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Design Guidelines For Post-Processing Of Laser Beam Melting In Context Of Support Structures

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Abstract

Laser Beam Melting (LBM) is an Additive Manufacturing (AM) process on the threshold of serial production. Therefore, LBM has to overcome different problems such as a low productivity and minor economic efficiency. Support structures are essential for LBM; however, these structures contribute to the mentioned topics, because their removal is time consuming and cost intensive. To enable design engineers and operators to increase the efficiency of LBM, design guidelines for support structures suitable for post-processing are developed. For this purpose, the effect of different design parameters on various evaluation criteria is considered. Suitability for post-processing can be evaluated in terms of cost, quality and time. Therefore, test specimens are built and parameter impacts on material consumption as well as the post-processing time is examined. Furthermore, the roughness of the parts is analyzed and used as an indicator for the removability of the support structure. In addition, warpage is measured and the impact of the parameters on this criterion is examined. Based on the results, suitable design guidelines and hints for support structures are developed in order to reduce time and costs during manufacturing and post-processing.

Laser Beam Melting, post-processing, design guidelines, support structures

1. Introduction

Laser Beam Melting (LBM) is an Additive Manufacturing (AM) process which, due to its low economic efficiency and low productivity, is on the threshold of use in series production. The support structures have a significant influence on the economic efficiency as well as productivity. Thus, they are essential for the production of parts. They are used to support parts during manufacturing and dissipate heat from the part. A disadvantage is that the support structures must be removed from the part after manufacturing. Thus, support structures lead to an increased consumption of material, an extension of the manufacturing time and necessary post-processing of parts.

By optimizing the design of the support structures, the cost-effectiveness and productivity of LBM can be increased. This paper is intended to contribute to this by developing design guidelines for support structures considering a manual post-processing. They allow to select support structures easily and to find an optimized support structure with regard to costs, quality and time. Therefore, this paper illustrates the methodology used to determine this kind of design guidelines on the basis of one design parameter of the support structure.

2. Support structures

Support structures in AM processes serve to prevent or minimize manufacturing errors. The use of suitable support structures counteracts the sinking of the part into the powder bed and reduces warpage. Warpage is caused by an inhomogeneous cooling of the part and melt pool. Support structures are also used to support overhanging part areas. Particularly in processing metal powder, such as LBM, the support structure is used to dissipate heat into the building platform. This minimizes the inherent stress distribution of the part, local hardening and crack formation tendencies. Furthermore, the support structure serves to fix the part to the building platform. The use of support structures in the LBM extends both the manufacturing and the post-processing time. [1-8]

3. Experimental investigations

To develop design guidelines for support structures, first different geometries for the support structures are selected. These are block, cone, tree, contour and hybrid support according to the basic settings in the software Materialize Magics® (see Figure 1).

Furthermore, geometric parameters of the respective support structure can be varied in such a way that the required volume of the support structure is influenced and the connection area of the support structure to the part is changed. Consequently, these parameters are of interest. These are values like radius or diameter of tree and cone support structures as well as given distances of the individual support structure elements to each other (minimum distance, hatch distance and contour offset).

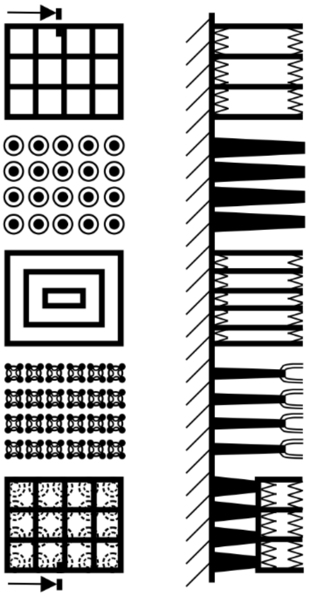

Figure 1. Investigated support structures

3.1. Test specimen

A simple rectangular geometry with a rectangular base is used to avoid possible warpage problems caused by asymmetrical parts and to simplify post-processing by straight contact surfaces. Since basic research is performed on the effects of individual parameters of the support structures in general, a complex part geometry is not required. Further investigations, which consider possible influences of the test specimen height, base area and shape as well as the height of the support structures, can subsequently build on the results obtained here. Furthermore, the production of parts with a large base area without massive and solid support structures is to be regarded as critical. To avoid critical manufacturing, a base area of 15 mm x 15 mm is used for the test specimen. A value of 5 mm is defined as the test specimen height.

Deployed from former research, a support height of 4 mm as the standard height of the support structure below the base of the test specimen has been used for tree, block, cone and contour support. The height of the support structure for hybrid support is set to 10 mm to keep the heights of the block and cone support at 4 mm while a solid layer of 2 mm is manufactured. This allows a comparison to the two support structures.

3.2. Manufacturing

The test specimens were manufactured with a SLM 250 HL LBM system from SLM Solutions GmbH. The material used is the stainless steel 316L (1.4404). The test specimens are manufactured with a standard parameter set at a layer thickness of 50 µm.

3.3. Evaluation of the support structures

The evaluation of the support structures is performed by four different criteria:

- Support volume,
- removal time,
- surface roughness of the bottom side of the part and
- warpage of the upper side of the part.

The calculated material consumption for the different support structures is derived from the support volume in the pre-processing software. These values are used in the following to evaluate the support structure on the basis of its costs. After manufacturing, the support structure is removed from the build platform. In a next step, the support structure is separated from the test specimen. A standardized procedure is used for this purpose (see 3.4.2). This is done to ensure comparability in the evaluation of the support structures. As a measure for the evaluation, the time for removal of the support structure from the test specimen is measured. This should make the effects of the parameter variation quantifiable with respect to a suitable post-processing design of the support structures. Furthermore, the finished test specimen is examined. Therefore, surface quality and the warpage are determined using optical measurement methods. Thus, the functional fulfilment of the support structures shall be evaluated with regard to warpage avoidance and the quality of the surface after removal the support structure. It is checked, to what extent the support structure design is suitable for manufacturing and post-processing.

3.4. Exemplary measurements results

In the following, exemplary results of the four evaluation criteria for the support parameter “hatch distance” of block support is given to show the different measurement methods and corresponding results. The hatch distance is the distance between the walls inside the block support. Thus, this parameter can also be used to influence the support volume and the connection area of the support structure to the test specimen. Values of 1, 2 and 3 millimetres are used for the hatch distance.

3.4.1. Support volume

By varying the hatch distance parameter from 1 mm to 3 mm, a reduction of the average support volume of 56.49% can be achieved (see Table 1). If the hatch distance is increased, the volume of the chambers in the block support is also increased. This leaves less space for the support structure due to the increase in distance from support wall to support wall. This results in a reduction of the support volume and the connection area between support and part.

Table 1 Support volume for different hatch distances

Hatch distance/mm	Support volume/mm³
1	264.17
2	151.80
3	114.95

By reducing the support volume, the material consumption and manufacturing time for the support is reduced and thus the manufacturing costs.

3.4.2. Removal time

The supporting structures are sawed off from the test specimen using a metal hacksaw. The time required to remove the support structures from the test specimen is measured for comparison purposes. The procedure is applied equally to all test specimens and support structures. Since the methodology is based on manual work, an influence of the operator on the result cannot be excluded. Here, the entirety of the determined data serves to detect possible operation-related errors and allows to make a statement about tendencies and conspicuities.

With this methodology, a possible influence of the respective parameters of the support structures on the post-processing duration is to be determined. Furthermore, this examination has to be carried out three times for each support parameter in order to verify the significance and to determine the influence of the operator.

Table 2 Removal time for different hatch distances

Hatch distance/mm	Removal time/s
1	48.6
2	32.6
3	30.0

Table 2 shows the average post-processing time for block support as a function of the hatch distance parameter. Again, it is apperant that an increasing hatch distance leads to a reduction of the post-processing time. With a hatch distance of 1 mm, the average of 48.6 s is by far the longest post-processing time. When comparing the post-processing times of the parameter values 1 mm and 2 mm, a reduction of 32.9 % can be determined. A comparison of the parameter values 1 mm and 3 mm results in a reduction of 38.3 %. An increase of the hatch distance results in a reduction of the support volume as well as the connection area of the support structure to the part. Both are due to the greater distance between the individual support walls. With a reduced connection area of the support structure to the part, the removal is again simplified and the post-processing time reduced.

3.4.3. Surface quality after support removal

Line roughness measurements of the support surface of the test specimen are used to assess the quality of the support removal. The aim is to determine a possible relationship between the parameters of the support structure and their removability from the test specimen.

A macroscope of the type VR-3100 3D Measurement Macroscope from Keyence is used for the line roughness measurements of the test specimen. In order to ensure a comparability of the results and to evaluate possible outliers of the measured values in an appropriate way, six-line roughness measurements are carried out on each test specimen in different directions on the surface. To evaluate the influence of the respective parameters on the roughness, the mean roughness value R_a is considered.

Table 3 Surface roughness Ra for different hatch distances

Hatch distance/mm	R_a/µm
1	102.3
2	108.5
3	131.3

It turns out that for the smallest parameter value, the lowest roughness results (see Table 3). For a hatch distance of 1 mm, the average roughness value is 102.3 µm and for a hatch distance of 2 mm, it is 108.5 µm. If the parameter value of 3 mm is selected, the average mean roughness value is 131.3 µm. If the hatch distance is reduced from 3 mm to 1 mm, the average mean roughness value is reduced by 22.09%. There is a tendency that a reduction of the hatch distance leads to a better surface quality of the underside of the test specimen.

3.4.3. Part warpage

LBM parts tend to bend up at the corners which is an important issue for a robust manufacturing since abortion of the manufacturing process might occur. The warpage of the upper surface of the test specimen is therefore an evaluation criterion. Higher warpage is an indication for weak support structures which might lead to higher post-processing efforts.

The warpage is determined using the diagonals on the upper surface of the test specimen. For this purpose, two profile measurements are carried out with the VR-3100 3D Measurement Macroscope and the maximum warpage is calculated.

Table 4 Warpage for different hatch distances

Hatch distance/mm	Warpage/µm
1	341.1
2	263.6
3	281.4

If the average warpages are compared as a function of the hatch distance, a parameter value of 2 mm results in the lowest average warpage (see Table 4). This is 263.6 µm and is 22.7 % lower than the average warpage of 341.1 µm for a hatch distance of 1 mm.

4. Design guidelines for support structures

Regarding the hatch distance for block support, the following results can be derived:

1. If the hatch distance is increased, both material consumption and manufacturing time can be reduced.
2. If the hatch distance is increased, the manual post-processing time can be reduced.
3. If the hatch distance is minimized, the surface roughness on the support surface of the part is also reduced.
4. The warpage is minimized for a hatch distance of 2 mm. For a further increase of the hatch distance, the warpage increases only minimally.

This allows the derivation of two design guidelines for a suitable design of block support for post-processing:

1. For a cost and time efficient design using block support, the hatch distance should be increased to a maximum.
2. The surface quality of a part can be increased by using a hatch distance of 2 mm.

5. Summary and outlook

Test specimens were produced using LBM and the influence of various parameters of different types of support were investigated by means of a parameter variation. Various evaluation criteria and test methods were used to evaluate the post-processing design of the support structures. The influence of the different parameters on the support volume and thus the material consumption by the support structures was investigated. Furthermore, a methodology was developed to quantify the post-processing time as a function of parameter variation. The methodology was applied to representative test specimens and the influence of the individual parameters was determined. Furthermore, it was evaluated which effort is needed to remove the respective support structure from the test specimen. For this purpose, line roughness measurements are carried out on the underside of the test specimen. In addition, the functional fulfilment of the support structures was assayed. The warpage at the top of the test specimen was measured using profile measurements and then the influence of the parameters on this was determined.

Based on the obtained results, design guidelines were developed for the respective evaluation criteria. An optimization of the parameters with regard to the evaluation criteria contributes to designing the support structure as suitable for post-processing as possible. If all four evaluation criteria are included, an optimization of the post-processing-oriented support structure design with regard to costs, quality and time can be carried out.

This work should be understood as a starting point for further research activity. The developed design guidelines are at first valid within the considered boundary conditions. In addition, it is problematic that the test specimens could only be manufactured and examined using a simple design. In this case, the test specimens can be re-manufactured and subsequently examined. The results of this work could thus be verified and the influence of outliers is reduced due to the larger amount of data. The procedure for the support removal should be further optimized so that the possible influence of the operator is minimized. A significant extension of the parameter variation would be useful to determine additional design guidelines as well as possible manufacturing limits. This will allow the design guidelines to be linked to exact parameter values for optimization. Statements could be made about up to which parameter values the support structures and parts are to be manufactured at all.

In addition, further parameters have to be examined in order to derive further design guidelines. Here, additional parameters should be pointed out, related to the support types examined in this paper, as well as to other support structure types. A possible influence of the part and support height, the parts base area and shape has to be investigated. Additionally, it is possible to investigate to what extent the material and the LBM machine influence the design of the support structures suitable for post-processing. The application of the developed method to a CNC post-processing should be investigated as well.

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