MECHANICAL PROPERTIES OF TWO TYPES OF LATTICE STRUCTURES FABRICATED WITH THE USE OF HP MULTIJET FUSION TECHNOLOGY

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Research in lattice structures and its application belongs to one of the most emerging disciplines in development of new types of engineering materials. High strength-to-weight ratio, special damping capabilities or auxetic behaviour are just a set of properties which can be directly influenced during design of these materials. Due to the geometric complexity of these structures, additive manufacturing is usually the only way to manufacture such a material. Among the others, HP Multijet Fusion additive technology with its supportless manufacturing approach offers one of the most convenient methods for production of lattice structures. Scope of this paper is design and mechanical testing of two types of lattice structures, namely body centred cubic structure and simple cross structure. Main attention is focused on printability of structures with different volume ratio in connection with their mechanical performance under uniaxial tensile loading. With respect to evaluated data, the cross structure shows more stiff behaviour for the same volume ratio and the same orientation in the build space of the machine. Body centred cubic structure on the other hand offers higher displacement to break.

KEYWORDS

MultiJet Fusion, mechanical properties, lattice structures, lightweight material

INTRODUCTION

3D printing is a progressive technology that allows the production of complicated parts without the use of conventional technologies (machine tools). These 3D additive technologies enable to process various materials such as metals, ceramics, photopolymers, etc. Specific production process, i.e. gradual application of individual layers, supports design freedom of the resulting product. Moreover, its inner sections (core) can be designed and manufactured with special approach. For these sections, it is advantageous to apply lightweight structures. These structures are usually characterized by a large weight loss compared to the typical solid part. The goal of each optimization is to maximally reduce the final weight while keeping the required mechanical properties. This paper deals with two basic light structures which were printed from PA12 (Polyamide 12) on HP Multi Jet Fusion (MJF) technology. In the following step, the structures were subjected to testing of mechanical properties. Each structure was made in a different volume ratio (25, 50, 75 percent of the original solid model).

Thermoplastic material such as PA 12 is widely used in the frame of injection moulding technology, which is the basic process given for batch production of plastic parts. This material is advantageous for its unique mechanical properties and temperature resistance.

MJF technology was introduced by the American company Hewlett Packard (HP). Due to its nature, HP Multi Jet Fusion technology enables the production of design or functional prototypes, as well as production jigs where increased mechanical resistance is required. Multi Jet Fusion does not try to push out or replace other 3D printing technologies. Its main goal is to widen the production speed and potential for manufacturing the parts without expansive and complicated modifications of production tools typical for injection moulding. This new approach to effectively produce small and middle-size batches of plastic parts should replace lengthy production preparation (preparation of the mould, injection moulding machine, etc.) [3DPRINTING.COM].

MULTI JET FUSION TECHNOLOGY (MJF) AND USED MATERIALS

MJF technology enables the additive processing of semi-crystalline thermoplastic powders. The HP Company defined standards for the so-called "Open Material Platform", where other technology companies may be a potential supplier of the powders. On the other hand, the material must meet the precisely specified quality criteria. Currently, several types of Polyamides are available - PA12, PA12 GB and PA11. At the end of 2019, the material TPU (thermoplastic polyurethane) delivered the company BASF was launched.

MJF is commercially available through several types of machines. HP Jet Fusion Series 300/500 for prototype and design production. HP Jet Fusion Series 4000 for individual and up to small batch production. Finally, HP Jet Fusion Series 5000 is the latest released machine, which is designed for middle-size and large-scale production batches [HP Development Company, L.P. 2019].

1.1 Principle of the MJF technology

The printing process of MJF technology is divided into several steps. In the first step, the printer applies a continuous layer of thermoplastic material in the form of powder to the entire printing surface. Subsequently, the powder is preheated by means of block of heating lamps situated above the whole building area. The preheating temperature is close to the melting point of the material. In the next step, special Agents (Fusion and Detailing Agents) are injected into the actual building layer. These Agents act as heat absorbent binders. Spots affected by agents are then activated by fusing lamps situated on the print head unit. As a consequence, these areas are instantly liquefied and connected with previous layer. The unique design of the combined printing head enables fast preparation of the entire printing layer, which is processed in one pass. The printing time of one layer is therefore constant and it is not affected by the size of the printed batch. The required time for completion of one layer is about 9 seconds. Principle of the technology MultiJetFusion is displayed in the Figure 1. After completing a given printed layer, the whole process is repeated until the entire print volume is processed. After the printing, the temperature of the products must be reduced to ambient temperature. This is usually accomplished by either a "natural cooling" or a faster "fast cooling" process. The total cooling time is directly proportional to the printed volume. After the cooling process, the parts must be mechanically cleaned and the unused powder must be removed from the parts and the building unit. [HP Development Company, L.P. 2019]

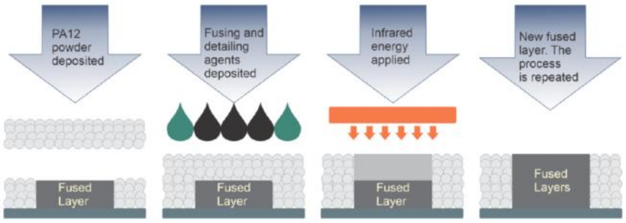

Figure 1. Principle of the technology MultiJetFusion [HP Development Company, L.P. 2019]

The unprocessed powder can be reused in the printing process, provided that it is partially mixed with unused (clean) powder. The basic mixing ratio of both components is 80/20. This means 80% of the used material and 20% of the new powder. However, it is also possible to set a different mixing ratio, up to 90/10 or 100% of the pure powder.

The products can be placed anywhere within the building unit with various orientations. The printer does not create any additional support structures. The products are surrounded by unprocessed powder (powder bed), which enables the production of complex parts without the need for supports. [HP Development Company, L.P. 2019].

1.2 *HP Multi Jet Fusion Series 4000*

The HP Jet Fusion Series 4000 is a manufacturing system consisting of several devices: Printer, Process Station, and Building Units. The colour of final products is grey. The printer and the process station form a pair of production machines and the building unit serves as a certain type of technological pallet. The powder is prepared (mixed) in the process station and then moved into the building unit. The building unit is then removed from the process station and placed into the printer where the printing process is accomplished. After the printing, the building unit is again removed from the printer to cool down the products. The cooling process can take place outside the process station (natural cooling) or within the process station (fast cooling). After the cooling, the building unit is loaded in the process station and further processing of the print job is enabled. The printer is therefore available during the cooling of the printing unit for the possible processing of another printing job (building unit). The presented device can be used for continuous production, provided that more building units are owned and the fast cooling of products within the process station is used. [HP Development Company, L.P. 2019]

Figure 2. Principle of the technology MultiJetFusion, [HP Development Company, L.P. 2019]

POLYAMIDE 12

In the frame of this study, the PA12 was subjected to several analyses and tests to verify the mechanical, chemical and thermal properties of the material. A basic mixing ratio of 80/20 was used for printing the samples (table 1).

Type of the material PA12	Fresh material [%]	Used material [%]
80/20 powder	20	80

Table 1. Basic mixing ratio of the material PA12 on technology MJF

The basic properties of the PA12 based on the supplier's datasheet are listed in the table 2, [Matbase.com 2019, HP Development Company, L.P. 2019].

Measurement	Value	Method
Powder melting point (DSC)	187 °C	ASTM D3418
Particle size	60 µm	ASTM D3451
Bulk density of powder	0,425 g/cm^3	ASTM D1895
Density of parts	1,01 g/cm^3	ASTM D792
Tensile strength	48 MPa	ASTM D368
Tensile modulus	1 800 MPa	ASTM D368
Elongation at break (XY, XZ, YX, YZ)	20 %	ASTM D368
Elongation at break (ZY, ZX)	15 %	ASTM D368

Table 2. Mechanical properties of material PA12 from HP

In the frame of this study, the chemical and thermal impacts on the tested powder with standard 80/20 mixing ratio were tested in comparison with pure material. Results are summarized in tables 3 and 4.

Type of the material PA12	C [wt.%]	O [wt.%]	Al [wt.%]	Si [wt.%]	P [wt.%]
Pure powder	85,55	14,06	0	0,17	0,20
80/20 powder	85	14,65	0	0,16	0,18

Table 3. Chemical composition of the HP MJF PA12 material

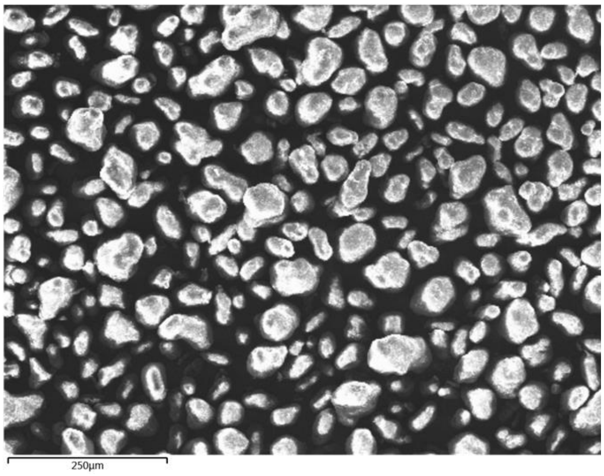

Figure 3. SEM image of PA12 80/20 mixed material

From the DSC analysis point of view, the powder meets the declared parameters. During the analysis, pure powder reached melting point of 177.3°C. The 80/20 mixed powder reached melting point of 177.5° C , [SHMID 2019, SILLANI 2019].

Type of the material PA12	T_{pm} [°C]	ΔH_m $[J \cdot g^{-1}]$	X_c [%]	T_{pc} [°C]	ΔH_c $[J \cdot g^{-1}]$
Pure powder	177,3	46,9	49,4	146,5	-57,6
80/20 powder	117,5	47,8	50,4	147,6	-57,5

Table 4. Thermal composition of the material PA12

T_{pm} peak melting point after removal of the thermal history from analyzed the material

T_{pc} peak crystallization temperature

ΔH_m change in melting enthalpy, the magnitude of which is directly proportional to the degree of crystallinity

ΔH_c change in enthalpy of crystallization from the melt

X_c degree of crystallinity, for the calculation of which the enthalpy of melting of fully crystalline PA 12 was used (ΔH_{m0} = 95 J * g-1), [NETZSCH 2019].

LIGHTWEIGHT STRUCTURE

In the frame of this study, several designs of core structures were created. The samples also contained several volume variants of these structures. Comparisons the mechanical properties of these structures and determination of the effect of volume ratio and shape of the structures in the core of the solid part on the resulting performances were the main aim of these studies. Considering the practical usability of the lightweight structures, which are used in additive technologies in the scale units of millimetres, the structures with a size of 5 mm were created. The structures were defined by a unit within a theoretical box with dimensions of 5 x 5 x 5 mm, which means that the full material volume was 125 mm^3 [HABIB 2018, WANG 2019],

Cross Structure

The structure is based on the commonly used structure "Cross", simple geometry of cylindrical rods positioned in the direction of three Cartesian axes, intercepting each other in its middle positions. The structure was made in several volume variants (Table 5).

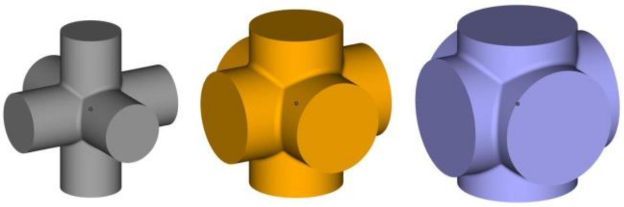

Figure 4. Cross lightweight structure – 25, 50, 70 volume of full box

Structure	Diameter of rod (mm)	Volume (mm^3)
Cross 25%	1,84	31,25
Cross 50%	2,83	62,5
Cross 70%	3,62	87,5

Table 5. Cross structure volume variability

A structure with 10% of the full-body volume was also designed. Unfortunately, such a fine structure could not be printed using MJF technology, so it was not included in the study.

Structure BCC (Body- Centered Cubic)

Unit present in crystalline structures, where one atom occupies each vertex of a cube and its center position “BCC”. The structure was designed in several volume variants (Table 6).

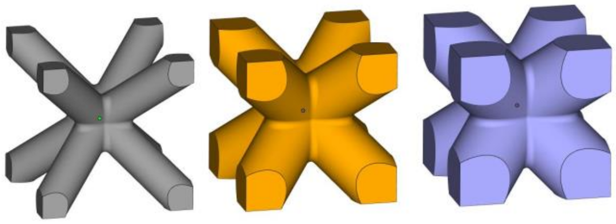

Figure 5. BCC lightweight structure – 25, 50, 70 volume of full box

Structure	Truss diameter [mm]	Volume $[mm^3]$
BCC 25%	1,21	31,25
BCC 50%	1,86	62,5
BCC 70%	2,37	87,5

Table 6. BCC structure volume variability

For the purpose of this study, the specimen was designed with a testing area of 20 × 20 mm (Figure 6). This shape enabled to place 16 cells in the testing area. Finally, 160 cells were distributed in the body of the specimen (Figure 7), which resulted in increasing the sensitivity of performed measurements.

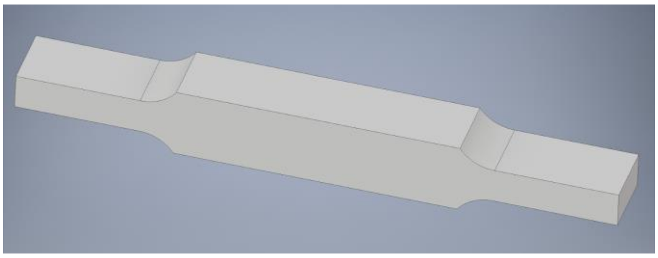

Figure 6. Solid model which was used for lightweight structure

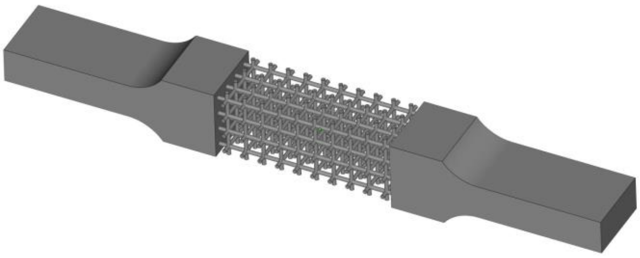

Figure 7. Solid model with cross lightweight structure

Figure 8 shows the two positions in which the specimens were manufactured. Considering the building space of HP MJF 3D printer, the X axis complies with direction of movement of print head unit. The Y axis on the other hand corresponds with recoating unit direction of movement. Longitudinal axis of the first group of specimens lies in X-axis of the described build space. Build orientation of the second group of specimens is defined in such a way that the longitudinal axis is coincident with the XZ vector. In comparison with the first group, the specimens are rotated 45° around Y axis [RIEDELBAUCH 2019, PALMA 2019].

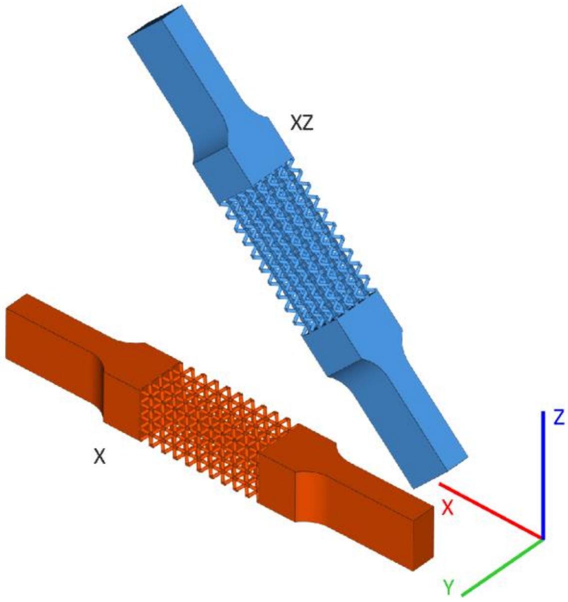

Figure 8. Position of the specimens in HP MJF build space

TENSILE PROPERTIES OF THE SPECIMENS

Tensile properties of described structures were determined in a standard 23/50 environment by methods stated in the ISO 527 / 1A / 50. Measurements were carried out on the universal testing frame TiraTest 2300. Each specimen was fastened into standard tensile clamping system and gradually loaded until rupture. Test itself was position-driven with load rate of 10 mm/min. During the test, displacement of machine's cross head and force were acquired. Figure 9 shows repeatability for three samples of BCC structure with 25% volume ratio built in X direction. Displacement-Force curves had similar behaviour for all the tested groups. Each group contains three specimens [ISO 527-2:2012, O'CONNOR 2018, MORALES-PLANAS 2018].

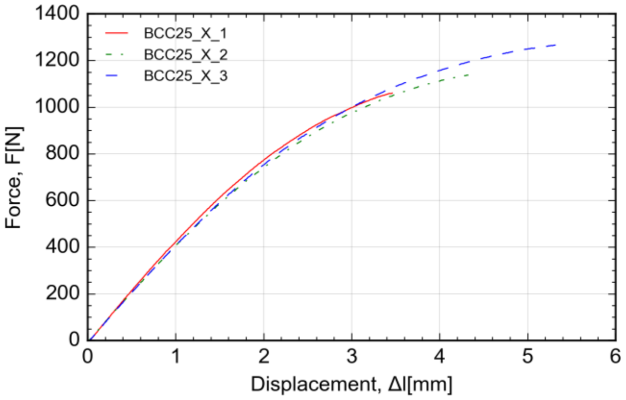

Figure 9. Comparison of results; Maximal Force, X direction

In the Figure 9 and 10, results for Maximal force and Displacement at break are displayed for the specimens which were printed in X direction. The data are displayed in the form of mean value from three measurements with the value of standard deviation. In general, value of maximal force increases with increasing volume ratio for both types of tested structures. BCC specimens show almost half values of maximal force in comparison with cross structure. Interesting behaviour can be seen in comparison of displacement at break values (Figure 10). While Cross structure maintains same behaviour as in the case of maximal force, the BCC structure shows decrease in displacement at break with increasing volume ratio. This fact can be caused by nature of rupture mechanisms in the structure.

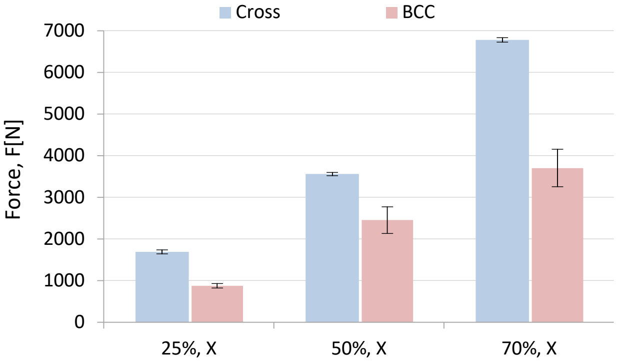

Figure 10. Comparison of results; Maximal Force, X direction

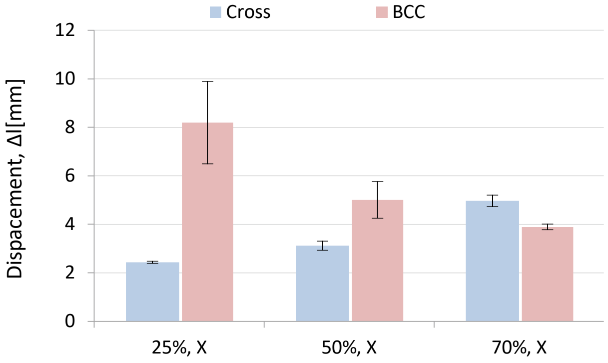

Figure 11. Comparison of results; Displacement at break, X direction

In figures 12 and 13, same graphs are displayed for specimens printed in XZ direction. Considering the overall behaviour, similar observation can be concluded in comparison with samples printed in X direction. Moreover, there is no considerable shift in maximal force and displacement at break values.

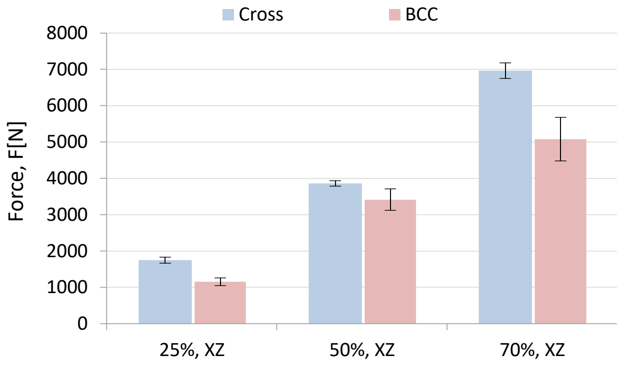

Figure 12. Comparison of results; Displacement at break, X direction

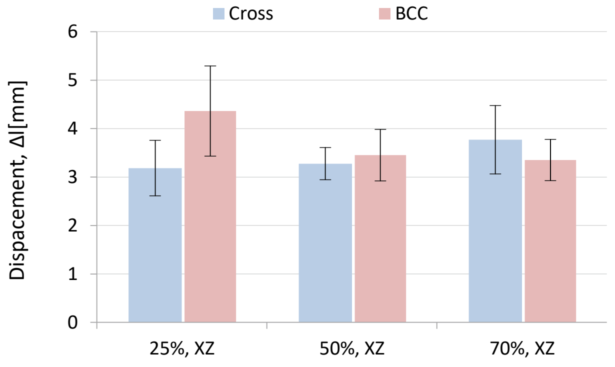

Figure 13. Comparison of results; Displacement at break, X direction

CONCLUSION

This article had two major goals. First of all, printability of two selected structures (cross and body-cantered cubic) using HP Multi Jet Fusion technology was evaluated. Structures were planned to be manufactured in four different volume ratios, specifically 10%, 25%, 50% and 70% of solid volume. During test prints, it was found out that 10% volume fraction was not possible to be printed. In order to achieve this volume ratio, trusses of the structure were less than 0.4 mm thick. After the print, major flaws such as visible pores and incorrect connections were found in the material.

Second part of the work was aimed to mechanical testing of the structures printed in two different orientations – along with X axis of the printer's print volume and along its with XY vector. With increasing volume ratio, the rupture occurs at higher force levels. This observation is natural as there is more material involved at higher level of volume ratio. Interesting observation was found in the case of Displacement at break values. While this value increases with higher volume ratio in the case of cross structure, we can observe vice-versa effect for the BCC structure. This phenomenon may be caused by different mechanism of rupture. While tensile stresses are dominating cause of the rupture in the case of cross structure, the situation will be more complex for the BCC. Nature of the BCC cell produces shear stresses during uniaxial loading of the specimen. Thus, higher volume ratios reduce tension capabilities of the structure.

When comparing values from different print orientations of the samples, no major differences were found. In the XY direction, displacement at break is reduced by approximately 25%. On the other hand, the data show higher scatter. Therefore, there is an uncertainty in the above statement. More tests are planned in the future work to support this observation.

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