Analysis of strength properties of 3D printed lightweight structures made of AlSi10Mg material

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Abstract. The main aim of this article is to compare two approaches to decreasing the overall weight of components by using additive manufacturing from AlSi10Mg alloy. This optimization is advantageous as it lessens both the production time of parts (components) and overall costs, in key industries such as aviation. The first method used to reduce the weight of a structure is the implementation of lattice structures, which replace filled parts with selected structures of different shapes, while maintaining key properties of the original structure. The other method to decrease weight is the topological optimization of prepared samples. In this article, these two options have been compared. The specially designed sample was first optimized topologically. Subsequently, it was lightened using selected structures (Octet truss and Rhombic dodecahedron) in SW Magics with different lattice parameters. These samples were then printed using DMLS technology from AlSi10Mg on the ConceptLaser M2 Cusing system. The material used was analysed by SEM, and a particle size distribution was also performed. Furthermore, a three-point bending test was performed on the bodies produced in this way. The results of this test were analysed and evaluated in terms of load (bending force), depending on the type of sample and the volume/weight saved.

1 Introduction
Today, industry is placing increasing emphasis on reducing the weight of manufactured components. One of the most important production areas concerned with lightening a structure’s weight is aviation, although this trend can also be seen in other industries. Thanks to modern, metal 3D printing technology, two possibilities have opened up to decrease the weight of products: the use of lattice structure and topological optimization.

Other articles have dealt with the topic of lattice structures prepared by 3D printing and its mechanical properties. The SLM method for cell lattice structures was used by Hanzl P. [1] This article proved the suitability of using gyroid structures in the machinery industry. The conclusion of the same article was the ability to create stiffer and lighter samples. The same method of additive manufacturing as the one used one in Hanzl’s work (DMLS) was also used by Yan C [2]. His article proved that this technology can manufacture quality lattice structures, as well as that strength and modulus increase by increasing the volume fraction and decrease by increasing the size of the cell. Rashid R’s article demonstrated the suitability of using a three-point bending test to determine mechanical properties, such as flexural strength and flexural modulus. [3] Tests made in this article were also key for proving a strong influence of lattice structure geometry on the deformation.
2 Experimental procedure

The experiment, which is described in more detail below, consists of creating sample designs and comparing lattice structures with topologically-optimized samples, and full, non-optimized samples. A comparison is made using a 3-point bending test. As mentioned in the introduction, the objective of this article is to reduce the weight of the sample and compare the strength of individual variants, not to strictly achieve better mechanical properties as it was in many articles [4-6].

2.1 Sample design and topology optimization

Sample design was based on topological optimization of the rectangle shape of a 2D beam 30x135 mm supported at the distance of 70 mm, and loaded with variable force between supports (3-point bending test). Software used for sample design was a specially created script in Matlab. The goal of optimization was to create a geometry to reduce the amount of material to 50 %, and to maximize the stiffness of the sample. The resulting sample was adjusted on the sides. The material was added so that the sample could be supported. The original geometry had a significantly thinner sidewall. Unlike in other articles [1-7], where the structures are not enclosed in any shell, lattice structures in this article were created into the shell (Figure 1) which is much closer to real applications. The shell was created in Autodesk Inventor.

![Figure 1](image1.png)

Figure 1. Design of topologically-optimized specimen and shell for lattice structure

2.2 Lattice structures

Lattice structures were created in the software Materialise Magics 23. These structures were designed to be axially symmetrical and have similar volumes (lattice structure + shell) as the topological structure. The designed and used lattice structures (octet truss (OT) 3 and 6 mm and rhombic dodecahedron (RD) 3 and 6 mm) from Magics software are in Figure 2.

![Figure 2](image2.png)

Figure 2. Lattice structures from left: octet truss 3 and 6 mm; rhombic dodecahedron 3 and 6 mm

2.3 Sample production and heat treatment

Samples were printed using Direct Metal Laser Sintering (DMLS) technology, which is a very common technique for creating lattice structures [1-2]. The material of the samples is AlSi10Mg. The printer used was a ConceptLaser M2 Cusing system. DMLS technology is used only for alloys, and is one of the...
most used AM technologies in the industry. The process (printing) parameters used are listed in Table 1. The layer thickness used for the material was 25 µm.

| Area   | Power [W] | Scan speed [mm/s] | Spot size [mm] | Offset to original contour [mm] | Trace spacing |
|--------|-----------|-------------------|----------------|---------------------------------|--------------|
| Support | 200       | 1600              | 0,05           | 0,1                             | -            |
| Skin   | 200       | 1250              | 0,1            | 0,175                           | -            |
| Core   | 370       | 1400              | 0,19           | -                               | 0,112        |

Each test sample was printed in 3 pieces. After printing, the building pallet with samples was heat-treated according to the recommendations of the powder manufacturer [8]. The process was stress-relief annealing: Heat up in 1 hour to 240°C, and then maintain the temperature for 6 hours. Then, cool down the oven to 100°C. Afterward, allow the parts to cool in the ambient atmosphere. After the heat treatment, the samples were cut from the building pallet and treated by sandblasting. The samples modified in this way are shown in Figure 3.

2.4 Material (powder) analysis
The default material for the DMLS technology is in powder form. For the powder analysis, the scanning electron microscope Tescan Vega 3 LMU with accelerating voltage 20 kV, detector SE +BSE was used following the particle distribution analysis by laser diffraction (ASTM B822).

Figure 3. Each type of sample after heat treatment and sandblasting

Figure 4. Powder quality comparison: powder used by us (A) x manufacturer's analysis (B) [7]
Figure 4. shows a comparison of the quality of the powder that was used with the powder analyzed by the manufacturer. At first glance, the powder from the manufacturer contains more regular and high sphericity particles. Furthermore, a smaller occurrence of satellites and imperfect particles can be seen. Particle size distribution declared by the producer is 15-63 µm. [7] In this analyze the average mean diameter 26.29 µm was measured. In Figure 5, we can see particle size distribution graph of analyzed powder.

Figure 5. Particle size distribution graph of AlSi10Mg powder

2.5 3-point bending test
For the 3-point bending test, the 100 kN LabTest 5.100SP1 testing machine was used. The test progress is shown in Figure 6, and the loading rate was 2 mm/min.

Figure 6. Three-point bending test

In Figure 7, we can see the results of the three-point bending test depending on the type of sample. Based on the experiment, the best result from the optimized samples was achieved by the sample after topological optimization.
3 Results
Results of the 3-point bending test and sample weight are in Table 2. The best results were archived by topologically-optimized samples, which were the lightest and had the highest endurance.

If we evaluate the bending force / saved weight ratio, the RD6 sample turned out best from the lightweight structures. By comparing the topologically-optimized sample and the RD6 sample, we conclude that the RD6 sample was about 5% heavier than the TO sample and had about 10% lower load capacity. However, if we consider that specialized software is needed for TO and the lattice structure can be created in common software for print preparation, then this result is acceptable.

Table 2. Results of the experiment

| Structure | RD3  | RD6  | OT3  | OT6  | TO   | Non-OPT |
|-----------|------|------|------|------|------|---------|
| Average value of bending force [N] | 10 057 | 9 690 | 9 944 | 9 564 | 10 730 | 13 399 |
| Percentage difference of maximum bending forces of samples and full body [%] | 24,94 | 27,68 | 25,79 | 28,62 | 19,92 | - |
| Average value of the weight of the sample [g] | 28,01 | 24,43 | 26,96 | 24,68 | 23,22 | 31,85 |
| Percentage difference in weight of samples and full body [%] | 12,06 | 23,30 | 15,35 | 22,51 | 27,10 | - |

4 Conclusion
In this article, the two options for the optimization of 3D printing have been compared. The specially-designed sample was first optimized topologically. Subsequently, it was lightened using selected structures (Octet truss and Rhombic dodecahedron) in SW Magics with different lattice parameters. These samples were then printed using DMLS technology from AlSi10Mg on the ConceptLaser M2 Cusing system. Based on this experiment, the following was found:
- Topologically-optimized samples have the highest endurance and smallest average value of the sample weight, but can be disadvantageous as they require special software to make them
- Lattice structures had ~ 10% less endurance than a topologically-optimized sample; the highest endurance was reached with a rhombic dodecahedron 3 mm lattice structure
- The finer the lattice structure, the better endurance, but also higher weight
- Issue of fine lattice structures is that powder might stay inside the structures, which may be dangerous for one’s health

Based on the results of this experiment, it is necessary to verify the effect of the outside shell in the next step. The shell, which encloses the structures, could be so rigid that the influence of inner structure is almost insignificant.

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