Solid Freeform Fabrication 2016: Proceedings of the 27th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

MANUFACTURABILITY AND MECHANICAL CHARACTERIZATION OF LASER SINTERED LATTICE STRUCTURES

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Abstract

The implementation of lattice structures into additive manufactured parts is an important method to decrease part weight maintaining a high specific payload. However, the manufacturability of lattice structures and mechanical properties for polymer laser sintering are quite unknown yet. To examine the manufacturability, sandwich structures with different cell types, cell sizes and lattice bar widths were designed, manufactured and evaluated. A decisive criterion is for example a sufficient powder removal. In a second step, manufacturable structures were analyzed using four-point-bending tests. Experimental data is compared to the density of the lattice structures and allows for a direct comparison of different cell types with varied geometrical attributes. The results of this work are guidelines for the design and dimensioning of laser sintered lattice structures.

Introduction

Additive Manufacturing (AM) technologies enable a great design freedom that can be used to reduce the weight of parts and structures. If the material is only deposited where high stresses occur within a part, a weight reduction is possible maintaining the same or even better payload. Due to their complexity, such optimized structures, for example via topology optimization tools, may only be manufactured using AM. Another lightweight design method is for example the implementation of sandwich structures, which consist of a lightweight core and a minimum of two stiff skins (Fig. 1). Typical core materials are foams, honeycomb or lattice structures. Next to lightweight design, medical products (implants and prostheses), damping structures or heat exchangers are further applications of lattice structures [1]. Another great advantage of AM technologies is that manufacturing costs are more or less independent on part complexity. In contrast, manufacturing costs usually increase with part complexity using conventional manufacturing technologies [2].

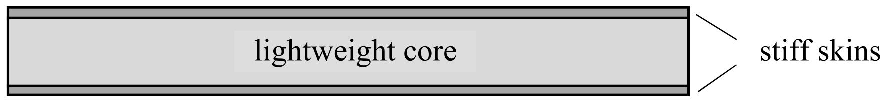

Fig. 1: Design of a sandwich structure

In this study, the manufacturability of lattice structures is investigated at first. Therefore, different structures with varied cell types and geometry parameters (cell size and rod width) are designed, manufactured and analyzed. Significant criterions are for example the removability of adhered powder particles between the cell rods and the minimum manufacturable rod width. To specify the mechanical properties, sandwich structures with different cellular cores are tested under four-point-bending load. Measured values are correlated with the individual solid volume fractions of the core structures to classify the tested parameter sets according to their lightweight index.

State of the Art

In the laser sintering process, the raw material is a polymer powder. Thin layers of powder are recoated onto the so-called part cake and then heated up to approximately 5 K below melting temperature measured at the part cake surface. The thermal energy needed to fully melt the particles and ensure inter-layer bonding is brought in by a laser. Layer by layer, even very complex structures are manufactured without additional effort. In contrast to metal AM technologies, no support structures are needed since the unmolten material supports itself [3].

Lattice structures can be implemented using a great variety of different base cells types. Unit cells are often cubic, but there are also special types, for example diamond cells. Typical cubic unit cell types, which consist of face-centered rods (fcc), body-centered-rods (bcc) and z oriented rods (z), are shown in Fig. 2 [1]. The solid volume fraction, which will be needed to calculate the lightweight index, is the ratio of the lattice volume and the overall lattice structure volume.

Additive manufactured lattice structures have been investigated in the past: Considering metal AM processes, some studies can be found in literature. For laser sintered lattice structures made of polymeric material, many examples can be found, but only few deep investigations have been published. There is no information about manufacturable and proven cell types, cell sizes and solid volume fractions. Also, mechanical properties of laser sintered lattice structures and the influence of varied geometry parameters and base cell types are quite unknown yet. Neff et. al. investigated mechanical properties of laser sintered diamond structures varying the cell size and rod width. They figured out that the stiffness increased with increasing rod width and decreasing cell size. These effects could also be proven via simulations [4].

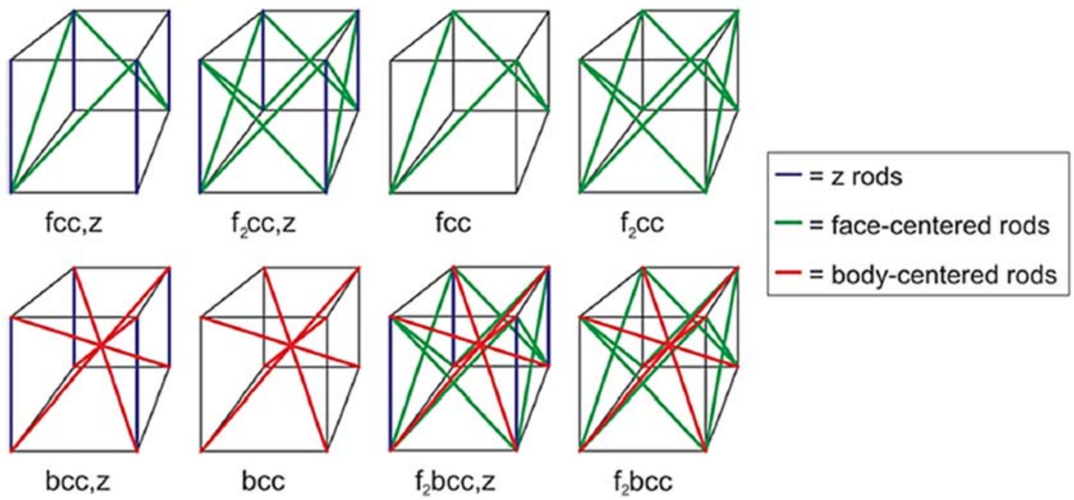

Fig. 2: Lattice cell types based on a cubic base cell [1]

Manufacturability

To investigate the manufacturability of laser sintered lattice structures, the following parameters and variation steps have been set:

- **Cell type:** In total, 6 different cell types are investigated. Four cell types were obtained from Fig. 2. In addition, the cell types square-collinear as an „easy“ type as well as a diamond cell as „natural“ type are selected (see Fig. 3).
- **Rod width:** The smallest possible rod width is determined by the laser focus diameter or the heat affected area respectively. In literature, different values for minimal wall thicknesses can be found from ~ 0,5 to 1 mm [5][6]. Pre-investigations have shown that the minimum rod with for the laser sintering system used here is approximately 0,7 mm. Further tested rod widths are 1,0 mm, 1,3 mm and 1,6 mm.
- C**ell size:** The tested cell sizes are 2,5 mm, 3,3 mm, 5 mm and 10 mm. Since the core height is set to 10 mm according to the used test standard, it consists of exactly 1 to 4 unit cells in height.

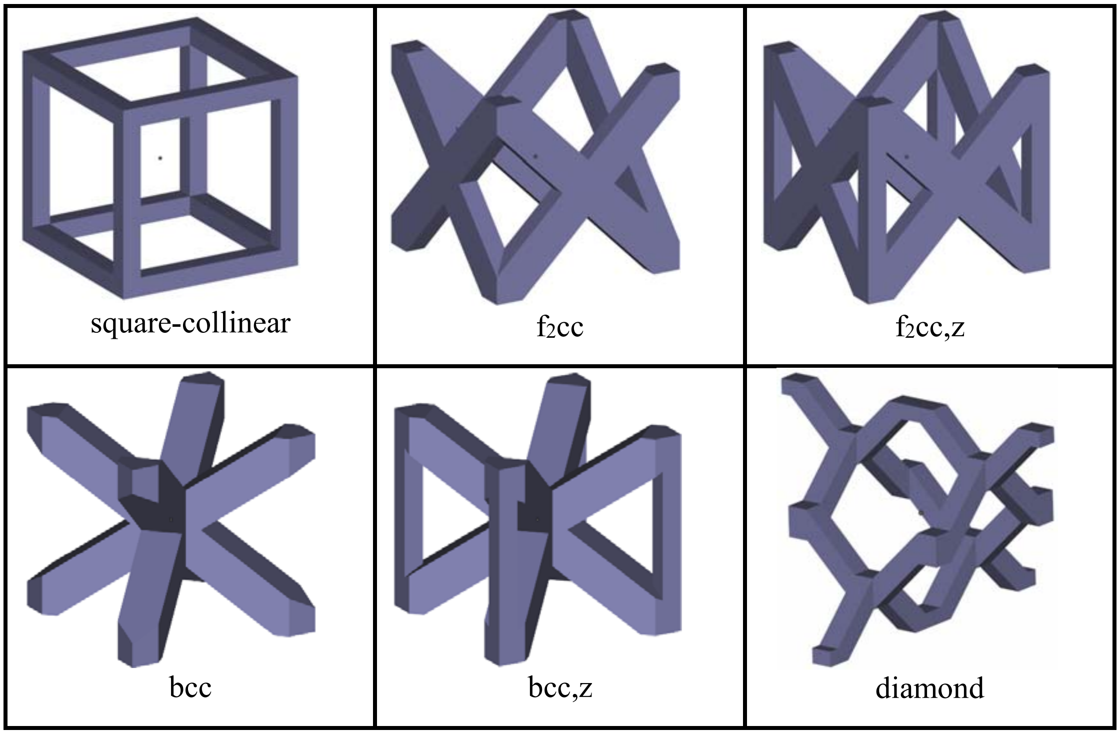

Fig. 3: Tested cell types

Respective unit cell types with their individual geometric parameters are designed discretely in a CAD software and duplicated and merged in the software used to pre-process the build jobs for the laser sintering system. To obtain a sandwich structure for testing, top and bottom skins are merged to the cellular core. In total, 6 x 4 x 4 = 96 combinations have been designed and built on an EOS P396 laser sintering system using PA 2200 (PA12) material, refreshed with 50 % virgin powder, with a layer thickness of 0,12 mm. An evaluation of the manufacturability has been performed considering the following criteria:

- **Trapped volumes (N/A):** Especially for small cell sizes and big rod widths, trapped volumes occur within the inner cell structures. Such combinations are excluded from the investigations from the start since a powder removal is not possible.
- **Not removable powder (A):** The powder within the cavities between the cell rods cannot be removed even after very intense glass sphere blasting. These combinations are also excluded from further investigations since adhered powder within the lattice structure negates the lightweight properties of the sandwich core.
- **Failure of specimens during post-processing (B):** The specimens or the inner rods break during unpacking of the part cake or during adhered powder removal using glass sphere blasting. Such combinations are excluded from the mechanical characterization experiments.

An exemplary manufacturability evaluation for the $f_2$cc,z cell type is shown in Fig. 4. Parameter combination leading to trapped volumes are marked N/A. Combinations marked in red lead to either not removable powder (A) or failures during port-processing (B). All other combinations marked in green are suitable for manufacturing. The percentual number represents the individual solid volume fraction of the core structure.

Manufacturability		Rod width / mm			
Cell type	Cell size / mm	0,7	1	1,3	1,6
f_2cc,z	2,5	N/A	N/A	N/A	N/A
	3,33	22,08 %	N/A	N/A	N/A
	5	10,90 %	20,37 %	31,24 % (A)	N/A
	10	2,99 % (B)	5,87 %	9,53 %	13,84 %

Fig. 4: Evaluation of the manufacturability for the cell type f_2cc,z

Considering all six cell types, 58 combinations are excluded from the originally 96 combinations due to the named criteria (34 x N/A, 12 x A, 12 x B). As a dimensioning guideline, it can be concluded that – independent on the used cell type and geometry parameters, the optimum solid volume fraction is approximately 6 to 35 %. Furthermore, calls should have a minimum size of 5 mm to ensure an applicable powder removal. The rod width should be greater than the heat affected area of one laser path – her more than approximately 0.7 mm. Manufacturable combinations are tested subsequently.

Mechanical Characterization

The mechanical characterization is performed according to the German test standard DIN 53 293, which describes test methods for sandwich structures under bending load. Four-point-bending tests are performed on specimens with a size of 40 x 240 x 13,6 mm using an Instron 5569 EH test system (200 mm support span, 100 mm load span), equipped with a 5 kN load cell, see Fig. 5. The skin thickness is set to (intentionally thick) 1,8 mm (= 15 x layer thicknesses) for all specimens in order to provoke core failures during testing. Since additive manufactured parts usually show an anisotropic behavior dependent on build orientation, specimens are built in all three main directions (upright, side and flat). Each specimen type is built and tested six times. Evaluated values are the maximum bending force, the bending stiffness and the ratio of these parameters compared to the solid volume fraction (lightweight index). Due to the multitude of results, selected data for only side oriented specimens of f_2cc, bcc and diamond cell types are shown here.

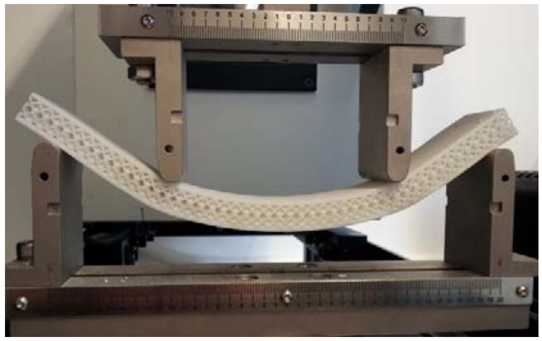

Fig. 5: *Four-point bending test of a sandwich structure*

Bending stiffness: The absolute bending stiffness (Fig. 6) is more or less equal and independent on cell type, rod width and cell size. Only values for the combination of a rod width of 1 mm with a cell size of 10 mm seem to be slightly lower. Partially, a slight trend to higher stiffnesses can be seen for the f_2cc cell type.

More interesting is the analysis of the specific stiffness (ratio of absolute stiffness and solid volume fraction, Fig. 7): Here, the diamond cell type has the lowest values for all cell geometries, while the f_2cc cell shows the highest values again. In contrast to the absolute stiffness, the combination (10/1,0) shows the highest values considering the lightweight index. This effect can be explained by a very low solid volume fraction that dominates over the stiffness deviations. For constant rod widths, higher specific stiffnesses are obtained for bigger cell sizes; for constant cell sizes, smaller rod widths show higher values.

If the stiffness is correlated with the solid volume fraction (Fig. 8), values increase slightly for low solid volume fractions. For higher solid volume fractions, the stiffness levels off more or less. This means that for solid volume fractions higher than approximately 20 %, only a slight increase of stiffness can be expected. Again, the f_2cc cell type shows the highest values.

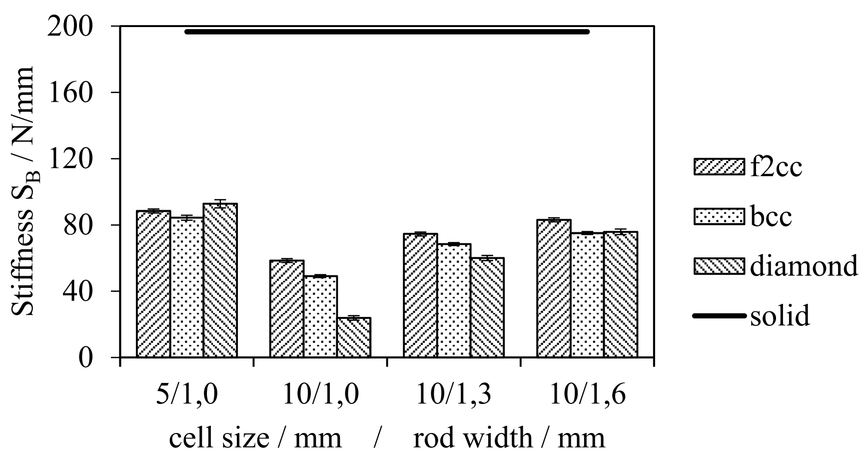

Fig. 6: *Bending stiffness*

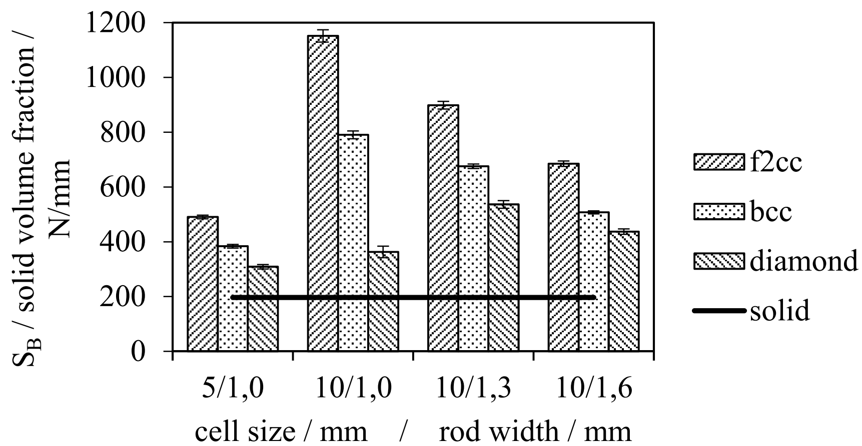

Fig. 7: Specific bending stiffness

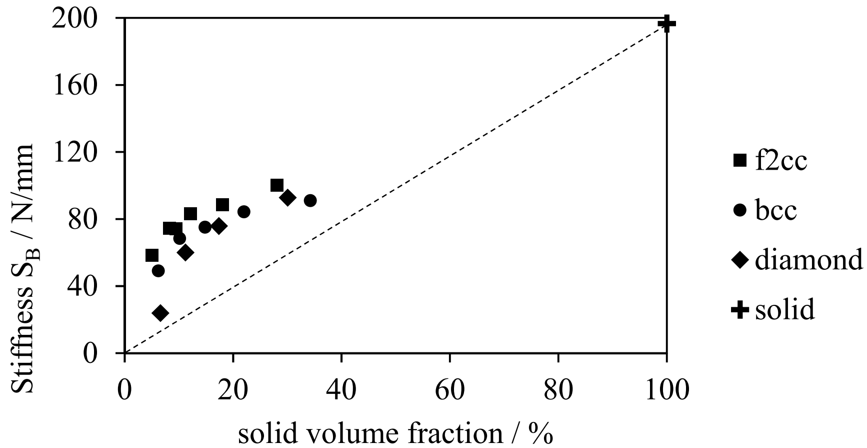

Fig. 8: Bending stiffness dependent on solid volume fraction

Maximum bending force: For the absolute maximum bending force (Fig. 9), values for the different geometries and cell types alternate significantly stronger compared to the stiffness values: The smaller the cell size and the higher the rod width, the higher the maximum bending force. Depending on the actual geometry, different cell types show the highest values. Hence, no specific cell type can be emphasized in general.

As already mentioned, considering the stiffness, the qualitative trends differ if the values are referred to the solid volume fraction (Fig. 10). Again, the f2cc cell shows the most robust values. A slight trend to higher specific maximum bending force is observed for small cell sizes and high rod widths. The diamond cell type performs worse compared to the absolute bending force due to its very high solid volume fraction.

Analyzing the relation between maximum bending force and solid volume fraction (Fig. 11), there is a nearly proportional trend for low solid volume fractions: The higher the solid volume fraction, the higher the maximum bending force. However, this effect is less intense for solid volume fractions higher than approximately 30 %, no significant maximum payload deviations are expected beyond this point.

A possible reason for the above average behavior of the f2cc cell type for stiffness and maximum bending force may be the orientation of the lattice structure compared to the coordinate system of the laser sintering machine: Since the specimens were manufactured "on the side", half of the rods inside the f2cc cell lie parallel to the built layers, which is generally stronger than in direction perpendicular to the layers. For complex cell types like the diamond structure, most of the rods are tilted to the built layers, which may explain the relatively low values.

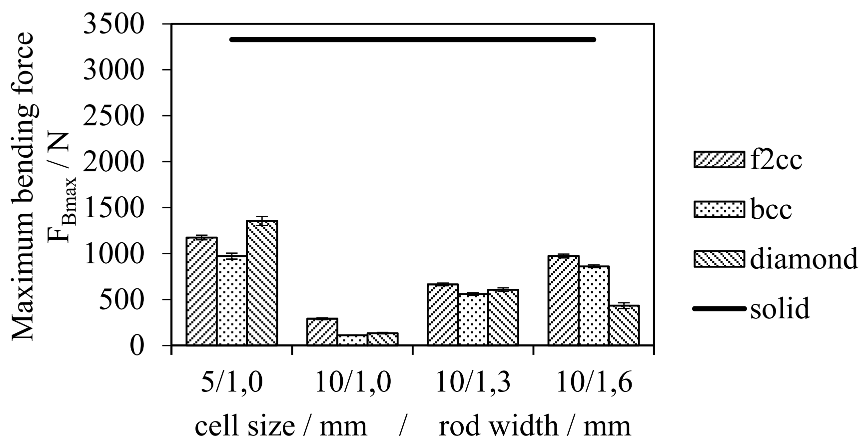

Fig. 9: Maximum bending force

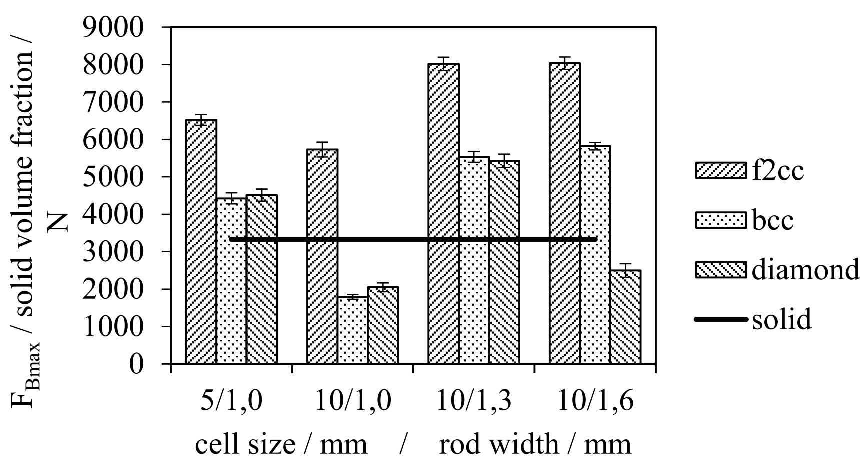

Fig. 10: Specific maximum bending force

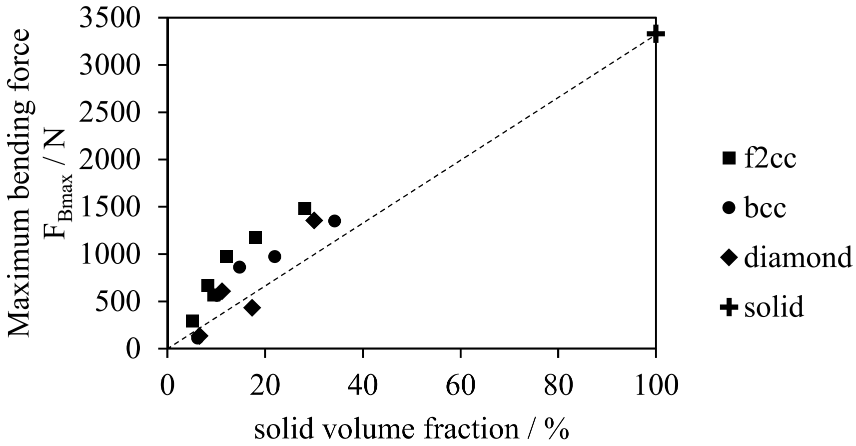

Fig. 11: Maximum bending force dependent on solid volume fraction

Failure modes: Different failure modes are observed for different cell types and geometries (Fig. 12) and may be another reason for varying stiffness and payload values. For example, the core may fail inside due to shear stress. Also the skin on top and below the lattice core may break in total. Other failure modes are the delamination of core and skin or a plastic deformation of the skin indenting the core. However, no clear scheme is observed regarding the failure modes.

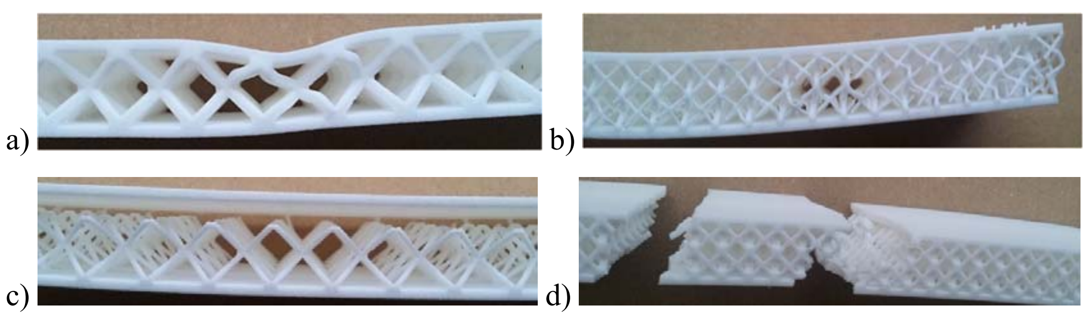

Fig. 12: Failure modes: a) top layer deformation, b) core shear failure, c) top layer delamination, d) total break (top layer fracture)

Attention should be paid to the other cell types and build orientations not shown in this work. For example, other "best cell geometries" may be observed for other build orientations. The actual mechanical behavior of the structures is the outcome of complex interactions between cellular geometry and process parameters. Nevertheless, the results shown here act as a coarse guideline in dimensioning and manufacture of laser sintered lattice structures, which may be checked for individual applications.

Conclusions & Outlook

Lattice structures are a suitable method to integrate lightweight design into parts. In the present work the manufacturability and mechanical properties of different laser sintered cell types as part of sandwich structures have been investigated. The manufacturability is limited by too low solid volume fractions due to failure during post-processing and by too high solid volume fractions due to an insufficient powder removal. Considering the lightweight ratio, big cell sizes with thin rods show the highest stiffnesses, while small cell sizes with thick rods are better for a high bending payload. Even if measured values may alternate for other build orientations, the f_2cc cell type presented acts more or less as a robust "allrounder". For further research, simulation techniques may be developed to predict the deformation behavior of laser sintered lattice structures. Furthermore, graded structures that combine different cell geometries and rod widths within one part are interesting for complex loaded parts.

Acknowledgement

The authors want to thank all industry partners of the DMRC, the federal state of North Rhine-Westphalia and the Paderborn University for the support within the project "Robust Simulation of Complex Cellular Structures" and the "NRW Fortschrittskolleg Leicht – Effizient – Mobil" funded by the Ministry for Innovation, Science and Research of the State of North Rhine-Westphalia. Special thanks for the contribution of Dennis Menge.

References

[1] S. Merkt, C. Hinke, J. Bültmann, M. Brandt, Y. M. Xie: Mechanical response of TiAl6V4 lattice structures manufactured by selective laser melting in quasistatic und dynamic compression tests, Journal of Laser Applications, 2015

[2] J. Breuninger, R. Becker, A. Wolf, S. Rommel, A. Verl: Generative Fertigung mit Kunststoffen – Konzeption und Konstruktion für selektives Laserintern, Springer Vieweg Verlag, Berlin Heidelberg, 2013

[3] M. Schmid: Selektives Lasersintern (SLS) mit Kunststoffen, Hanser, 2015

[4] C. Neff, N. Hopkinson, N. B. Crane: Selective Laser Sintering of Diamond Lattice Structures: Experimental Results and FEA Model Comparison, SFF Symposium, Austin, USA, 2015

[5] A. Wegner, G. Witt: Konstruktionsregeln für das Lasersintern, Universität Duisburg-Essen, Zeitschrift Kunststofftechnik, 2012

[6] G. A. O. Adam: Systematische Erarbeitung von Konstruktionsregeln für die additiven Fertigungsverfahren Lasersintern, Laserschmelzen und Fused Deposition Modeling, Dissertation Universität Paderborn 2015, Shaker Verlag, Aachen, 2015