmann et al., 2013). In comparison to the powder bed fusion, LMD offers the possibility to manufacture customized products with a higher build-up rate and larger assembly space (Ravi et al., 2013). More precisely, powder is passed through a nozzle into the melting zone and melted by a laser beam. A three-dimensional component is produced by the layer-wise convergence towards a particular contour (Buchfink, 2007).

Nevertheless, there are still obstacles that hinder a broad application of LMD. For instance, the increasing post-process efforts associated with the partial dimension and the complexity of the component is a major issue (Tang and Landers, 2011). Furthermore, there is still little knowledge about fine tolerances and dimensional stability (Cottam and Brandt, 2011). In order to establish customization and design freedom as a common practice, appropriate guidelines are required for indicating the limits of the LMD process. Thus, it will be possible to make use of the full LMD potential. Preliminary recommendations for design and development strategies have been developed. Möller et al. (2016) already built thin walls with an angle up to 30°. Thin walls have been identified as typical basic shapes used in lightweight design and represent a basic geometry for numerous applications (Kranz et al., 2015). The aim of this paper is the investigation of producing thin walls LMD components through different development strategies for the production of dimensionally stable geometries.

2. Material & Method

The to be achieved component quality features are determined by numerous properties and dependencies. Examples are the required quality objectives, the properties and parameters of the production plant and build-up strategy, as well as the supplied raw material. The focus of this study is the determination of a suitable building strategy for inclined and thin-walled structures. Based on a vertical wall, two different variants are investigated (Fig. 1). On the one hand, inclined walls are built up when the vertical process head is displaced in horizontal orientation. On the other hand, tilted walls should also be constructed in combination of a base plate inclined by an angle φ. In both variants, the construction is realized by a meandering process in the direction in which the layers are built. Laser ramps were used at critical positions of the geometry – the wall start and end. Due to the double-crossing of the laser beam within a short time, heat build-up occurs due to reduced cooling times. In order to reduce the heat input and achieve a higher geometrical accuracy, corresponding ramps are driven with the laser power. The width of the test walls corresponds to a track width of the laser. In addition, a constant processing speed is used.

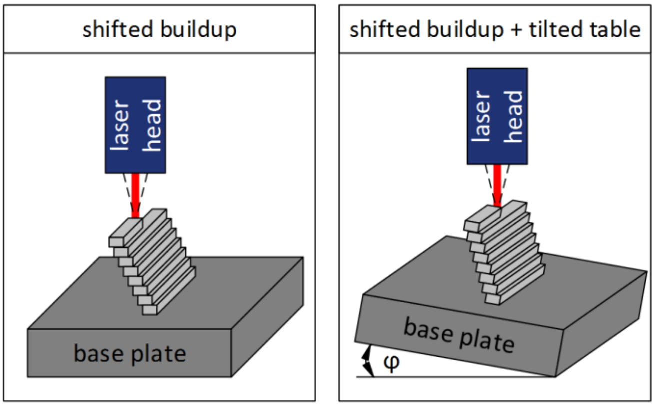


Fig. 1. Principle sketches of the two building directions

2.1. Procedure and experimental set-up

The aim of the geometrical investigations is to determine the two building strategies regarding their geometrical accuracy. For that reason, angled walls are generated in five degree steps. Subsequently, the results are evaluated according to their geometrical accuracy using a target/ actual comparison with the CAD reference model. Experiments are first performed in the horizontal plane in order to determine the maximum angle α_{max} that can be realized. α_{max} is defined as the maximum angle at which the wall is still being erected without buckling. In the next step an angle φ is determined based on which the building platform is tilted. This is intended to reduce the influence of gravity on the construction process in order to enable larger overhangs. Afterwards, walls are carried out on the φ inclined base plate. Again a maximum angle of oblique walls can be determined ($\alpha_{max\ tt}$). For statistic protection, three walls are generated for each angle.

The process of LMD is executed with a Trumpf TruDisk 6001 multi-mode continuous wave and a wavelength of 1.03µm. The processing head is equipped with a three blast nozzle, which is equipped with a rotational table feeder. Moreover, the laser cell uses a turn and tilt table in order to realize different angles of the building platform. To prevent the oxygen influence and ensure an inert atmosphere, an argon floated shield cabin is used. Measurements verify a remaining oxygen level of 50ppm. To ensure a uniform constant shield gas distribution and a minimized influence to the powder jet, the gas flows through several distribution nozzles from different directions (Fig. 2). The used spherical Ti-6Al-4V powder has a particle size of<80 µm. A performed measurement shows a powder mass flow of approx. 12.3 g/min. The parameters according to Fig. 3 were used for the subsequent tests.

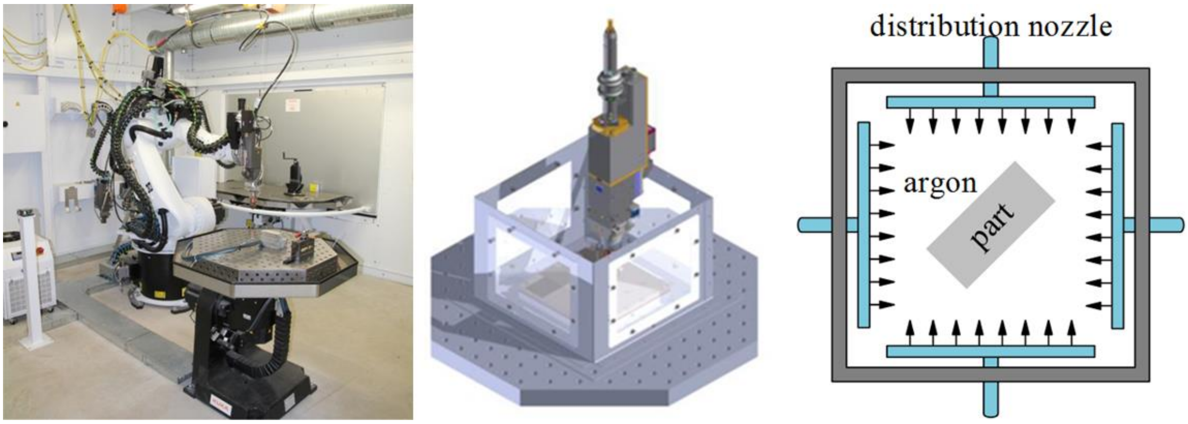
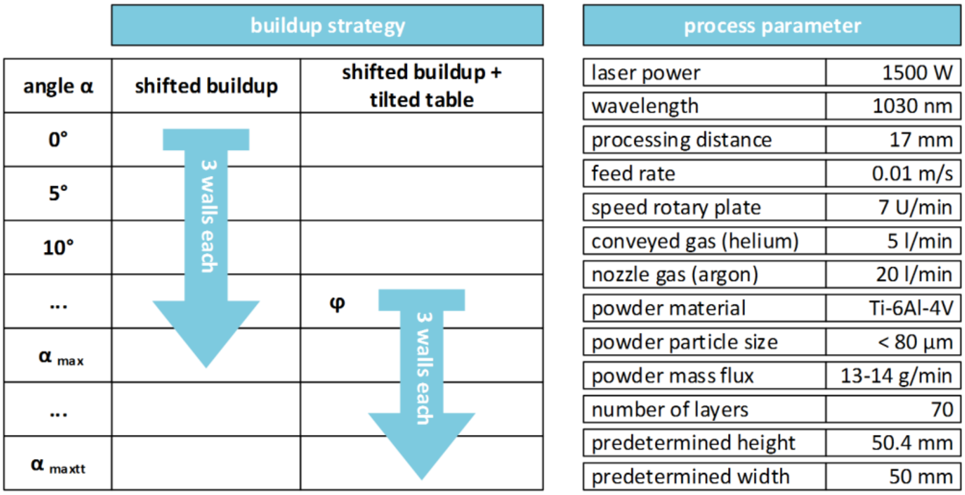


Fig. 2. (a) Robot cell, (b) shielding cabin, (c) shield gas inlet

2.2. Geometrical investigations

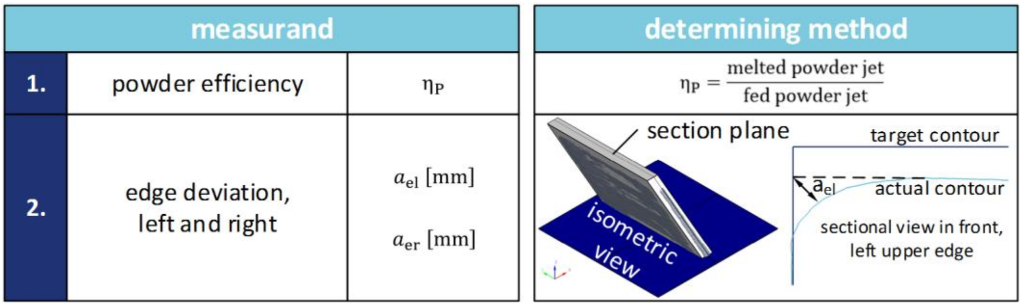
For the geometric evaluation of the different angles, generated samples are examined with respect to their geometrical accuracy and powder utilization. For this purpose the individual walls are three-dimensionally measured using a laser line scanner (Wenzel shapetracer) and a coordinate measuring machine (Wenzel LH 87 Premium X3M). Here, an associated point cloud is created and digitally recorded. To reduce the reflection of the laser beam and the accompanying increase of the measuring accuracy, the walls are sprayed white with a wet developer. Therefore, the unused points are first deleted and thinned out of the raw data. Subsequently a surface network is created by triangulation with a distance of 0.5 mm. Particularly, a virtual ball is rolled over the point cloud and a triangle is stretched at the positions where this sphere touches exactly three points. This results in a closed surface model with which the volume and the surface area can be determined. In a further step, a CAD reference geometry of the corresponding wall is positioned above the triangulated model. Finally, a target-actual comparison can be carried out. In order to proof the manufactured thin wall structures, some characteristics were defined which allow for a quantitative geometric evaluation of the geometrical accuracy (Fig. 4). On the one hand, the powder efficiency is used which describes the ratio of supplied powder and molten powder and gives a measure for the material utilization. On the other hand, the corner deviation is used as a further variable. This describes the maximum deviation a_e between the actual and desired contour in the corner. Preliminary examinations show particularly strong deviations in the corner area whereas the center of the wall can be reconstructed relatively well even at large angles.



	buildup strategy	
angle α	shifted buildup	shifted buildup + tilted table
0°		
5°		
10°		
…		φ
α_{max}		
…		
α_{maxtt}		

process parameter	
laser power	1500 W
wavelength	1030 nm
processing distance	17 mm
feed rate	0.01 m/s
speed rotary plate	7 U/min
conveyed gas (helium)	5 l/min
nozzle gas (argon)	20 l/min
powder material	Ti-6Al-4V
powder particle size	< 80 µm
powder mass flux	13-14 g/min
number of layers	70
predetermined height	50.4 mm
predetermined width	50 mm

Fig. 3. (a) Experimental plan oblique walls, (b) process parameters



measurand			determining method
1.	powder efficiency	η_P	$\eta_P = \frac{\text{melted powder jet}}{\text{fed powder jet}}$
2.	edge deviation, left and right	a_{el} [mm] a_{er} [mm]	

Fig. 4. Geometrical parameters for the evaluation of the geometrical accuracy

3. Results and discussion

First it was determined up to which angles α_{max} walls with high dimensional stability could be built with a horizontal base plate. For this purpose, a limit value was identified through visual inspection of the built-up walls and the triangulated model. As a result of this evaluation it was found that up to an angle of $\alpha_{max} = 30°$ no substantial change in shape with respect to the 0° reference wall occurs. Therefore, for the tests with a tilted base plate, the inclination angle was defined to be set at $\varphi = 30°$. This completes the experimental plan (Fig. 3).

The evaluation of the built-up walls was carried out on the basis of the parameters defined in section 2. First, the corner deviation is examined as a relevant geometric quantity. This proves to be particularly critical in geometrical accuracy and can be attributed to a resulting heat build-up. This heat build-up causes a rounding of the corner geometry as the build-up height increases due to decreasing cooling times in the edge region and the unfavorable direction of action of the gravity when large overhangs occur (Fig. 5).

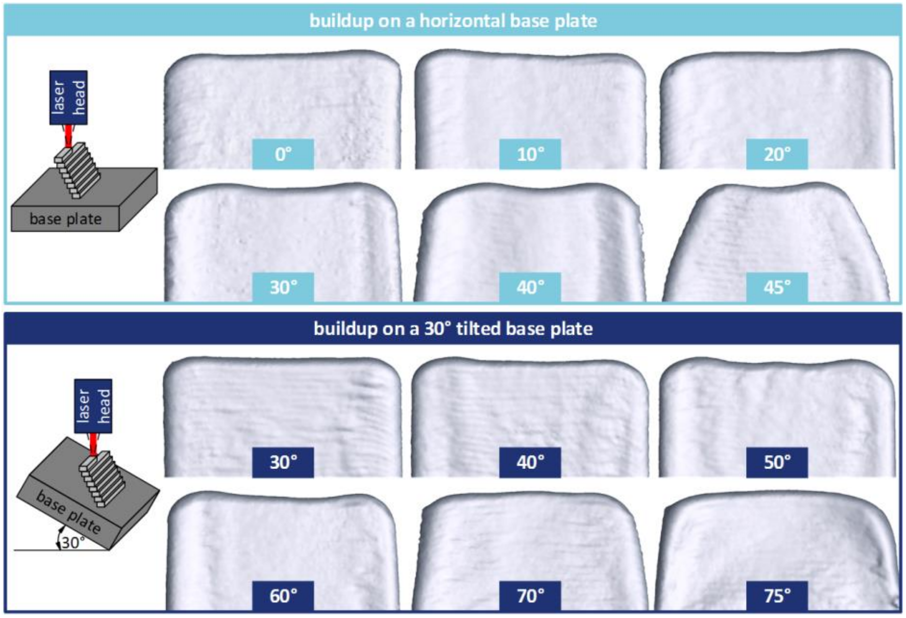


Fig. 5. Corner rounding on triangulated models for different overhang angles

The course of the corner deviation as a function of the angle of overhang is shown in Fig. 6. It can be seen that the graphs for the left and right corner of the respective build strategy have a similar profile. For the horizontal base plate the corner deviation increases approximately linear from 3 mm to 4.5 mm up to an overhang angle of 35°. For the angles 40° and 45°, an exponential increase to 12.5 mm deviation occurs with a large standard deviation of 2.2 mm. The samples of the 30° base plate show significantly smaller corner deviations up to a bevel angle of 55°. These also run approximately linear in a range from 2.2 to 4.3 mm. The rounding effect increases significantly for angles of 60° and closes at a maximum of 8.4 mm and 75°. Thus, it can be seen that higher geometry accuracy and pronounced corners can be realized by inclining the base plate.

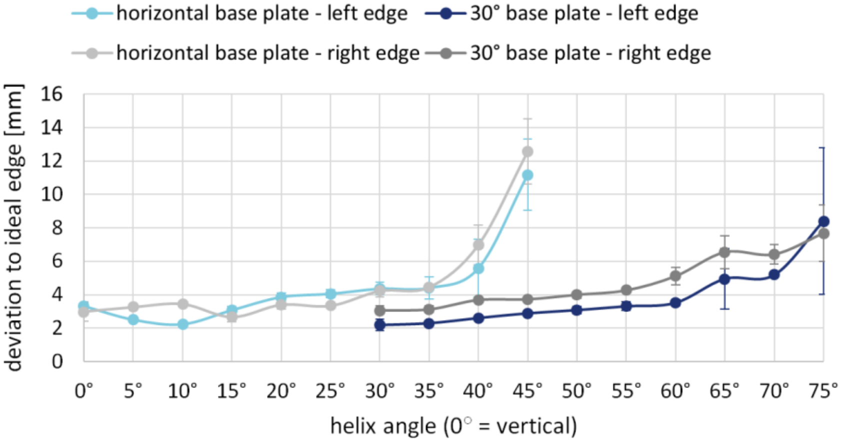


Fig. 6. Edge deviation as a function of the overhang angle

Furthermore, the powder efficiency is now regarded as an evaluation parameter. For angles up to 35° the measurement results fluctuate by the reference value of 0.69 for the powder efficiency of a vertical wall. With the horizontal base plate, the values drop at a rate of 40°. On the other hand, the graph of the angled base plate remains roughly stable at 0.67 up to a 50° angle. Even at a maximum build-up angle of 75° the powder efficiencies of an inclined base plate are better than in the case of horizontal alignment at 45° angles. Thus, it becomes obvious that the material usage can also be increased by tilting the construction platform and the amount of unused powders can be reduced (Fig. 7).

4. Conclusion

Through the introduction of geometrical parameters a quantitative evaluation of the geometrical accuracy can be carried out. The evaluation of the powder efficiency and the corner deviation enable conclusions and predictions on the geometrical tendencies. As a general trend it can be seen that with increasing overhang the geometrical accuracy and the reproducibility are reduced. The geometrical accuracy is shown in the form of increasing deviations from the reference values and the reproducibility due to an increasing standard deviation. For the samples produced on the horizontal base plate, a critical angle of α_{max} = 30° respectively 35° is obtained from where the characteristic values show an exponential deterioration. Particularly pronounced is the rounding of the wall edges in the form of corner deviations at high angles. Due to the design of the test walls on a base plate rotated by 30° to the horizontal, it is shown that the intrusion of the characteristic values can be delayed to an angle of overlap of 60°. This is mainly due to the improved direction in action of gravity.

The essential findings are summarized in the following:

- An inclined base plate allows larger overhangs to be achieved than with a horizontal platform,
- An angled base plate improves geometrical accuracy and increases powder efficiency when building inclined walls,
- Thin-walled structures can be reached up to an overhang angle of 60°.

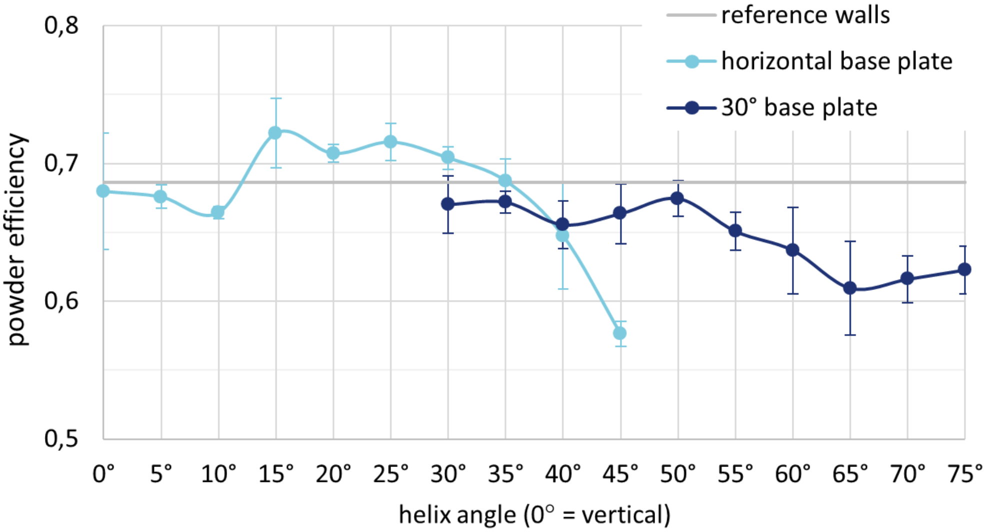


Fig. 7. Powder efficiency as a function of the overhang angle

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