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Benchmark parts for the evaluation of optimized support structures in Laser Powder Bed Fusion of metals

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Abstract

Laser powder bed fusion (PBF-LB/M) of metals belongs to the advanced additive manufacturing processes on the brink of industrialization. Successful manufacturing often requires the utilization of support structures to support overhangs, dissipate heat, and prevent distortion due to residual stresses. Since the support structures result in increased costs, research, as well as industry, aim at optimizing the application of those or the support structures themselves. New approaches are validated with individual use cases, though, preventing an objective comparison of optimization strategies. This paper contributes to the advance of support structure optimization by providing a benchmark strategy including part geometries, which enables to evaluate technical as well as economical aspects of support structures or support strategies. The benchmark process is demonstrated with the help of the currently most used block and pin support structures.

Keywords: support structures; optimization; benchmark; laser powder bed fusion (PBF-LB/M); selective laser melting (SLM)

1. Introduction

With additive manufacturing exhibiting market growth rates above 26% over the last 30 years, laser powder bed fusion of metals (PBF-LB/M), also known as selective laser melting, being the leading manufacturing process in the field of final production of metal parts plays an important role in the establishment of additive manufacturing in industry [1]. To successfully manufacture metal parts, PBF-LB/M often requires support structures to support overhangs, dissipate heat, and prevent distortion due to residual stresses. Because support structures do not belong to the final part and hence need to be removed, they increase the overall costs of the parts. For this reason, numerous approaches on optimizing support structures are found in literature, which can be categorized according to their overall goal [2]: (1) Reduction or avoidance of support structures, (2) Optimization of existing support types, and (3) Creation of new support structures. To reduce or even completely avoid the use of support structures, the design process offers several possibilities. While the compliance with design rules, either manually or by utilizing topology optimization [3-5], is the most obvious approach, the correct choice of the part orientation on the build platform [6-8] is an essential tool given that the geometry of the part is fixed. Other studies aim at incorporating finite element method to properly choose the sections in need of support as well as the appropriate amount of support [9,10]. Mumtaz et al. [11] explored the possible combination of eutectic alloys and specific process parameters in order to avoid the use of support structures. Nonetheless the efforts put into this category of support structure optimization, until a product is designed completely for additive manufacturing, there will always be a need for support structures, though.

With regard to already existing support types, a lot of research is done to optimize the geometry of those by determining the limits of manufacturability [12] or introducing

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new features such as perforation or additional material for improved heat dissipation [13-15]. Furthermore, support structures can be built using specific process parameters [16] to tailor them to the expected loads. Lefky et al. [17] as well as Hildreth et al. [18] take the first steps to transfer the multi-material approach common in polymer additive manufacturing to metal processing. Despite the extensive research done within this approach of support structure optimization, the success is limited to use cases ideal to the already existing support types.

The creation of completely new support structures has been becoming increasingly popular during the last years. The design of unit cells, especially lattice structures, is a promising approach in terms of support volume reduction that is capable of keeping the needed computational resources at a reasonable level [19-22]. Because of the overall space the unit cells occupy this approach is limited to the support of surfaces. To design completely individual support structures, algorithms such as topology optimization [2,23-25] or other computational algorithms [26,27] are employed.

A major issue in support structure optimization, though, is the lack of standardized part geometries for validation, hampering the objective assessment of the different approaches. While in the field of polymer material extrusion (MEX/P) certain models such as the minotaur, gymnast, or rabbit [28-30] have been somewhat established as commonly used validation geometries (even though they do not allow a systematic technical assessment) there is no such geometry in PBL-LB/M besides the cantilever beam [2]. The cantilever beam represents a simple use case to quantify residual stresses and is not fit to thoroughly examine support structures, though. Jiang et al. [31] addressed issue of standardized geometries in the field of polymer material extrusion (MEX/P) by designing a single benchmark part. Since MEX/P support structures are only needed to support overhangs, the developed benchmark part focuses on features related to overhangs. This is not sufficient for PBF-LB/M, leaving a need for benchmark parts for the evaluation of optimized support structures in PBF-LB/M.

This study aims at creating a standardized procedure for PBF-LB/M to assess the performance of support structures and general support strategies because the way of the utilization of currently applied support structures can also influence the manufacturability of a part [12]. Therefore, the benchmark parts do not characterize support structure properties such as tensile strength directly but provide a set of common features testing the overall performance of the support structures regarding those. To ensure the wide applicability of the benchmark procedure, care has been taken to integrate measurement methods that are broadly available. Additionally, all files required for a quick and reliable implementation of the benchmark procedure (CAD files, evaluation sheet, manual) are provided under CC BY-SA license via the research data repository of Hamburg University of Technology [32].

2. Development of the benchmark procedure

In the first step, the criteria suitable to evaluate the performance of support structures are determined. On the one hand, the criteria have to meet the general requirements of a benchmark to create a valid comparison: benchmarks need to be objective, valid (criteria not influencing each other), reliable (measured variations are significant), and reproducible. On the other hand, several technical as well as economical details shall be assessed, which are representative of the overall task of support structures. To define relevant criteria, the consequences of a poor support structure performance are considered (see Tab. 1), since they provide identifiable characteristics of support structure performance.

Table 1. Consequences of poor support structure performance.

Task	Consequence of poor performance
Supporting overhangs	Overhangs not build, dross formation, distortion, delamination
Dissipating heat	Discoloration, distortion
Counteracting residual stresses	Distortion, cracks, support structure detachment, part detachment from the substrate

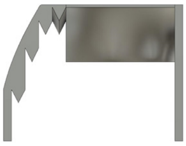
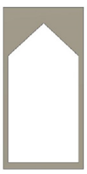
Based on the characteristics displayed in Tab. 1, a two-phase procedure for the technical performance assessment is proposed. First, a qualitative visual inspection of the benchmark parts is carried out. Here, the existence of cracks, notches, distortions, discolorations, delamination, edge errors and any detachment of either part or support structure is noted. Second, criteria that can be quantified are assessed in detail. To keep the benchmark procedure simple, the second phase is restricted to geometrical means, since they can be measured via images and coordinate measuring machines (CMM) with no need for complex laboratory setups.

Besides the technical performance of support structures, the economic point of view due to the increase in costs is also of interest. Therefore, a dedicated third phase is added to the benchmark procedure. Here, the focus lies on three aspects that greatly influence the support structure costs [33]: material consumption, ease of support structure removal, and the influence on the surface quality. To determine the material consumption, the benchmark parts are weighted before and after support structure removal, because the volume of the digital support structures does not include possibly entrapped powder. The ease of removal is assessed according to the scale proposed by Gralow et al. [3]: (1) Close to no resistance/very easy to remove, (2) low resistance/easy to remove, (3) medium resistance/moderate effort to remove, and (4) high resistance/hard or impossible to remove. Here, the resistance of the structure against removal respectively the necessary effort for removal is judged by the responsible person. Only manual support removal is considered. Additionally, the time needed to remove any residuals of the support structures is measured. The goal of the post-processing is a state where the effect of the support structures on the surface does not influence further surface finishing by sandblasting.

In regard of the surface quality, which is influenced by material residuals or even craters, the supported features are visually inspected and rated applying the following scale: (1) residuals can be removed by sandblasting (commonly applied post-processing method, no further effort due to support structures), (2) Residuals need to be removed by files, and (3) pitting (existence of craters).

To develop the benchmark procedure, the criteria and measurement methods defined in the first step are mapped to common geometrical features found in parts manufactured by PBF-LB/M. Support structures are generally used for overhanging features, which can be planes or edges. Furthermore, the planes and edges can be straight or curved. A special case is the merging of two structures into one. Paying attention to the results of step one and the identified geometrical features, five benchmark parts are designed, whose features are summarized in Tab. 2. The exact dimensions of each respective feature, which are based on many years of experience in determining and optimizing process parameters for a broad range of metal alloys within the research group, can be taken from the CAD files [32]. In general, the size of the benchmark parts is kept at 50mm height and 20mm thickness as a compromise of cost and reliable measurement of geometrical features. Additionally, to avoid that interfacing features of the support structures, e.g. tooth geometries, influence each other, a minimal support height of 30mm is planned for.

Table 2. Benchmark parts and their features.

Part No.	h x w x d [mm]	Features
1	 52.5x52x30	• Straight surfaces with 0°, 10°, 20°, 30° inclination • min. support height: 30 mm
2	 50x66x20	• Straight edges with support heights of 15 mm, 30 mm, 40 mm • Edge with curvature in horizontal direction • Edge with curvature in vertical direction
3	 57x90x20	• Holes (curved surface) with 56 mm, 36 mm diameter
4	 50x25x20	• Structural transition, edge • min. support height: 33 mm
5	 50x25x20	• Structural transition, curved • min. support height: 33 mm

Part no. 1 includes overhanging planes. Since surfaces with an inclination angle of 0° to 30° (with regard to the build plate) need support [34], this interval is covered with a step size of 10°, leading to four respective planes. To allow for a representative plane, the size of the part is slightly altered from the general dimensions described earlier in terms of height and thickness. Part no. 2 integrates the edge overhangs. On the one hand, the ability to build the support structure over various heights is tested by incorporating straight edges with different distances to the ground. Furthermore, two edges with a varying contour in vertical (continuous arch) as well in horizontal direction (wavy curve) challenge the support structures ability to follow an edge. With holes as the key feature, part no. 3 represents the case of curved planes. Two different diameters allow for the interpretation of different curvatures. Part no. 4 and 5 tackle the special case of the merging of two structures, in this case the merging of two thin walls. While part no. 5 integrates the continuous merging via an arch, also adding a third (smaller) diameter to part no. 3, part no. 4 features the discontinuous merging by an inverted edge, challenging the support structures ability to prevent distortion of the thin walls while manufacturing the upper area of the part.

In terms of geometrical aspects that are measurable, the following features are integrated: At the overhangs of part no. 1, the angle deviation as an indicator of residual stresses as well as the edge deviation as a mean of heat dissipation (particle sinter on the edges when temperatures are too high) are measured. Part no. 3 provides holes where dross formation can occur at the top of the holes if not properly supported, therefore the deviation in diameter is evaluated. Last, the levelness of the side surfaces of part no. 4 and 5 indicate how well the structural transition has been held in place, so the deviation of the upper and lower edges is measured. Part no. 2 is only evaluated in the first step and does not include any measureable features.

3. Validation of the benchmark concept

To validate the developed benchmark procedure, it is applied to common support structures, whose general performance is well known. The block support consists of thin, perforated walls, which are positioned in a two-dimensional grid. Block supports are considered non-solid support structures [3] and mainly applied to surfaces because of their 2D appearance. Pin supports have opposite characteristics compared to the block supports. Their geometry is represented by columns, which are not connected to each other. That is why pin supports are categorized as solid support structures [3]. Pin supports are mainly applied to edges and where high residual stresses are expected since the volumetric nature results in higher strength. Evaluating [3] with regard to the characteristics of block and pin supports, the following results of a direct comparison are expected by the authors:

- Supporting overhangs: block supports will perform better on surfaces, pin supports on edges
- Dissipating heat: pin supports will dissipate more heat than block supports because of the volumetric geometry compared to the single scan, perforated walls of the block support, even though the overall volume may be smaller
- Counteracting residual forces: pin supports will be more effective than block supports because of their higher strength

- Material consumption: pin supports have a greater individual volume, but block supports are connected and prone to powder entrapment, therefore block supports will have higher material consumption
- Removability: block supports will be easier to remove and leave fewer residuals than pin supports because of their non-solid nature and comparatively small interface cross-section

The data preparation, i.e. generation of support structures as well as slicing, is done using the software Materialise Magics (Version 20.01). The production system for the manufacturing of the benchmark parts is the SLM500HL (SLM Solutions AG, Lübeck, Germany). The build chamber employing a build platform of 500x280mm² allows distancing the respective benchmark parts in a way that they do not influence each other.

The material of the benchmark parts is Ti6Al4V. A standard set of process parameters (see Tab. 3) as well as argon atmosphere is applied. For the benchmark, each of the five parts is manufactured once, all together in the same build job and slightly scaled down in size to meet material availability. An alternating scan pattern is chosen. After manufacturing, the parts are manually cleaned and detached from the build platform by wire electrical discharge machining. Geometrical measurements are performed using the CMM type Wenzel LH87 (WENZEL Group GmbH & Co. KG, Wiesthal, Germany) equipped with an optical measurement device.

Table 3. Process parameter applied in validation.

Parameter	Value
Laser power [W]	240
Scan velocity [mm/s]	1200
Hatch distance [µm]	100
Layer thickness [µm]	60

The results of the visual inspection of all five parts are shown in Fig. 1 and summarized in Tab. 4. All parts have been successfully manufactured regardless of the support type. The block supports resulted in more cracks (e.g. as seen in Fig. 1a), occurring in part no. 1, 2 & 3. In terms of discoloration, the block support is more severely affected than the pin support: part no. 3-5 show light discoloration in areas with large volumes, part no. 2 even strong discoloration, whereas for the pin supports part no. 2 is only slightly discolored (Fig. 1b&d). Furthermore, some of the outer block supports detached in part no. 3. On the other side, the pin supports resulted in a notch at the bottom of the 50mm diameter hole of part no. 3. Since the notch is localized at the bottom of the hole, the notch is attributed to the manufacturing system though, not to the pin support.

Tab. 5 displays the measurements of the CMM. Overall, the pin supports result in greater deviations compared to the block supports, nearly doubling the values of the block supports.

The data gathered for the economic evaluation is presented in Tab. 6. Here, the data of all five parts for material consumption as well as the time needed for removal is summed up, while the rating of the removal of the supports is averaged. The block supports consumed more material and took

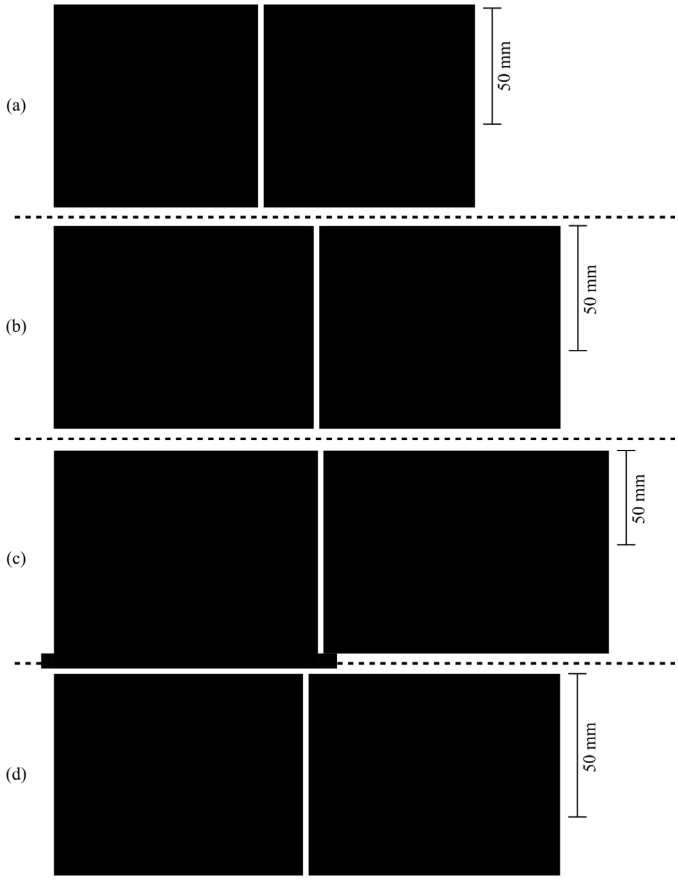


Fig. 1. Benchmark parts (left: block support, right: pin support) prior to support removal, with indicated visual issues. (a) Part no. 1, (b) part no. 2, (c) part no. 3, (d) part no. 4 and 5.

significantly longer to be removed, although they were easier to remove than pin supports. In terms of material consumption, the weighting result for both support types was 5% higher than the theoretical material calculation from the volume of the digital support structures, highlighting the need for weighting. The pin supports resulted in a surface quality worse than the block supports, see Fig. 2. This also shows in the time needed for the post-processing of the surface, which is nearly triple the amount necessary for the block supports. The detailed data that is shown summarized in Tab. 4 – 6 is available in the Excel sheet of [32].

Considering the results of all three benchmark evaluation steps, the following statements regarding the differences between block and pin supports are made: (1) Pin supports have a higher tensile strength than block supports. This is mainly

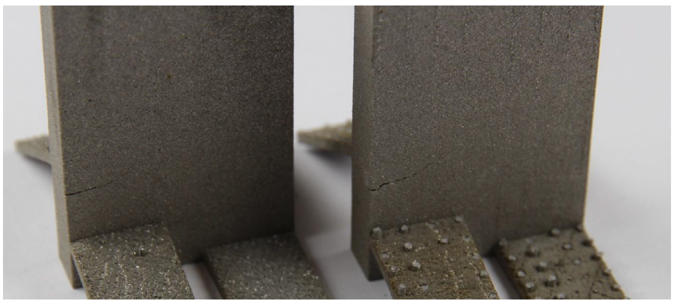


Fig. 2. Benchmark part no. 1 (left: block support, right: pin support) after support removal.

evident in the increased number of parts with cracks and detached support structures. (2) Block supports have higher shearing resistance than pin supports. The grid layout of the block supports creates a stable structure in terms of shear forces. In the benchmark, this is visible in the geometric deviations, especially in the smaller edge deviation of side surfaces compared to the pin support. (3) Pin supports dissipate more heat than block supports. The lower discoloration of the benchmark parts indicates that a lower temperature was reached faster than within the benchmark parts with the block supports. (4) Pin supports require less material than block supports. (5) Block supports are easier to remove and result in a higher surface quality than block supports. Even though the time necessary solely for the removal of the support structures is higher compared to the pin supports, the post-processing time is significantly lower, and the ease of removal is slightly better.

Table 4. Results of the qualitative inspection (step 1).

Criterion	Block support	Pin support
No. of parts successfully built	5	5
No. of cracks	5	3
No. of notches	0	1
No. detached support structures	1	0
No. of parts with light discoloration	3	4
No. of parts with strong discoloration	1	0

Table 5. Results of the quantitative evaluation (step 2).

Criterion	Block support	Pin support
Edge deviation of overhangs [mm]	0.41	0.72
Angle deviation of overhangs [°]	0.90	1.60
Edge deviation of side surfaces [mm]	0.28	0.43
Diameter deviation of holes [mm]	0.22	0.15

Table 6. Results of the economic evaluation (step 3).

Criterion	Block support	Pin support
Material consumption [g]	88.89	71.24
Time for removal [h:min:s]	00:32:30	00:17:00
Time for post-processing [h:min:s]	00:25:00	00:65:00
Ease of removal [-]	1.8	2.0
Surface quality after removal [-]	1.2	2.2

Reviewing the formulated expectations of the benchmark (see beginning of Section 3), it is concluded that the results meet the expectations. Only the first thesis regarding the preference of the support structures towards either surface or edge supporting is not confirmed: Both support types were able to successfully support every feature. This may be due to the small distance of the pin supports (maximum distance of 2 mm), which allowed for the support structures to effectively support a surface. In terms of the block supports performing on the edges, the block supports were positioned at the edge as well as a small zone beneath the edge. This makes it possible for block supports to act on edges, but increases the post-processing effort significantly if any residuals are present after the removal of the support structures. Additionally, this concept is only possible due to the broadening of the edge with increasing height; if the edge represents the beginning of a small overhanging wall, block supports might not be able to sufficiently support the edge.

One issue, which became apparent during the evaluation period, lies with the interpretation of cracks. Cracks can occur due to stresses perpendicular or parallel to the build platform. Only the perpendicular stresses indicate a fault in the support structure layout, they are not able to counteract stresses in the build plane. Therefore, caution and experience are necessary for a correct interpretation of cracks and a decision whether to include them in the benchmark result.

4. Conclusion

In PBF-LB/M, the optimization of support structures is important to the successful manufacturing at minimal costs. Current optimization approaches do employ their own use cases for validation though, hindering the objective comparison of the approaches. In this paper, a benchmark procedure was developed to enable the direct comparison of different support structures or strategies. The procedure includes a qualitative inspection, the quantitative evaluation of geometrical key factors, and the evaluation of economic aspects. All tasks of support structures, namely the support of overhangs, heat dissipation, and the counteracting of residual stresses, are considered in five distinct benchmark parts. The validity and significance of the procedure are demonstrated with the help of two common support structures, the block and the pin support. The benchmark results meet the expectations derived from experience:

1. Pin supports have a higher tensile strength than block supports.
2. Pin supports have a lower shear resistance than block supports.
3. Pin supports dissipate more heat than block supports.
4. Pin supports require less material than block supports.
5. Pin supports are harder to remove and result in a lower surface quality than block supports.

Today, the cost due to support structures are displayed indirectly by the material consumption as well as the time needed for removal and post-processing. To gain more insight into the cost evolution, the development of a cost model for PBF-LB/M support structures is a goal of future work.

Furthermore, the benchmark procedure can be extended by a quantitative characterization of the support structure performance. Possible experimental setups include tensile tests, or bending tests to evaluate the effort necessary for the support structure removal, substituting the subjective assessment by the operator. Additionally, while the dimensional and shape accuracy is already evaluated by the optical measurements of the CMM, the surface quality is not assessed in detail. Optical measurement of the surface roughness via microscopy could provide insights into the processing of the material as well as the heat dissipating capability of the support structures. The integration of such experimental measures requires thoughtful design of the specimen as well as the experimental setup, though, to ensure a fair comparison of support structures designed for specific applications; e. g. testing a support structure optimized for surfaces with only a single line or vice versa may lead to wrong or imprecise conclusions. Also, to conduct those experiments, one must have access to a broad range of testing equipment.

Benchmark procedures are only useful if adapted by as many studies as possible. To help other parties with their development of optimized support structures or support strategies, the files necessary to perform the presented benchmark are freely available under CC-BY SA license [32]. This includes the CAD files of the benchmark parts, an Excel sheet for the evaluation of the benchmark results as well as a short tutorial with aids for the interpretation of the results, e.g. the categorization of the discoloration as “light” or “strong”.

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