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Reviewed Paper

A CAD-BASED WORKFLOW AND MECHANICAL CHARACTERIZATION FOR ADDITIVE MANUFACTURING OF TAILORED LATTICE STRUCTURES

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Abstract

Lattice structures are highly recommended for lightweight applications and cost reduction in additive manufacturing (AM). Currently, parts with lattice structures are still mainly used for illustrative purposes and rarely in industrial products. One important reason is that, due to their high dependency on macro- and micro-geometry, the mechanical properties of manufactured structures are difficult to predict. Thus, even and precise struts are needed. In this paper, a workflow for fabrication of lattice structures with strut-diameters from 150 µm to 400 µm on commercial laser beam melting (LBM) systems is presented. Based on a CAD-integrated user-interface for lattice design, a customized slicing algorithm determines database-aided suitable exposure parameters which ensure that the properties of the manufactured struts will just be as specified upon design. Subsequently, compression tests are performed in order to verify the established workflow. The developed tool enables designers to integrate AM-specific geometries into their components with little specific experience in AM.

Introduction

Additive manufacturing processes such as LBM offer significantly greater scope than conventional manufacturing processes with regard to the geometry of the product. A wide variety of shapes can be produced without the need to set up the machine or make any significant adjustments to the process.

For solid components it is usually sufficient to use the standard parameters provided by the machine manufacturers. This applies both to the generation of slice data and to the production itself. Generally, within each layer the geometrical contours are determined and subsequently filled with hatches (contour-hatch exposure, CH). However, if the smallest part dimension approximates the laser focus diameter, the resulting geometry increasingly deviates from the nominal one when using the CH exposure [1,2]. This is particularly problematic with lattice structures, since their struts are usually very filigree. For example, own preliminary tests have shown a minimum achievable value of 400 µm for a targeted strut diameter of 200 µm when using CH-exposure [3].

Since the effective mechanical properties of lattice structures disproportionally depend on their (heavily deviating) geometry, it is a rather futile task to tailor or even predict these properties for specific use cases. This is one of the main obstacles on the way to integrating lattice structures into industrial products [4]. To solve this problem, uniform and precise struts that closely match the nominal geometry are needed.

This paper presents a workflow that covers the entire process chain from design to production of precise lattice structures even at strut diameters close to that of the laser focus. A custom CAD add-in for lattice design as well as a tailored slicer that uses point-like exposure and a database for exposure parameters are shown. Furthermore, compression tests are executed in order to verify the mechanical properties.

Lattice Design

There are several commercially available software solutions that feature lattice structures for additive manufacturing, most notably Netfabb by AutoDesk and 3-matic by Materialise. These are all stand-alone software products that require a part design to be frozen before lattice structures can be integrated. Furthermore, they demand a significant amount of training and cause high license costs which render them uneconomical for small businesses. Meanwhile, even the smallest engineering companies own a CAD software that is used on a daily basis. Using this premise, we developed an add-in that enables designers to easily integrate lattice structures in parts directly within their familiar CAD environment and workflow.

The first step is the definition of the volume which will subsequently be filled with lattice. Based on an existing volumetric body there are two ways of defining: creating a shell or extruding a sketch (Figure 1). The shell mode uses the user-defined wall thickness and open faces to determine the remaining solid body and (via a Boolean cut operation) the lattice volume. If the wall thickness equals zero, the whole body is filled and open faces are irrelevant. The sketch mode expects an arbitrary 2D sketch and two extrusion depths as input. Extruding the sketch in both normal directions according to the specified depths, a cutting body is created which is then used to determine the remaining solid and lattice volume via Boolean operations.

With the volume now defined, the creation of the lattice structure itself is the next step. Therefore, the user selects a unit cell topology and size as well as the cell orientation. Given this input, the oriented bounding box of the lattice volume is calculated and meshed according to the

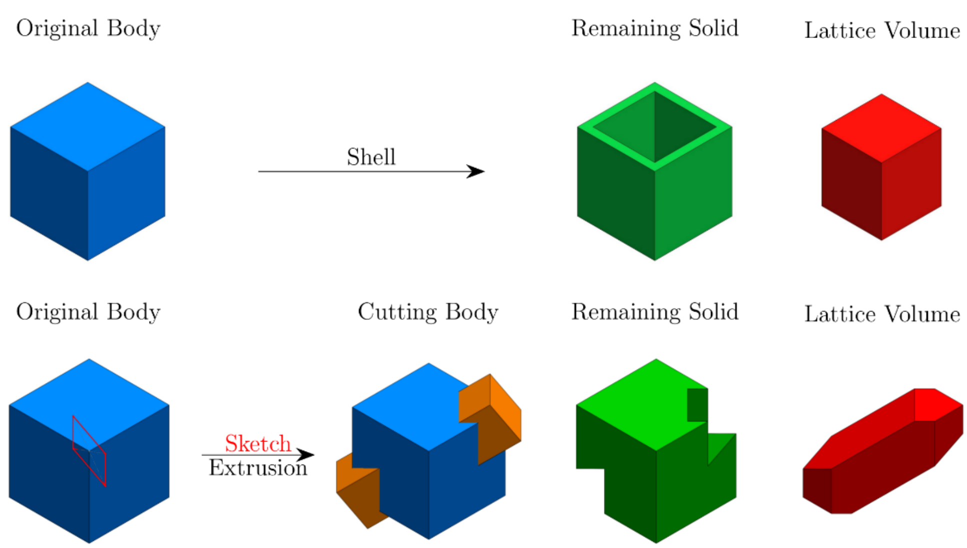

Figure 1: Definition of lattice volume – top: via shell operation; bottom: via sketch extrusion

cell size. The selected unit cell then is copied at each grid element that is at least partly inside the volume. Finally, struts exceeding the volume boundary are trimmed.

As most CAD environments are based on Constructive Solid Geometry (CSG), which works by Boolean combinations of geometrical primitives, modeling the lattice will quickly crash the software due to the high number of strut intersections even in medium sized lattice structures [5–7]. To avoid this problem, the lattice structure will not be modeled, but the geometrical information is stored in a custom data structure in the backend instead. This data structure contains a list of nodes with their spatial coordinates and a list of struts connecting two nodes each. Additionally, each strut carries information about the geometry of its cross section. To give the designer visual feedback on the just created lattice structure, a rough tessellation is computed and imported into the CAD environment (Figure 2).

Slicing

In order to manufacture the designed parts on a LBM machine, slice data is needed. As described above, the standard slicing tools and exposure parameters provided by the machine manufacturers are usually optimized for massive parts and therefore not suitable for filigree lattices. Furthermore, these slicers expect triangle meshes of the parts as input which propagates the discretization error inherent in every triangulation to the slice data. When employing our lattice design approach the solid body is stored as CSG and the lattice as parametric data, both of which are exact representations. To make use of this major advantage we developed a custom slicer that consists of two modules: one for the solid body and one for the lattice structure.

With the contour-hatch exposure being perfectly suitable for massive regions this strategy is adopted for the solid body. For this, the first step is the creation of a stack of parallel planes inside the CAD environment. The planes are oriented according to build direction and the distance is equal to the selected layer thickness. Intersecting the solid body with the plane stack the contour within each layer is determined as a sequence of straight lines, curves, and splines. This sequence

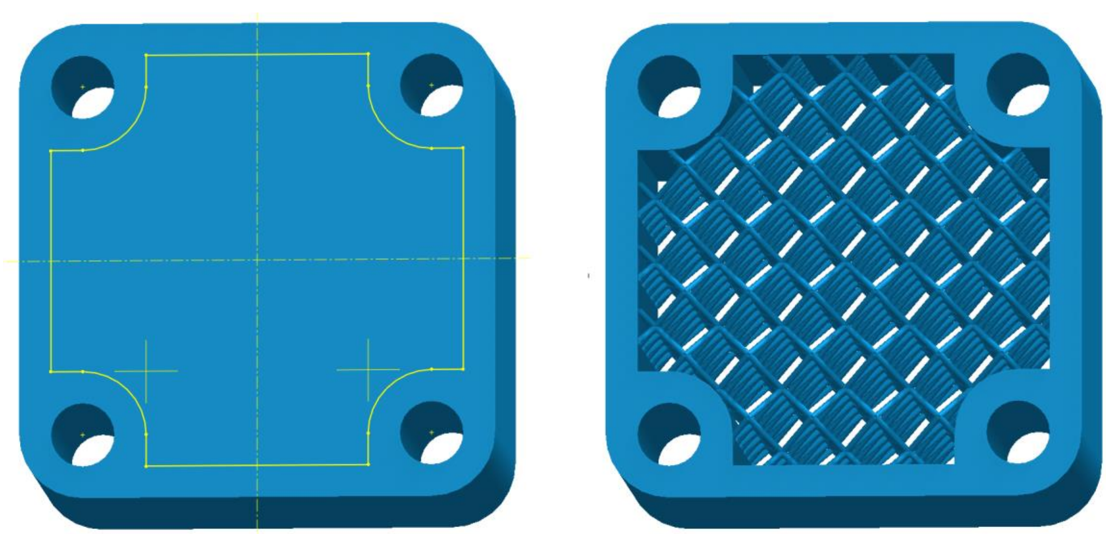

Figure 2: Lattice design via sketch mode – left: original body with selected sketch for extrusion (yellow); right: generated lattice visualized as triangle mesh

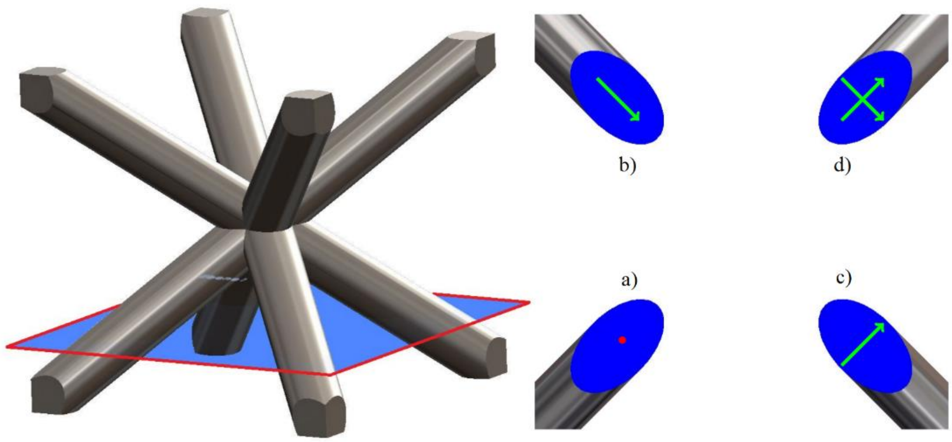

Figure 3: Slicing of a single BCC unit cell – left: slicing plane
right: a) point exposure; b) collinear line; c) normal line; d) combined lines

is then tessellated with straight lines, offset, and filled with hatches as needed. The tessellation will of course introduce a discretization error, but higher qualities can be achieved with significantly less memory overhead compared the common method of slicing triangle meshes.

Slicing the lattice structure is not as straightforward, especially when targeting thin struts with diameters close to that of the laser focus. Scanning the strut contour will already result in diameters diverging from the nominal value, as described above. One idea to avoid this deviation is to expose just a single point coinciding with the center of the strut cross-section in each layer and adjust the resulting strut diameter by varying laser power and speed [8]. We modified this idea: the exposure point is expanded to one (or two) short straight exposure line(s) that are either normal or collinear (or both) to the projected strut direction (Figure 3). The resulting strut diameter is then adjusted by varying the line length while keeping the laser parameters constant. This strategy is hereafter referred to as Pseudo-P-exposure.

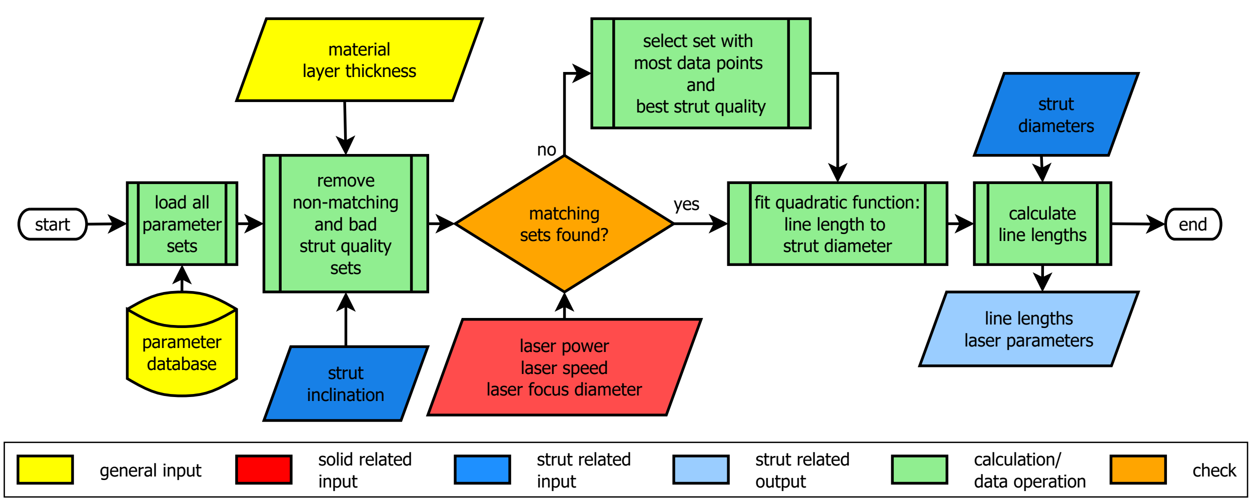

Figure 4: Flowchart of line length estimation for Pseudo-P-exposure

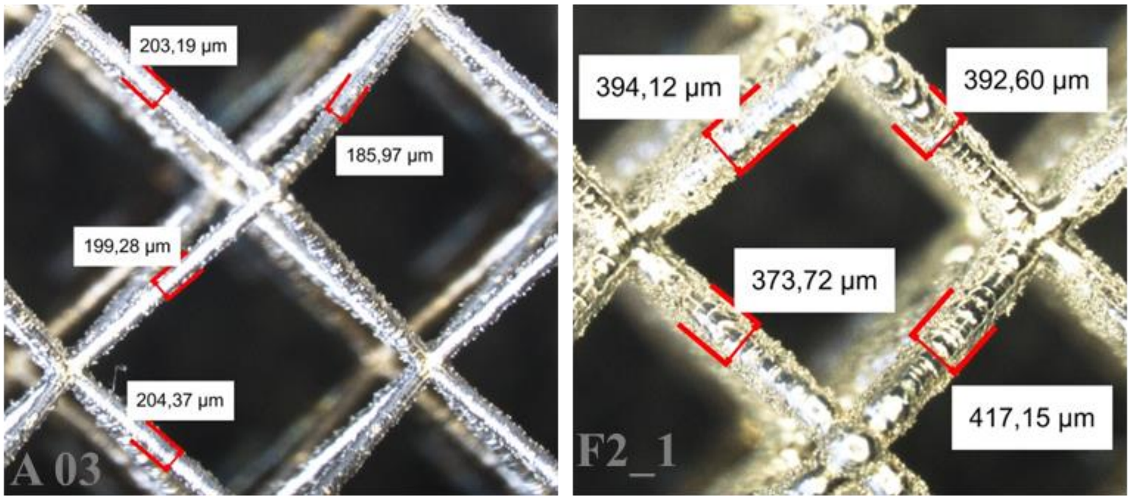

Figure 5: Differences of lattice structures manufactured with different exposure strategies but same laser parameters left: Pseudo-P-exposure; right: CH-exposure

Estimating suitable line lengths is not recommended to be done manually by an arbitrary designer using the add-in as it requires very specific know-how. Instead, the needed line lengths are computed automatically using a parameter database of previously executed build jobs (Figure 4). Line lengths are always computed simultaneously for all struts with the same inclination to the building plane. Firstly, of all available parameter sets the ones that match the current powder material, layer thickness, and strut inclination are selected. Sets with bad strut quality are discarded at this step, too. Secondly, the remaining parameter sets are checked if there are any that match the laser parameters previously used for slicing the solid. If yes, these sets are selected for further processing. If not, all the remaining parameter sets are grouped by laser power, speed, and focus diameter. The group with the most data points is selected, with achieved strut quality serving as a tiebreaker. A quadratic function is then fitted to the data point, linking used line length to resulting strut diameter. With this relation it is possible to calculate a suitable line length for each strut of the current build job.

The qualitative and quantitative advantages of Pseudo-P-exposure (left) over CH-exposure (right) can be seen in Figure 5. Both lattice structures are manufactured on the same LBM machine using the same parameters: Ti-6Al-4V, 25 µm layer thickness, 625 mm/s laser speed, 100 W laser power, and 150 µm laser focus diameter. For Pseudo-P the line length is 141 µm and for CH the targeted strut diameter is 200 µm. The Pseudo-P-exposure leads to noticeably finer and more even struts.

Compression tests

To verify the described workflow for lattice structure manufacturing, test specimens are made and subjected to compression tests. The determined effective mechanical parameters are compared to other test results available in-house or in corresponding literature [9].

The specimen geometry is based on a basic body-centered cubic unit cell (bcc) with varying edge length L and strut diameter D (Figure 7 left). This unit cell is repeated 10x10x15 times to form a standing cuboid (Figure 7 right). The edge length L is either 1, 2, or 3 mm and the diameter D is ranging from around 180 µm to 800 µm as a result of varied line lengths. These

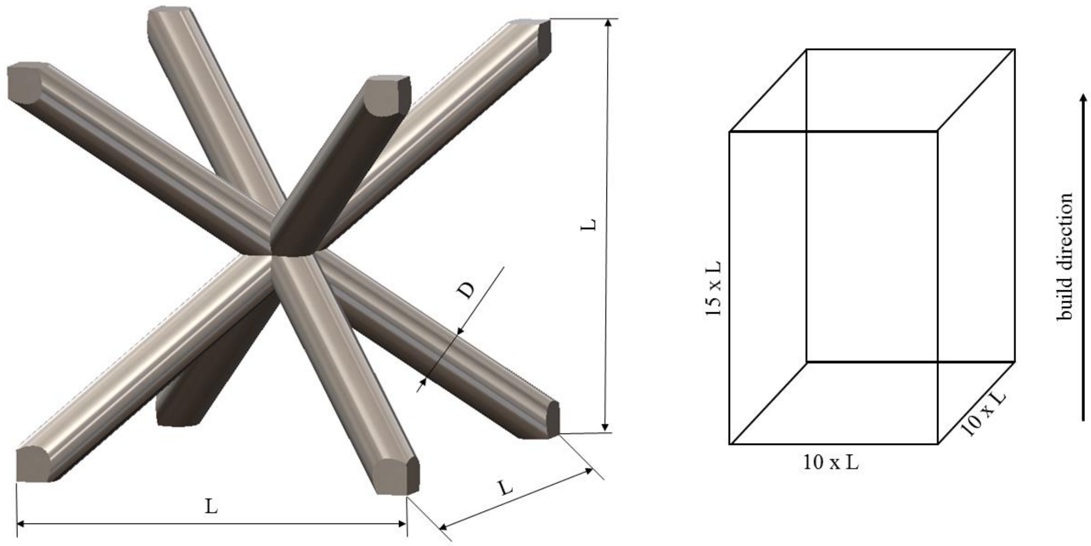

Figure 7: Compression test specimen – left: bcc unit cell; right: specimen geometry, consisting of 10x10x15 unit cells

variations lead to relative densities from 2% to 22% of the test specimens compared to block material.

An example of an executed compression test is shown in Figure 6. The test conditions are in accordance to German standard DIN 50134 and compression speed set to 0.1% per second (constant, based on the undeformed height of the specimen) [10]. With max. test forces of <5 kN on a 50 kN test machine, machine frame deformation is considered negligible and therefore the displacement of the actuator is used to measure the strain. As the platens did not show dentations and gliding of the specimens is visible, uniform load distribution is assumed.

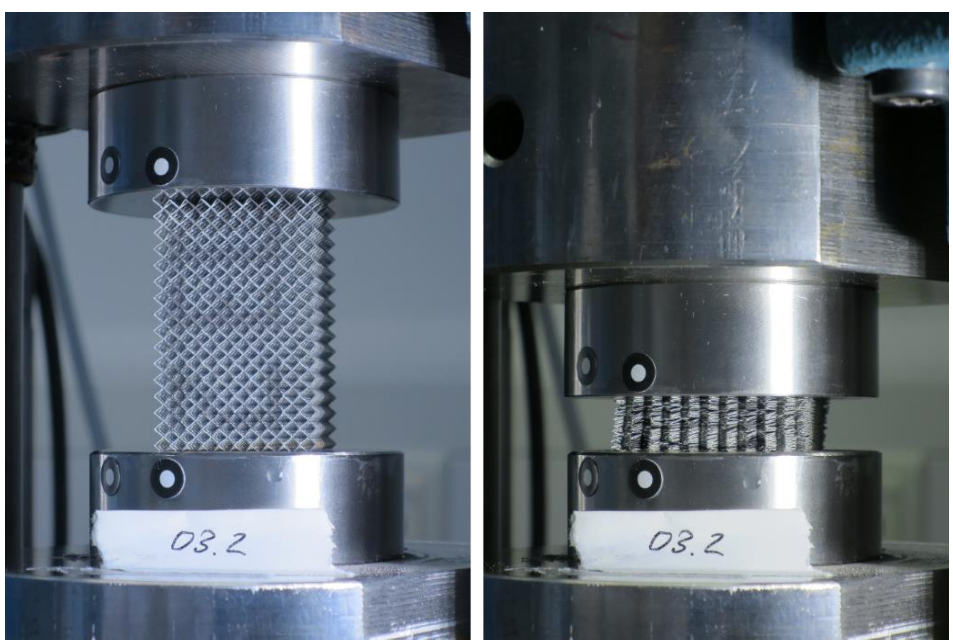

Figure 6: Compression test of specimen with L = 3 mm and D = 250 µm
left: initial state; right: compressed to block

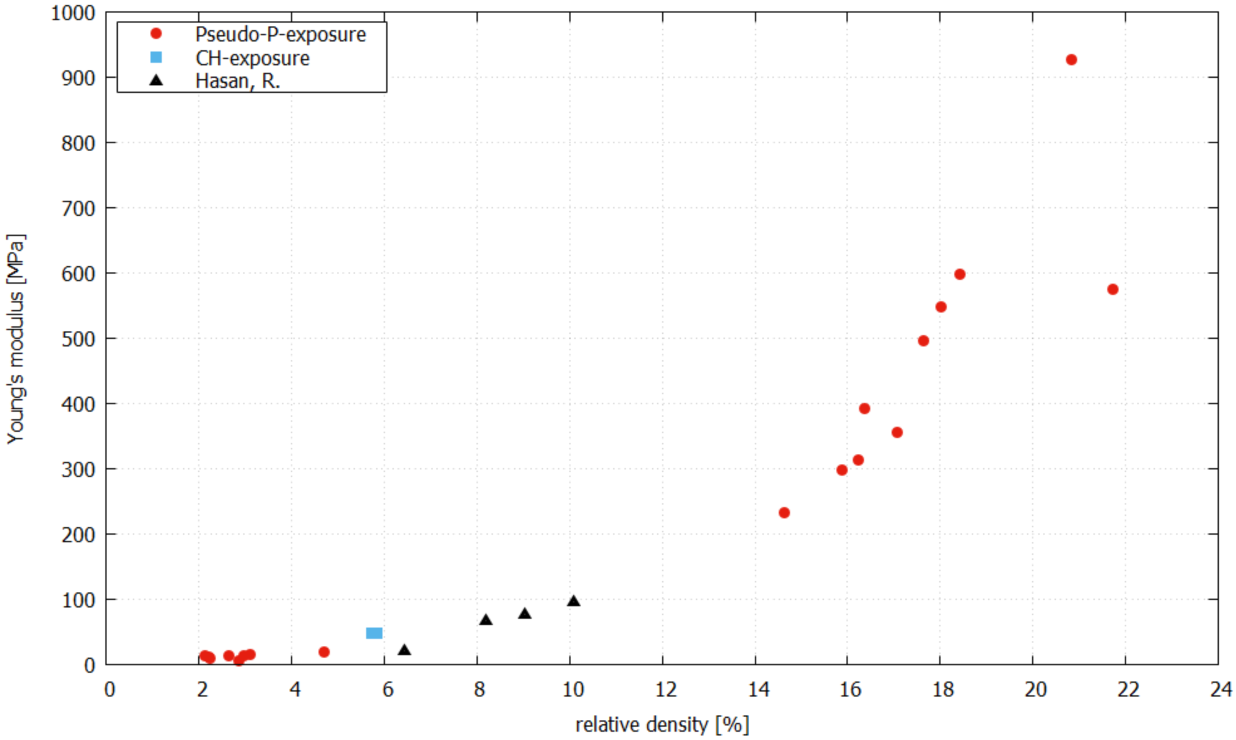

Figure 8: Young's modulus of specimens manufactured using Pseudo-P-exposure, CH-exposure, and results of corresponding tests

It is noticeable that even in the compressed state the cell structure is visible, which indicates a uniform compression due to homogeneous struts. This is matching the findings related to strut quality described above.

The measured Young's moduli as a function of relative density are depicted in Figure 8. Added are two data points of similarly tested lattice structures that had been manufactured using CH-exposure and four data points taken from [9]. It is evident that our proposed method of exposure results in lattice structures that are in line with the mechanical properties of those manufactured using established strategies or by other researchers. The advantage of our method is the wider range of possible modulus values, especially towards very flexible and fragile structures as well as higher manufacturing speed due to simpler scan line geometry.

Conclusion

In this paper we presented a workflow to design lattice structures for additive manufacturing directly within a CAD environment and integrate them into existing parts. The structures can be created using two different modes of volume definition and with selectable size, topology, and orientation. Upon creation, the geometrical information of the lattice is stored in a data structure in the backend and a rough triangle mesh is generated for visualization purposes.

After lattice design, a custom slicer is employed in order to calculate suitable slice data. First, the massive regions of the part are sliced and the scan vectors are determined using contour-hatch exposure. As this exposure strategy yields insufficient results when dealing with filigree lattice structures these are sliced using an exposure strategy consisting of short straight lines with precisely defined length. To calculate the required line length, a database of previous build jobs is employed and considering solid as well as strut related input suitable laser parameter sets are selected and the data points are fitted with a quadratic function.

The executed compression tests show that using our exposure strategy results in lattice structures that are on par with other strategies regarding structural and mechanical properties. Furthermore, a wider range of properties is achievable, especially towards very flexible structures, but also when aiming at higher stiffness.

Using the developed tools any designer can integrate lattice structures in arbitrary parts even with little AM-specific knowledge and only having prevalent CAD software at hand. In the future more features such as graded lattices will be implemented and the usability raised. Additionally, a guideline is planned on how the parameter database can best be filled to yield sufficient results for other materials or LBM machines with as few as possible build jobs.

Acknowledgements

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