Professional Paper https://doi.org/10.24867/GRID-2026-p93

FDM 3D Printing of Low-Density Lattice Structures Using Modified Infill Patterns

ABSTRACT

Lattice structures are extremely useful geometric structures that can exhibit a broad range of desired mechanical properties, allowing them to be tailor-made for specific purposes. However, manufacturing of such structures using traditional methods is difficult or even impossible. 3D printing technologies enable vastly easier production of such structures, allowing for easy and fast production of mechanically tuneable materials. While such structures can have any density, low-density variants provide certain properties that can be desirable in a broad spectrum of applications. This paper explores the tuning and production of one such type of lattice structure using desktop FDM 3D printers, with a special emphasis on lowest possible density that can be achieved. Lattice structures are derived from modified selected parametric infill patterns available in the slicer software. Structures are produced using Acrylonitrile Styrene Acrylate with optimised manufacturing parameters that allow for low-density lattice production.

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KEY WORDS
3D printing, lattice, infill, FDM

1. Introduction

Low-density or sparse lattice structures are low-relative-density cellular structures in which a limited amount of material is distributed through a network of interconnected geometric elements (Gibson & Ashby, 1997; Helou & Kara, 2018; Nazir et al., 2019). By placing material only where it contributes to structural or functional performance, these structures can achieve low mass and reduced material consumption while still providing useful stiffness, load-bearing capability, energy absorption or other desired property. Their internal geometry can also be tailored to influence properties such as fluid transport, heat transfer, anisotropy, and deformation behaviour (Panesar et al., 2018).

Additive manufacturing is particularly well suited to the production of sparse lattice structures because it builds components layer by layer, allowing complex internal networks, small repeating cells, and spatially varying geometries to be fabricated without many of the accessibility and tooling constraints associated with conventional manufacturing. It also enables lattice density, cell dimensions, and local geometry to be varied within a single component, making it possible to adapt structural properties to local loading or functional requirements (Ngo et al., 2018; Gibson et al., 2021). These advantages have led to the use of sparse lattice structures in lightweight aerospace and automotive components, impact-absorbing systems, biomedical implants, thermal management devices, sandwich structures, robotic components, and additively manufactured infill.

The lattice structures examined in this paper were designed to gradually absorb kinetic energy of maximum stable-diameter water droplets falling at terminal velocity. The goal of this designed part is to muffle the impact sound through gradual deceleration and breakup of the droplets.

It is important to note that this research paper investigates only the practical capabilities of manufacturing such sparse lattice structures using

additive manufacturing, not the actual acoustic performance of the lattice structure itself.

There are several methods that can produce such low-density lattice structures, but as mentioned, the most convenient one is additive manufacturing (AM), also known as 3D printing. There are two currently available AM technologies that can be thought of as a consumer technology: Stereolithography (SLA) and Fused Deposition Modelling (FDM). While the official technological categories into which these two methods fit are called Vat Photopolymerization and Material Extrusion, the two previously mentioned names have become most widely used, and so SLA and FDM names will be used in this paper (Gibson et al., 2021).

SLA is a very attractive method for lattice structures manufacturing – it has very high resolution and print speed, but the material selection is somewhat limited and using this method can be quite messy in the post-processing steps (Ngo et al., 2018; Gibson et al., 2021).

FDM is also very attractive, but for different reasons – it offers a huge range of materials, many of which are high-performance ones, and models are usable right out of the printer. The downside is limited resolution and slow print speed compared to SLA (Ngo et al., 2018; Gibson et al., 2021).

For the purpose of this research, FDM is the better suited AM method. There are multiple reasons for this. One of the most Important ones is the way that models are prepared for 3D printing. This preparation process is called slicing and it translates a 3D model into instructions that the 3D printer uses to build the actual part (Gibson et al., 2021).

Like all AM technologies, FDM slicing breaks down the 3D model into a series of vertical slices. Since every slice is constructed using material extrusion during printing process, the slices are composed of lines and curves thet represent extrusion paths. This means that a single slice can contain a complex collection of extrusion paths and every one of them can be controlled through slicing settings. This means that the user has an expansive range of options through which he can control material extrusion process.

SLA slicing process is much simpler, as it produces slices that are just images of model's cross-section. Therefore, if a user wanted to create a lattice structure, he would either have to model it by hand or use very limited slicing tools to fill the object with a very simple 3D grid infill.

This is the part where FDM slicing has a huge advantage – infill setting are very rich and customizable, which means that various lattice structures do not have to be modelled – they can be generated during the slicing process (Baich, Manogharan & Marie, 2015; Fernandez-Vicente et al., 2016). This is a huge advantage for FDM method, since the user simply has to model the general shape of the part, and slicer fills the model with the 3D lattice structure of choice. Further, FDM can on average use much stronger high-perfromance materials than SLA, which is important when manufacturing low-density lattices that can be very brittle when made of commonly used SLA materials.

With all this in mind, FDM is the clear choice for manufacturing sparse lattice structures for the outlined application.

2. 3D part design

The 3D model is very simple since it only has to catch water droplets that are falling on the same location. The model is a cuboid with dimensions 30x30x20 mm, with 20 mm being the height. Four vertical edges have a 4 mm fillet applied. Fillet is added to reduce stress on the otherwise sharp edges of the model – ASA is very prone to thermal contraction and warping, even on smaller parts. An easy way to mitigate this is to make sure there are no sharp corners in the horizontal plane. Model was created in Cinema 4D and exported in .stl format, which is the standard exchange format for 3D printing.

Given that 3D printed part quality was inspected visually, an additional part was deigned – a tray with recesses into which models could be neatly arranged for taking photographs. It was made from black Polylactic Acid (PLA) plastic.

3. 3D printing preparation

Next step is model 3D printing preparation or slicing. Model were 3D printed on Bambu Lab X1 Carbon 3D printer and Bambu Studio was used a sn official slicer software for this 3D printer. This printer represents a high-quality, higher-end (albeit by now somewhat old) 3D printer. It was introduced in 2022. at a price of €1,200.

This printer was chosen because of high print quality, ease of use and finely dialled-in printing profiles. Printer was upgraded to 0.4 mm E3D ObXidian hotend for a more stable and precise extrusion. Textured PEI build plate was used, with a thin layer of glue applied to ensure good adhesion.

Appropriate material also has to be selected. While there is a wide selection of materials, Acrylonitrile Styrene Acrylate (ASA) is a good material of choice for 3D printing lattice structures – it is thought, easy to print, low-cost and very resilient to UV light, meaning it can be used outdoors. ASA material was sourced from Bambu Lab.

Model was imported into Bambu Studio V2.7.1.62. ASA material preset was assigned to the model and 0.20 mm Standard printing process was used as the starting point. Although thinner layers can produce more intricate and detailed lattice structure, it also means that the extruded lines are weaker, therefore it was decided to use standard 0.2 mm layer height (Mohamed, Masood & Bhowmik, 2015; Chacón et al., 2017).

Sparse infill pattern was selected next (Baich, Manogharan & Marie, 2015; Fernandez-Vicente et al., 2016). Bambu Studio offers a wealth of infill patterns, 22 in total, and this is the aforementioned advantage that FDM AM has over SLA. Of course, not all pattern can be used successfully for the lattice structures application outlined in this paper.

The infill pattern must have open cells and ability to control the pattern distribution. Open cells are required so that the water can flow through the structure and drain away, while pattern distribution has to be controllable in order to control how the droplets disperse as they travel through the structure. Controllable distribution is key, as many patterns have cells that grow as density decreases. This causes the droplets to interact with very few lattice elements.

However, cell shape in some patterns can be controlled and with careful parameter selection very sparse structures can be created where droplets have many interactions with the lattice structure, even though the density is low. One such pattern of note is the Cross Zag pattern. This pattern is almost identical to classic Rectilinear pattern, meaning that it is an open cell structure composed of layers of spaced lines or struts, with each layer being rotated by 90 degress. The notable distinction is that the layers can be offset. Low density rectilinear pattern is a horizontal matrix of rectangular openings. Offsetting layer by an arbitrary amount shears the opening in a particular direction. If this offset amount is large enough and properly selected, it can lead to a very airy and open structure, exactly the kind that is need for the proposed application. With this in mind, Cross Zag pattern was selected for lattice manufacturing.

Sparse lattices are delicate structures, and high-speed 3D printing is not suited for their production. Slow print speeds produce more predictable extrusion and higher quality results (Mohamed, Masood & Bhowmik, 2015; Chacón et al., 2017). Of course, print time is always a critical factor in 3D printing – one wants to optimize for print speed and quality. Therefore, the first step is to study the impact of print speed on lattice quality. For this purpose, the original model was scaled in Z axis so that it was only 2 mm high – this translates to 10 layers given the selected 0.2 mm layer hight. 10 layers is suitable to establish the print quality and is also few enough layers to enable seeing straight through the lattice, which will be used to detect any lattice defects. Four infill printing speeds were selected: 80, 60, 40 and 20 mm/s. This covers a range from what is generally considered slow to extremely slow printing speed, where it is reasonable to expect that the lattice structures have the best chance of being successfully 3D printed.

Six lattice structure densities were selected for 3D printing, giving a good range of densities to examine the capabilities of the 3D printing process. “Sparse infill density” value determine the density, and the values selected were 10, 8, 6, 4, 2 and 1. It very important to note that density of lattice structures refers to relative density – the ratio between the space filled with material and space not filled with material (Gibson & Ashby, 1997). This does not refer to actual density, e.g. 11.34 g/cm^3 for lead. Realive density is expressed either as a percentage or a fill factor, but both denote the same thing. Selected values determine the theoretical percentage of volume filled with material, therefore these values translate to 90, 92, 94, 96, 98 and 99% empty space in lattice structure. Although there is no set limit to what constitutes “low-density” lattice structures, densities lower than 10% are generally considered the lower limit for such structures.

After the optimal speed was determined, full scale models were produced in the same range of densities. Full models have a heigh of 20 mm or 100 layers.

Both thin and full scale models use the same slicing setting. “Wall loops” setting was set tp 5 In order to give the part structural strength, acting like an outside full density shell inside of which the lattice is held. Parts were printed with no top or bottom layers which exposes the lattice structure on top and bottom side. “Infil/Wall overlap” setting was set to 50 in order to anchor the lattice structure more firmly to the outer wall shell.

While the “Sparse infil density” setting provides the theoretical relative density of the lattice structure, it is expected that there will be deviations from this on account of the very low density of the structures, something that is almost never used in regular 3D printing. To determine the actual relative density, one model with only the wall shell was printed, and it’s weight was measured using a high precision Kern PCB 300-2 scale. Full scale models were weighted after printing, and the weight of the wall shell was subtracted from the weight of each full scale model. That gave the weight of the ASA plastic used for the lattice structure itself. Given the known thickness of the wall shell, a volume for the interior space dedicated to lattice structure was calculated at 25.16 cm^3. ASA material density is defined by Bambu Lab as 1.05 g/cm^3. With volume, weight and density provided, actual relative density was calculated for each full scale model.

4. Parts manufacturing

Models were sliced and saved as .3mf files. 31 models were printed In total: 6 thin models for each of the 4 infill printing speeds, 6 full scale models and one tray model. Each batch of models was printed separately. Printer was allowed too cool down for 30 minutes after printing, which made removing delicate models form the build plate much easier.

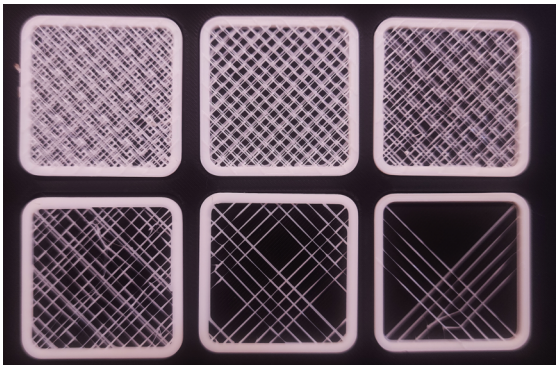
Print time for different batches are noted in Table 1.

Table 1
Batch print time

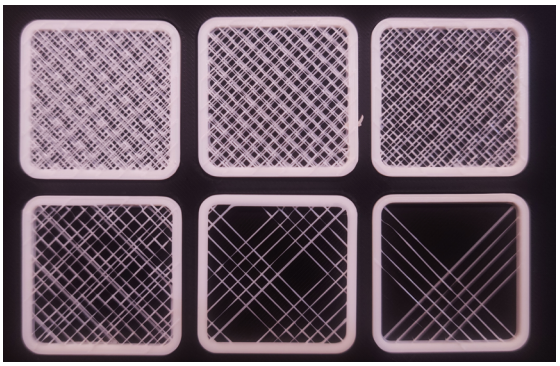
Model batch	Print time
Thin models at 80 mm/s	8m 15s
Thin models at 60 mm/s	9m 3s
Thin models at 40 mm/s	10m 40s
Thin models at 20 mm/s	15m 36s
Full scale models at 20 mm/s	2h 25m

5. Results

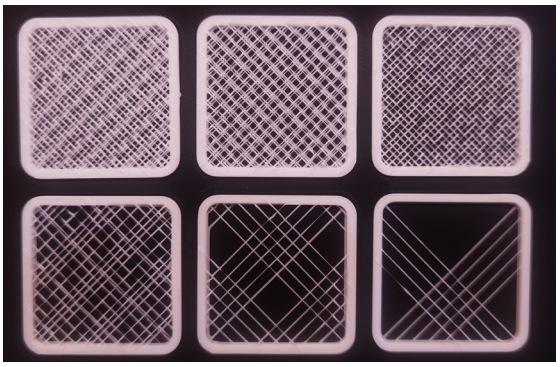
After printing, thin models were placed in a tray and photographed, starting with the 80 mm/s infill printing speed. They were photographed with a Sony A6400 camera, equipped with a Sigma 30mm f/1.4 DC DN Contemporary. Images were cropped to taste. Same was done for full scale models. Results can be seen on Images 1-5. All images show the same model order: top row, left to right: 10, 8 and 6% infill, bottom row, left to right: 4, 2 and 1% infil.



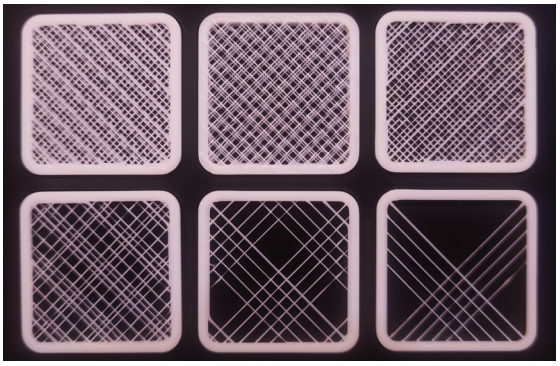
» **Figure 1:** *80 mm/s infill printing speed*



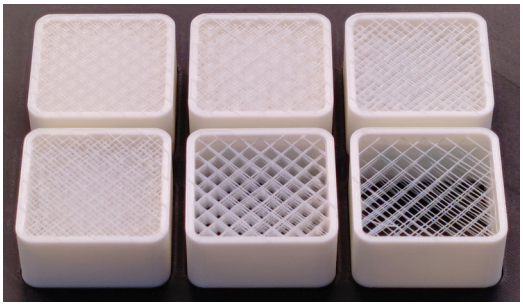
» **Figure 2:** *60 mm/s infill printing speed*



» **Figure 3:** *40 mm/s infill printing speed*



» **Figure 4:** *20 mm/s infill printing speed*



» **Figure 5:** *Full scale parts printed at 20 mm/s infill printing speed*

Wall shell model was weighted, as well as six full scale models. Wall shell model measured weight was 5.82 g. Real relative values were calculated from this. Results are noted in table 2.

Table 2
Full scale model measurements and calculations

Model infil (%)	Model weight (g)	Lattice/infill weight (g)	Real relative density (%)	Difference real/ specified density
10	8.83	3.01	11.39	1.14x
8	8.37	2.55	9.67	1.21x
6	7.64	1.82	6.93	1.16x
4	7.11	1.29	4.92	1.23x
2	6.53	0.71	2.68	1.34x
1	6.19	0.37	1.41	1.41x

6. Discussion

Thin model images show that extrusion quality increases as the speed decreases.

There are numerous extrusion line breaks in 6,4,2 and 1% infills at 80 mm/s. 10 and 8% infills have better quality, since the next layer is always supported by more lines underneath, but the quality is still visibly degraded.

60 mm/s infill are better at 10, 8 and 6%, but 4, 2 and 1% infills are on par with degraded quality from 80 mm/s models.

Quality is significantly better at 40 mm/s speed as there are fewer breaks in 4, 2 and 1% infills. There is still some quality degradation but the extrusion is much more stable.

20 mm/s extrusion speed yields by far the best results. Extrusion is very stabler, and there are only a few line breaks across the entire infill range. Given the large number of lines per layer and number of layer, these rare, sporadic breaks are insignificant.

Full scale models were printed almost flawlessly, with only a few visible extrusion breaks over the entire model range. It is difficult to resolve individual lines in the photographs of the models with higher infills, but close naked-eye and high-resolution image inspection shows that all version have high-quality lattice structures.

Real relative density calculations show that there is on average a 25% volume increase between real and specified relative density and it somewhat increases as the lattice density drops. This means that the printer is over-extruding material compared to what was expected by the slicer. This can be easily fixed since extrusion multiplier can be adjusted to produce the correct amount of plastic. However, this discrepancy does not detract from the fact that very sparse lattice structures were successfully created.

7. Conclusion

Results show that FDM 3D printers can produce remarkably delicate and low-relative-density lattice structures. Even 1% infill density model was printed almost flawlessly, which is impressive given that relative lattice structure densities below 3% are considered extremely low density or ultralight. It is also interesting to note that 1% is the lowest possible value that Bambu Studio allows for infill density. Results are even more impressive if actual, calculated density is considered.

The results demonstrate that FDM 3D printing ia a viable technology for producing very low-density, sparse lattice structures, which can lead to exciting new possibilities for consumer 3D printer applications.

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