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Reviewed Paper

GENERAL RULES FOR PRE-PROCESS PLANNING IN POWDER BED FUSION SYSTEM – A REVIEW

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Abstract

Powder bed fusion (PBF) is one of the current additive manufacturing techniques that can fabricate almost fully dense functional metal components. Through a layer by layer fabrication methodology, complex geometries to meet the requirements of aerospace, automotive, biomedicine industries, etc. can be produced. The success of a build largely depends on having a flawless pre-process planning, including build orientation selection, support structure optimization, process parameter chosen, etc., which closely relates to the quality of the final products. Geometric inaccuracy and poor surface quality can occur due to a bad build plan. This review presents the crucial general planning rules for the build process. Build orientation selection, support structure optimization, and process parameter chosen in terms of residual stress reduction are the mainly concerns, which have been surveyed and discussed. The overall objective of this work is to help setup build plans that can ensure precise dimensions and high surface quality among the built components.

Introduction

Powder bed fusion (PBF) employs a manufacturing process by sintering or melting the raw material with a heat source (usually a laser or electron beam) then cooling and consolidating the material layer by layer to allow the fabrication of light-weighted components. The layered manufacturing methods enable the fabrication of the small-size components with the complex geometry. The geometry complexity is of difficulty for the conventional manufacturing techniques to realize.

However, some consequences of an unsuccessful pre-processing plan hold back the prevalence of PBF system. Given that the fabricated products usually possess a poor surface finish [1,43-47], which needs machining during post-process. Besides, the strong support structure is necessary to be applied to constrain the overhang or inclined angle structure so as to improve the stiffness of the supported structure and dissipate the redundant heat efficiently, otherwise most time, the build will fail [13,14]. Nevertheless, the conventional support is usually a volume column underneath the supported material. The additional build of the support structure leads to the extra cost of material and time to design during pre-processing, manufacture during the build processing and remove at post-processing [16]. The residual stress because of improper use of process parameter gives rise to the deformation, distortion, and delamination or even build failure [30]. The origin of the residual stress in the layered manufacturing process is temperature gradient mechanism. That the large thermal gradient comes from the rapid heating and relatively slow cooling induces stress inside the material. The stress is not allowed to fully release by an elastic (stress less than the yield stress of the material) or plastic deformation (stress more than the yield stress of the material) due to the fast solidification, so part of the stress remain inside the components. [29-30,32,38]

Proper pre-process planning is one of the inspirations that could liberate the build process from those limitations. In this review, a pre-process planning in terms of the optimization of build orientation, the selection of the support structure as well as the reduction of residual stress from changing the process parameter are presented as a guideline to achieve a better geometric accuracy, surface finish and save more build time and material.

Pre-Process Planning Setup

Build orientation selection

The feature and objective of the build need to be specified first so as to obtain an optimized build orientation [24]. Shape features need to be identified to determine the manufacturability of the Additive Manufacturing (AM) processes, which related to the constraints of the layer-wise manufacturing process and the contact between the components and the machine. The shape features are machine and build geometry dependent. For instance, for different manufacturing processes based on powder bed fusion (PBF), such as Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Electron Beam Melting (EBM), there are some special rules regarding the contact between the fabricated parts and the wiper or recoating blade to prevent the extreme rise of the edge of the part [25].

a. No long parallel contact to reduce the force induced by a wiper or recoating blade to a single part. It can be solved by rotating a small angle of the part (Figure 1). For multiple parts in one build, the parts could not be positioned along the wiper to eliminate simultaneous initial contacts [25].

b. The inclined overhang or support structure need to face away from the wiper or recoating blade so as not to exacerbate the upward trend of the part deflection on account of the force induced by the movement of the wiper [25].

c. Avoid too large aspect ratio. The force from the wiper will bend the thin, tall part eventually [25].

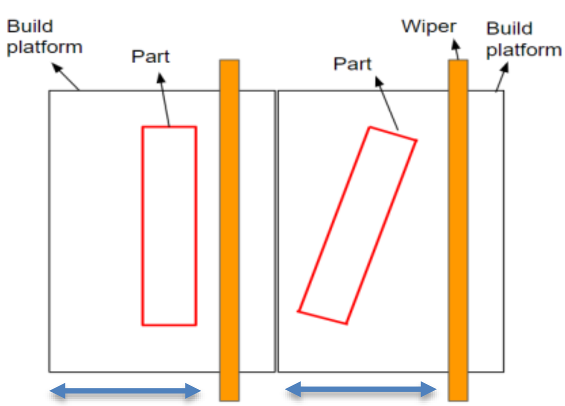

Figure 1: Build orientation chances by a small angle rotation

General objectives that need to be defined in terms of the designer preference and requirement to achieve the better functional products. The main general objectives include surface quality [24,26,35], part accuracy [24], support volume [24,26], mechanical properties [24], build time (build height) [24,26], build cost [24], post-processing [24], favorableness of AM feature [24], and other potential attributes [26]. Given that the surface finishes of the upward and downward facing surface of a fabricated overhang are distinct [48]. The build orientation of the overhang needs to be changed upside down if the user requires a better surface finish of the down skin, as shown in Figure 2.

After the features and objectives are specified, two main tasks need to be figured out [21,24]. First, select a set of the alternative orientations from the infinite build orientation for a part based on the shape feature. Rule or knowledge-based method, sampling or listing method could be employed, listed in Table 1. Genetic algorithm and Response Surface Methodology are the two representatives in sampling or listing method. Then refine the alternative orientation to get rid of duplicate orientations. The second step is to determine the optimized orientation in terms of the identified general objectives or attributes applying multi-criteria decision-making method [20,23,24].

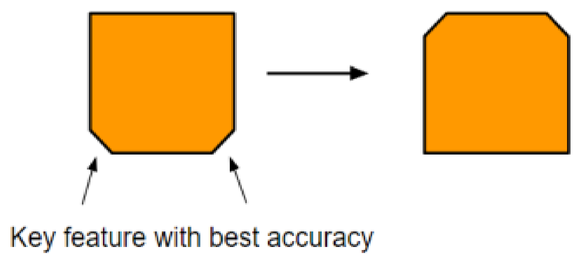

Figure 2: Build orientation changing with a key feature

Zhang et al. [21] use a feature and rule-based method to generate finite orientation sets for every single part. Then apply the multi-criteria decision-making method to rank and weight the criteria to determine the optimized orientation for multi-part. Byun and Lee [19] determine their optimized build orientation from all the possible candidates by genetic algorithm (GA). They rank and weight the importance of each criterion (surface roughness and build time as a priority in this case) to identify the optimized orientation. Zhang et al. [20] point out a two-step solution to determine the optimized orientation for multi-part production. The single part orientation sets can first be selected regarding the key feature of the user preference. Then the optimized orientation for multi-part can be identified by setting the global objectives and applying the GA. The authors of [28] propose a software using Matlab with an optimization algorithm to determine the build orientation with least support volume, which could be applied to both single part and multipart.

Ahsan et al. [26] further develop an analysis for concurrent determination of both optimal build orientation and tool-path direction. The analysis combines the basis of geometry, the part attributes, and genetic algorithm. Recently, Langelaar [27] provides a method, which could be applied to optimize the part geometry, build orientation and support layout simultaneously.

Table 1: The method used to optimize the orientation

Reference	Objectives	Methods	Applied Part Numbers
[19]	Average weighted surface roughness and build time	Simpling or listing method (GA)	Single part
[20]	AM feature based & global criteria	Simpling or listing method (GA)	Multi-part
[23]	AM feature based & global criteria	Rule or knowledge based method	Multi-part
[21]	Part quality, build time and cost	Rule or knowledge based method	Multi-part
[22]	Minimization of surface roughness and build time	Simpling or listing method	
[26]	Ensure manufacturability and minimize fabrication complexity	Simpling or listing method (GA)	
[35]	Improve the quality of the overhanging feature and minimize the supoort volume	Rule or knowledge based method (Altering the inclined angle to larger & controlling the local energy input	
[28]	Minimize the support volume	Simpling or listing method (Matlab with a unconstraited optimisation algrothm)	Multi-part

Support structure for overhang problem

The supports used in building process are significant structures designed as sacrificial structures so as to reinforce the resulting components. The designed support structures are well needed under the following situation in SLM process [48]:

I. The overhang plane (length more than 1mm) with an angle of less than 45 degrees with regard to (w.r.t.) the horizontal plane. Otherwise, either a relatively low density or a rough finish of the down skin surface could happen. The length of the plane within 0.3mm to 1mm can self-support without support structures [48].

II. Local minima refer to any areas of the component that are not connected to the layer below, which will need the support to anchor them. If not, the first layer of the local minima is possible to be displaced by the wiper, which may result in inaccurate geometry, or even failure [48].

III. Lateral holes or arches on the side surface of the component with the radii more than 5mm will also need the support in order to prevent geometry distortion from happening [48].

Support structure optimization is of importance. With a proper selection of the support structure, material and build time could be saved, better surface finish could be achieved, and the support could be easier to be removed. The reviewed support optimization strategies are mainly categorized into two types. One is designed in terms of the support geometry selection. The other is optimized by changing the process parameter for both downward facing surface and support.

These two support design strategies are listed in Table 2.

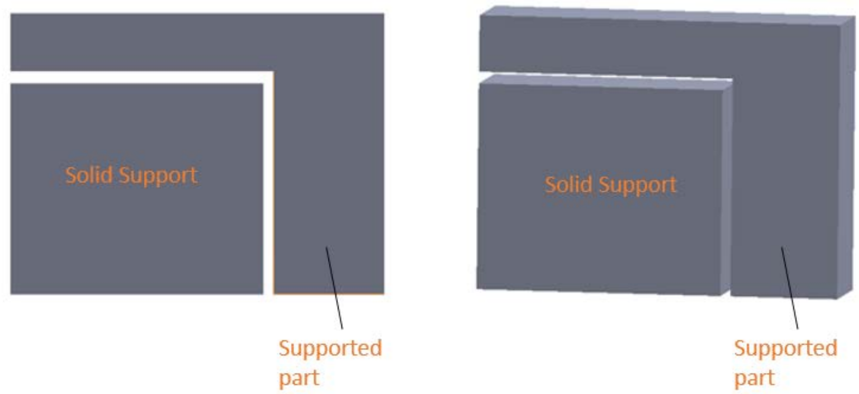

Figure 3: Conventional solid column support after EDM

I. Support Geometry

To achieve simple support and fast computation, the authors of [13] present a model and algorithm to optimize the shape and topology of the support. The shapes of conventional support structures are usually solid column like Figure 3, which are waste of the material and build time. So instead of a conventional solid column, lattice support structure is a better choice. Hussein et al. [42] study the two types of advanced lattice support structures, gyroid and diamond. They point out that in the best case, only 8% relative volume is used with gyroid lattice support structure by changing the size and struts of the unit cell, which means 92% of the powder can be saved and reused. The diameters of the struts of the support structure and the distances between the adjacent points connected to the down skin surface are two determinant factors to influence the manufacturability. The authors of [12] also present the feasibility of the gyroid and diamond cellular support structure with different size of unit cell and volume fraction. The manufacturability and performance of the gyroid type cellular support structure made by SLM are evaluated by Yan et al. [6]. The conclusion shows unit cell size between 2 to 8mm can be fabricated properly without additional support and the geometric accuracy of the produced structure is sound.

The authors of [11] present a pure mathematical 3D implicit functions for design and optimize the cellular support structure. Vaidya and Anand [17] propose an approach to generate a cellular support structure. They combine the space filling hollow cellular support with Dijkstra's shortest path algorithm to create the support with minimal volume fraction.

Another commonly used geometry of the support structure is teeth support [7]. Poyraz et al. report a design of the teeth support then conclude that the tooth parameter is less important than the hatching distance which greatly determines the extent of the distortion of the overhang. Calignano [8] investigates the optimized teeth parameter for AlSi10Mg and Ti6Al4V in terms of process efficiency and effectiveness by selective laser melting and demonstrates the importance of build orientation selection to reduce the amount of support and the possibility of distortion. Figure 4 illustrates the teeth support below the fabricated part. The authors of [7] propose the easiness of the removal of the teeth support during post-process due to the weak tip of the teeth.

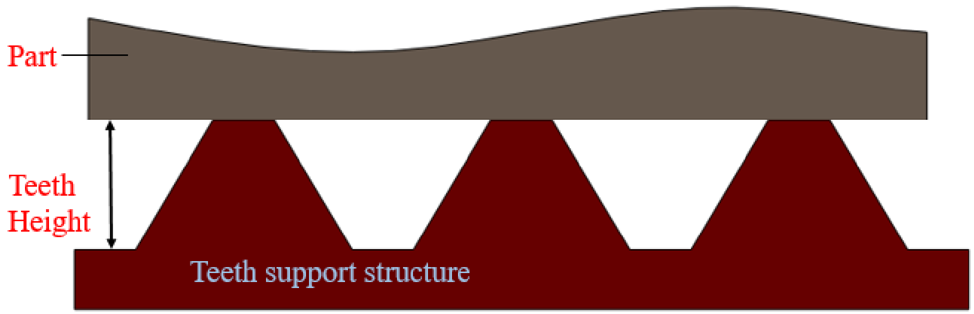

Figure 4: Teeth support geometry

In addition to the lattice and teeth support structure, there are still some effective support structures with different geometry developed. Gan and Wong [2] investigate three support structures, inverted 'Y' shape, 'Y' shape, and pin and came to the conclusion that the relatively levelled thin overhang plates can be achieved with the help of the inverted 'Y' supports with only 2.2% overhang-support contact area. The authors of [10] come up with a point contact support which can dissipate heat efficiently with the minimal contact area, which is also easy to remove during post-processing.

Recently, a new concept of the support structure realizes in Electron Beam Melting (EBM) process, which is developed by Leprince-ringuet and Vignat [3]. They point out a contact-free support which could not only be removed without any mechanical tool but reduce the extent of distortion efficiently. But the problem is that the contact-free solid column which could not be recycled is still a waste of material and production time. The optimization is proposed to add a constraint at the front of the part end, which can also effectively prevent the overhang from curling at the edge meanwhile maintain the ease of support removal and save the material significantly. Cooper et al. [4] also come out with the idea of contact-free support as a heat sink. They demonstrate the applicability of the heat support with no or little post-processing by both simulation and experiment and figure out that the effectiveness of the support is sensitive to the gap distance between the downward facing skin and the support and thickness of the support. Li et al. [16] also propose a lightweight and support-free design method to design a support.

II. Process parameter

Besides the optimization of geometry of the support structure, altering the process parameter of the downward facing surface and the support also helps. Mertens et al. [9] propose an optimized laser power and scan spacing for downfaces of the horizontal and inclined overhang to achieve better performance without support. However, this design is just for short structure while the extra support has to be provided for long downfacing structures. Cloots et al. [10] demonstrate that the support structure can be eliminated for the overhang with an angle of more than 20° w.r.t horizontal plane. They change the hatching space, scan angle and scan speed to reduce the heat input and achieve the build without support while still retaining acceptable density and surface roughness. Jhabvala et al. [15] present that support structure could be built using pulsed laser accounting for easy removal and time-saving. Bobbio et al. [18] use a relatively lower energy input to build the support structure than the solid part to achieve a low structural strength, which could be of benefit to ease the support removal during post-process.

Table 2: The strategies of different support geometries and process parameter

Reference	Strategy	Process	Material	Conclusion
[1] [6] [12]	Gyroid and Diamond lattice cellular structure	DMSL, SLM	Ti6Al4V, Stainless Steel 316 L (SS 316L)	Save build time & the reduction of cell size and volume fraction
[2]	Y, inversed Y(IY), pin support structure	SLM	SS 316L	2.2% overhang-support contact area
[3] [4] [5]	Contact-free support structure	EBAM	Ti6Al4V	Overhang length effect on deformation, supprot column effect and solid piece gap effect
[7] [8]	Teeth support	DMLS, SLM	In 625, AlSi10Mg, Ti6Al4V	Optimized tooth parameter
[17]	Hollow cellular structure			Reduce support volume
[18] [9]	Low heat input	SLM	Ti6Al4V, AlSi10Mg	Ease the support removal & Optimize the process parameter
[15]	Palsed laser	SLM	SS 316 L	Reduce the build time and make the removal easier
[10]	Point contact support & hatching space, scan angle, scan speed	SLM	SS 316 L	The overhang angle of 20° can be achieve without support with acceptable density and surface finish

Process parameter chosen in terms of residual stress reduction

The consequence of the high residual stress may result in a severe build failure like delamination in Figure 5. Therefore, it is necessary to evaluate and control the magnitude of residual stress during the build process to prevent the curing or warping happening. The authors of [32] give a detailed review of residual stress and further a future study direction. Many researchers report the methods they use to measure the residual stress and analyze the effects of different factors on the residual stress.

Figure 5: The consequence of large residual stress

Kruth et al. [31] provide a method called bridge curvature method used to assess the angle of curvature α of the bridge structure made by SLM to imply the magnitude of the residual stress, shown in Figure 6. Thus, this method can be employed to assess and compare the extent of the influencing factor on residual stress. Zaeh and Branner [30] analyze the residual stress by using neutron diffractometer. Safronov et al. [36] put forward that the top surface of the part could be concave on account of residual stress induced shrinkage. Thus, the magnitude of the residual stress is related to the curvature radius R. The authors of [37] evaluate the residual stress by hole-drilling strain gauge method and conclude the residual stresses in some area of the part exceed the yield stress of the material, which indicates the distortions in the specimen result from the residual stress. Liu et al. [38] measure the residual stress by X-ray diffraction and propose the stress perpendicular to the scanning direction are much smaller than that parallel to the scanning direction. In addition, the peak values of residual stress always exist at the beginning of scanning tracks, which means the deformation or distortion are easier to happen at the edge of the part. The authors of [39] also demonstrate that the greatest stress occurs parallel to the scan vectors since there is larger thermal gradient parallel to scan vector using a thermo-mechanical model.

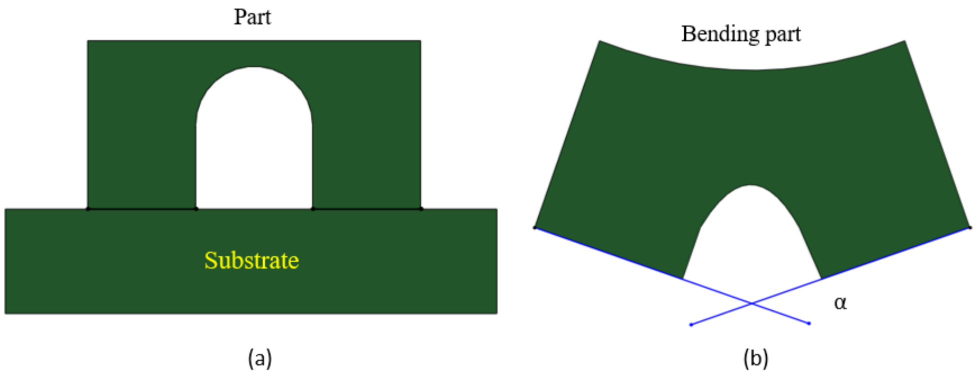

Figure 6: (a) Before, (b) after removal from the base plate. The geometry of the test parts

Mercelis and Kruth [29] propose the distribution of the residual stress, which contains large tensile stresses at both top and bottom of the final part while intermediate compressive stress in between. They also investigate the parameter influencing the magnitude of the residual stress and the method to reduce the residual stress; details are generalized in Table 3. The application of island scan strategy generates lower residual stress than that of longitudinal scan direction or alternating scan direction. Zaeh and Branner [30] also report the parameters which effect on residual stress and deformation. They conclude that the residual stress could be a function of the scanning direction, cantilever thickness, layer thickness and initial platform temperature. Further, Ali et al. demonstrate that pre-heating the bed to 570° C for Ti6Al4V could significantly reduce the residual stress and improve the yield strength and ductility of the final components [34]. The authors [39] indicate the longitudinal stress increases with scan vector length and a non-uniform anisotropic stress field is generated during the layer by layer manufacturing process. Vasinonta et al. [40] employ a thermo-mechanical model with a thin-walled structure to quantify the effect of wall height, scan speed, laser power and the preheating of the substrate on the size of the melt pool and the residual stress. Two process maps are applied to predict the melt pool size and maximum residual stress. The process parameter can be determined using this method to optimize the melt pool size while controlling the residual stress.

Table 3: The effect of different factors on residual stress

Reference	**Factors**	**Effect on residual stress**
[29] [35] [40]	Number of layer	The final residual stress increases with number of layers
[29]	Thickness of the base plate	The residual stress decrease with the thickness of the base plate for a fixed part thickness
[29]	Yield strength of the material	The resulting residual stress could be increase with yield stress of the materal
[30]	Cantilevel thickness	No obvious effect
[30] [31]	Powder layer size	Smaller layer sizes are responsible for larger residual stress
[29]-[31] [33] [35] [38]-[40]	Scanning stretagy (direction and the length of the scan vectors) *	Shorter scan length is better. Rotation a scan angle each layer to prevent the accumulation of stress.
[31]	Post-scanning	Only low scan speed of remelting reduce residual stress slightly
[31]	Pre-scanning	Reduce residual stress slightly
[29]-[31] [34] [40]	Pre-heating of the substrate plate	Reduce temperature gredient and residual stress and enhance yield stress and ductility
[38] [40]	Energy input (scan speed and laser power)	Low power & fast scan speed to reduce the thermal gradient

Conclusion

To keep the build from distortion and deformation, and ensure the quality of the final components, a proper build setup need planning in powder bed process. In this review, the setup rules with regard to orientation selection, support structure optimization and residual stress reduction are concluded as follows:

1. Build orientation

The rules of orientation optimization consider the geometry feature and wiper interaction. The orientation needs to be selected in terms of preventing the extreme rise of the edge of the part on account of the interaction between the build part and the wiper movement during the build process. The alternative orientation sets can be generated by either rule (knowledge) based method or sampling (listing) based method. After general objectives of the build are specified by the user, the optimal orientation could be selected from the sets.

2. Support structure optimization

The structures with the angle of a plane less than 45° w.r.t the horizontal plane, with local minima or with lateral holes with large diameter need to be supported. To save the build time and minimize the support material, different geometry of the support structure which can still self-support could be applied. In addition, the support structure could be built using pulsed laser or low energy input to ensure the ease of the final support removal. The process parameter with lower energy input could also be employed to build the downward facing surface to achieve a better surface finish without support.

3. Process parameter chosen in terms of residual stress reduction

The effect of different factors, including the number of layers, the thickness of the base plate, the scan pattern, and energy input, etc., on residual stress, are mainly listed in Table 3.

Acknowledgments

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Reference

[1] Calignano, F., Manfredi, D., Ambrosio, E. P., Iuliano, L., & Fino, P. (2013). Influence of process parameters on surface roughness of aluminum parts produced by DMLS. *The International Journal of Advanced Manufacturing Technology*, *67*(9-12), 2743-2751.

[2] Gan, M. X., & Wong, C. H. (2016). Practical support structures for selective laser melting. Journal of Materials Processing Technology, 238, 474–484. https://doi.org/10.1016/j.jmatprotec.2016.08.006

[3] Leprince-ringuet, C. L., & Vignat, F. (2017). New concept of support structures in Electron Beam Melting manufacturing to reduce geomtricdefects, (73), 1–6.

[4] Cooper, K., Steele, P., Bo, C., & Chou, K. (2015). Contact-Free Support Structures for Part Overhangs in Powder-Bed Metal Additive Manufacturing PB-EBAM System PB-EBAM Process Characteristics. Prog Addit Manuf, 1, 9–20. Retrieved from https://www.sme.org/uploadedFiles/Membership/Members-Only_Content/Chou-Kevin_Contact-Free-Support-Structures-for-Par.pdf

[5] Cheng, B., & Chou, K. (2015). Geometric consideration of support structures in part overhang fabrications by electron beam additive manufacturing. CAD Computer Aided Design, 69, 102–111. https://doi.org/10.1016/j.cad.2015.06.007

[6] Yan, C., Hao, L., Hussein, A., & Raymont, D. (2012). Evaluations of cellular lattice structures manufactured using selective laser melting. International Journal of Machine Tools and Manufacture

[7] Poyraz, Ö., Yasa, E., Akbulut, G., Orhangül, A., & Pilatin, S. (n.d.). INVESTIGATION OF SUPPORT STRUCTURES FOR DIRECT METAL LASER SINTERING (DMLS) OF IN625 PARTS. Retrieved from http://sffsymposium.engr.utexas.edu/sites/default/files/2015/2015-45-Poyraz.pdf

[8] Calignano, F. (2014). Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting. Materials {&} Design (Vol. 64). https://doi.org/10.1016/j.matdes.2014.07.043

[9] Mertens, R., Clijsters, S., Kempen, K., & Kruth, J. P. (2014). Optimization of scan strategies in selective laser melting of aluminum parts with downfacing areas. *Journal of Manufacturing Science and Engineering*, *136*(6), 061012.
[10] Cloots, M., Spierings, A. B., & Wegener, K. (2013). Assessing new support minimizing strategies for the additive manufacturing technology SLM. International Solid Freeform Fabrication Symposium An Additive Manufacturing Conference, August 12-14 2013, 131–139. https://doi.org/10.1017/CBO9781107415324.004
[11] Cloots, M., Spierings, A. B., & Wegener, K. (2013). Assessing new support minimizing strategies for the additive manufacturing technology SLM. International Solid Freeform Fabrication Symposium An Additive Manufacturing Conference, August 12-14 2013, 131–139. https://doi.org/10.1017/CBO9781107415324.004
[12] Hussein, A., Yan, C., Everson, R., & Hao, L. (2011). Preliminary investigation on cellular support structures using SLM process. *Innovative Developments in Virtual and Physical Prototyping. Taylor & Francis Group, London*, 609-612.
[13] Allaire, G., & Bogosel, B. (2018). Optimizing supports for additive manufacturing.
[14] Malekipour, E., Tovar, A., & El-Mounayri, H. (2018). Heat Conduction and Geometry Topology Optimization of Support Structure in Laser-Based Additive Manufacturing. In *Mechanics of Additive and Advanced Manufacturing, Volume 9* (pp. 17-27). Springer, Cham.
[15] Jhabvala, J., Boillat, E., André, C., & Glardon, R. (2012). An innovative method to build support structures with a pulsed laser in the selective laser melting process. The International Journal of Advanced Manufacturing Technology, 59(1–4), 137–142. https://doi.org/10.1007/s00170-011-3470-8
[16] Li, Z., Zhang, D. Z., Dong, P., & Kucukkoc, I. (2017). A lightweight and support-free design method for selective laser melting. The International Journal of Advanced Manufacturing Technology, 90(9–12), 2943–2953. https://doi.org/10.1007/s00170-016-9509-0
[17] Vaidya, R., & Anand, S. (2016). Optimum Support Structure Generation for Additive Manufacturing Using Unit Cell Structures and Support Removal Constraint. Procedia Manufacturing, 5, 1043–1059. https://doi.org/10.1016/j.promfg.2016.08.072
[18] Bobbio, L. D., Qin, S., Dunbar, A., Michaleris, P., & Beese, A. M. (2017). Characterization of the strength of support structures used in powder bed fusion additive manufacturing of Ti-6Al-4V. Additive Manufacturing, 14, 60–68. https://doi.org/10.1016/j.addma.2017.01.002
[19] Byun, H. S., & Lee, K. H. (2005). Determination of the optimal part orientation in layered manufacturing using a genetic algorithm. International Journal of Production Research, 43(13), 2709–2724. https://doi.org/10.1080/00207540500031857
[20] Zhang, Y., Bernard, A., Harik, R., & Karunakaran, K. P. (2017). Build orientation optimization for multi-part production in additive manufacturing. Journal of Intelligent Manufacturing, 28(6). https://doi.org/10.1007/s10845-015-1057-1
[21] Zhang, Y., De Backer, W., Harik, R., & Bernard, A. (2016). Build Orientation Determination for Multi-material Deposition Additive Manufacturing with Continuous Fibers. Procedia CIRP, 50, 414–419. https://doi.org/10.1016/j.procir.2016.04.119
[22] Padhye, N., & Deb, K. (2011). Multi-objective optimisation and multi-criteria decision making in SLS using evolutionary approaches. Rapid Prototyping Journal, 17(6), 458–478. https://doi.org/10.1108/13552541111184198
[23] Zhang, Y., & Bernard, A. (2014). AM Feature and Knowledge Based Process Planning for Additive Manufacturing in Multiple Parts Production Context. Proceedings of 25th Annual

International Solid Freeform Fabrication Symposium, 44(4), 1259–1276. https://doi.org/10.1017/CBO9781107415324.004
[24] Zhang, Y., Bernard, A., Gupta, R. K., & Harik, R. (2016). Feature based building orientation optimization for additive manufacturing. *Rapid Prototyping Journal*, *22*(2), 358-376.
[25] Moylan, S. P., Slotwinski, J. A., Cooke, A. C., Jurrens, K., & Donmez, M. A. (2013). Lessons learned in establishing the NIST metal additive manufacturing laboratory. *NIST Technical Note*.
[26] Ahsan, N., Habib, A., & Khoda, B. (2016). Geometric Analysis for Concurrent Process Optimization of AM. Procedia Manufacturing, 5, 974–988. https://doi.org/10.1016/j.promfg.2016.08.085
[27] Langelaar, M. (n.d.). Structural and Multidisciplinary Optimization Combined optimization of part topology, support structure layout and build orientation for additive manufacturing. https://doi.org/10.1007/s00158-017-1877-z
[28] Jonnalagadda, J. A. C. S., & Sienz, D. E. J. (2016). Part orientation optimisation for the additive layer manufacture of metal components. The International Journal of Advanced Manufacturing Technology, 1679–1687. https://doi.org/10.1007/s00170-015-8151-6
[29] Mercelis, P., & Kruth, J. (2006). Residual stresses in selective laser sintering and selective laser melting. Rapid Prototyping Journal, 12(5), 254–265. https://doi.org/10.1108/13552540610707013
[30] Zaeh, M. F., & Branner, G. (2010). Investigations on residual stresses and deformations in selective laser melting. Production Engineering, 4(1), 35–45. https://doi.org/10.1007/s11740-009-0192-y
[31] Kruth, J.-P., Deckers, J., Yasa, E., & Wauthlé, R. (2012). Assessing and comparing influencing factors of residual stresses in selective laser melting using a novel analysis method. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 226(6), 980–991. https://doi.org/10.1177/0954405412437085
[32] Patterson, A. E., Messimer, S. L., & Farrington, P. A. (2017). Overhanging Features and the SLM/DMLS Residual Stresses Problem: Review and Future Research Need. Technologies, 5(2), 15. https://doi.org/10.3390/technologies5020015
[33] Cheng, B., Shrestha, S., & Chou, K. (2016). Stress and deformation evaluations of scanning strategy effect in selective laser melting. Additive Manufacturing, 12, 240–251. https://doi.org/1
[34] Ali, H., Ma, L., Ghadbeigi, H., & Mumtaz, K. (2017). In-situ residual stress reduction, martensitic decomposition and mechanical properties enhancement through high temperature powder bed pre-heating of Selective Laser Melted Ti6Al4V. Materials Science and Engineering: A, 695, 211–220. https://doi.org/10.1016/j.msea.2017.04.033
[35] Wang, D., Yang, Y., Yi, Z., & Su, X. (2013). Research on the fabricating quality optimization of the overhanging surface in SLM process. *The International Journal of Advanced Manufacturing Technology*, *65*(9-12), 1471-1484.
[36] Safronov, V. A., Khmyrov, R. S., Kotoban, D. V., & Gusarov, A. V. (2016). Distortions and Residual Stresses at Layer-by-Layer Additive Manufacturing by Fusion. Journal of Manufacturing Science and Engineering, 139(3), 031017. https://doi.org/10.1115/1.4034714
[37] Knowles, C. R., Becker, T. H., & Tait, R. B. (2012). Residual stress measurements and structural integrity implications for selective laser melted ti-6al-4v. Sajie, 23(November), 119–129.
[38] Liu, Y., Yang, Y., & Wang, D. (2016). A study on the residual stress during selective laser melting (SLM) of metallic powder. The International Journal of Advanced Manufacturing Technology, 87(1–4), 647–656. https://doi.org/10.1007/s00170-016-8466-y

[39] Parry, L., Ashcroft, I. A., & Wildman, R. D. (2016). Understanding the effect of laser scan strategy on residual stress in selective laser melting through thermo-mechanical simulation. Additive Manufacturing, 12, 1–15. https://doi.org/10.1016/j.addma.2016.05.014
[40] Vasinonta, A., Beuth, J. L., & Griffith, M. L. (2000, August). Process maps for controlling residual stress and melt pool size in laser-based SFF processes. In *Solid Freeform Fabrication Proceedings* (Vol. 8, p. 206). Proc. 2000 Solid Freeform Fabrication Symposium, Austin.
[41] Strano, G., Hao, L., Everson, R. M., & Evans, K. E. (2013). Surface roughness analysis, modelling and prediction in selective laser melting. *Journal of Materials Processing Technology*, *213*(4), 589-597.
[42] Hussein, A., Hao, L., Yan, C., Everson, R., & Young, P. (2013). Advanced lattice support structures for metal additive manufacturing. Journal of Materials Processing Technology, 213(7), 1019–1026. https://doi.org/10.1016/j.jmatprotec.2013.01.020
[43] Strano, G., Hao, L., Everson, R. M., & Evans, K. E. (2013). Surface roughness analysis, modelling and prediction in selective laser melting. *Journal of Materials Processing Technology*, *213*(4), 589-597.
[44] Pfefferkorn, F. E., Duffie, N. A., Li, X., Vadali, M., & Ma, C. (2013). Improving surface finish in pulsed laser micro polishing using thermocapillary flow. *CIRP Annals*, *62*(1), 203-206.
[45] Baicheng, Z., Xiaohua, L., Jiaming, B., Junfeng, G., Pan, W., Chen-nan, S., ... & Jun, W. (2017). Study of selective laser melting (SLM) Inconel 718 part surface improvement by electrochemical polishing. *Materials & Design*, *116*, 531-537.
[46] Morton, W., Green, S., Rennie, A., & Abram, T. (2011). Surface finishing techniques for SLM manufactured stainless steel 316L components.
[47] http://www.renishaw.com/en/design-for-metal-am-a-beginners-guide--42652