IMPACT RESISTANCE OF LATTICE STRUCTURE MADE BY SELECTIVE LASER MELTING FROM AlSi12 ALLOY

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This article describes the impact resistance of lattice structure made by metal additive technology Selective Laser Melting using AlSi12 aluminum powder material. Powder particle distribution was analyzed for verification of distribution and shape of particles. Samples of lattice structure are composed of three segments. The main part – lattice structure is made from repeated Body Centered Cubic (BCC) unit-cell composed of four thin trusses. The other parts are thin plates on upper and bottom side of the sample. Four series of BCC lattice-structured samples with different diameter of the truss were designed. The samples were tested by the impact testing device with the spherical shape of indenter. During tests the samples were fixed to the base plate using four bolts.

The measured data were used for calculation of the absorbed energy using numerical integration in software MATLAB. The results show that the BCC structures with the diameter of the truss d = 0.8 mm have the best combination of stiffness and energy absorption for the parameters of the impact test.

KEYWORDS
Selective Laser Melting, lattice structure, impact resistance particle distribution, energy, AlSi12

1. INTRODUCTION

Selective Laser Melting (SLM) is a metal additive technology which produces parts from very fine metal powder using a high-performance laser beam. Metal parts are built layer by layer in the powder bed due to this technology is suitable for producing components with complex shapes and very fine mechanical properties. An example of such components are porous structures composed of periodical truss cells which are called lattice structured materials. These parts are used especially in air- or spacecraft for their low weight and good mechanical properties. SLM technology also enables to produce parts which are topologically optimized without the need of modifying the final piece for the production by conventional technologies. [Smith 2013], [Tsopanos 2010], [Yan 2014]

Lattice structured material produced by SLM is one of many type light-weight materials which have potential for protective mechanism applications. Currently the metal foams or honeycombs produced by conventional technologies are used. The advantage of the lattice structured material produced by SLM is that its stiffness can be controlled by the geometrical properties (the shape of the unit-cell, dimensions of trusses and unit cells, used material). [Yahaya 2015], [Shen 2013][Shen 2013] studied a range of stainless steel and titanium alloy lattice structures manufactured using SLM technology. The influence of manufacturing parameters on the properties of lattice structures was studied through a series of single-filament tensile tests. The quasi-static and low-velocity penetration behavior of lattice structures panels has been examined. Deformations of samples were investigated using a scanning electron microscope. The results show that the properties of lattice structures are determined by the laser energy during the manufacturing process. Drop-weight tests (up to 6 m/s) show that the penetration behavior of the titanium lattice structure and aluminum honeycomb are similar.

[Mines 2008] studied the penetration behavior of sandwich panels with lattice structure core and foam core with composite skins. This behavior is important during impact of foreign objects and perforation of sandwich structures. Results for drop-weight penetration show that lattice structured material and metal foam are similar and comparable. They suggest that there is still potential for improvement of the impact resistance performance of the micro-lattice by changing the shape of the unit cell or the parent material (i.e. titanium). In the further work [Mines 2013] studied the drop weight (low velocity) behavior of BCC lattice structured panels (100 x 100 mm) with carbon fiber–reinforced polymer (CFRP) skins. The lattice structure is produced by SLM technology from Stainless steel 316L a Ti6Al4V titanium alloy. The mechanical behavior of the micro lattice structured panels is compared to aluminum honeycomb which were produced by conventional technologies.

[Liu 2015] studied behavior of tetrahedral lattice truss core under impact loading. Experimental investigations were performed using a standard mechanical testing machine. Results showed that the peak of force increased about 23% from quasi-static loading to dynamic loading. The lattice structured panel was able to transfer higher load in dynamic loading.

Several authors [Herburt 2003], [Mousanezhad 2014] compared lattice structured panels with different basic unit-cell or parent material with another porous material produced in conventional technologies such as metal foam or honeycomb.

In this article, BCC type of lattice structure is used because the mechanical properties and deformation of BCC structure are well described in the literature. This will be useful for further development of FEM model and understanding of its impact deformation. The samples are made from AlSi12 powder which is very light and common material for SLM application with good mechanical properties and therefore is suitable also for aircraft industry. The samples with different ratio *d/a* (*d – diameter of the trusses of unit cell; a – the length of the unit cell size*) are tested to find the optimal setup of these geometrical parameters for maximum absorption of the energy. Absorbed energy by lattice structured is calculated.

2 MATERIAL AND METHODS

2.1 Selective Laser Melting Technology

Samples were manufactured using SLM 280^{HL} device (SLM Solution GmbH). Machine is equipped with 400W ytterbium fiber laser which allows to produce components from aluminum, steel and titanium alloys. The laser has a Gaussian beam profile. For manufacturing the samples from aluminum alloy AlSi12 following laser parameters were used (Tab. 1). Distribution of powder was examined by laser size analyzer.

Process parameters		
	Border	Volume
Laser speed	500 mm/s	930 mm/s
Power output	350W	350W
Focus offset	1	1
Layer thickness	50 µm	50 µm
Platform heated	120°C	120°C
Oxygen level	0.1 – 0.2%	0.1 – 0.2%
Atmosphere	nitrogen	nitrogen

Table 1. SLM process parameters

2.2 Samples

The lattice-structured samples for impact testing are shown in Fig. 1a. They are created from three segments – the upper plate *(t = 0.3 mm)*, the bottom plate with fixing holes *(t = 0.5 mm)* and the structured part in the middle. The structured part of the sample is created by the repeating BCC (Body Centered Cubic) unit cell composed of four trusses (Fig. 1b). Dimensions of the lattice-structured part of the sample were *40 x 40 x 16.8 mm*.

Four series of samples with various d/a ratio *(d – diameter of truss; a – the length of the unit cell size)* were designed. Parameters of series are shown in Tab.2. All unit-cells in the single sample are made by trusses with constant diameter *(d)*. The size of the unit-cell edge length *(a)* is the same for all samples.

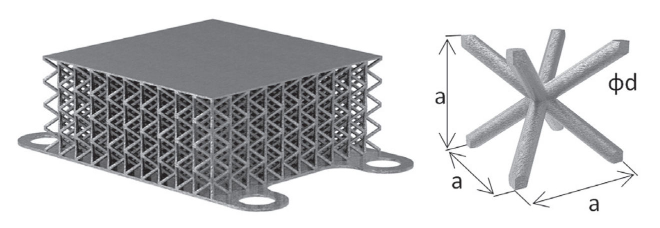

Figure 1. (a) Lattice structured samples (b) Body Centered Cubic (BCC) unit cell

Dimensions of Samples					
Series	d/a	d [mm]	a [mm]	Volume [mm³]	Relative density [%]
01	0.1	0.4	4	2676	4.95%
02	0.15	0.6	4	4120	10.59%
03	0.2	0.8	4	5978	17.85%
04	0.25	1	4	8156	26.35%

Table 2. Dimensions of Samples

2.3 Impact Measuring Station

The impact resistance of samples was tested using a drop-weight impact tester (Fig. 2). The principle of the impact tester is based on change of a kinetic energy of the falling head to the impact energy of indenter. The reaction force during penetration was measured with strain gauges XY31-3/120 which were placed on the deformation element. Signal was recorded using the data acquisition system QuantumX MX410B (HBM GmbH) with the sampling frequency of 96 kHz. The penetration body (indenter) had a spherical shape. Following parameters of the impact test were used – weight of falling head: *m = 5.75 kg*; drop height: *h = 1 m*; Diameter of indenter: *d = 16 mm*.

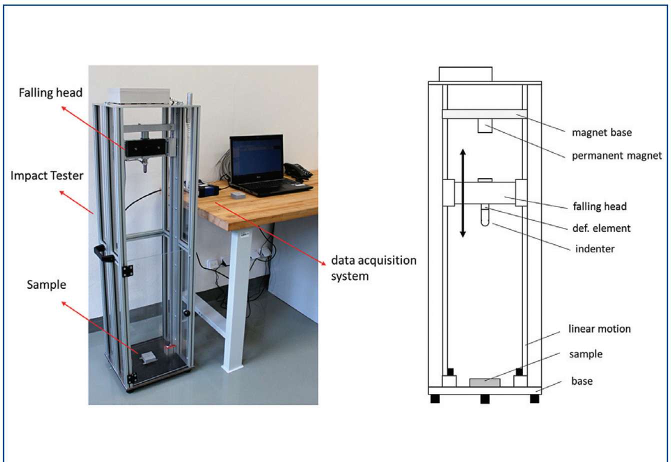

Figure 2. (a) Impact measuring station (b) schematic description

2.4 Evaluation

To explore the internal damage of the lattice structure, four samples were analyzed using a micro Computed Tomography (μCT). System GE phoenix v|tome|x L 240 is equipped with a 300 kV/500 W maximum power micro focus X-ray tube and the high contrast flat panel detector DXR250. The microCT measurement was carried out at 150 kV and 200 μA acceleration voltage and X-ray tube current, respectively. The exposure time was 400ms in every of 2000 positions around 360°. The tomographic measurement was performed at the temperature of 21°C and the voxel size of obtained volume was 60 μm.

The penetration of all samples was measured with 3D optical scanner Atos Triple III Scan (GOM GmbH, Germany) and GOM Inspect software. Before the scanning process, the samples were matted by spraying of thin layer of chalk powder. The samples were scanned on a rotary table in ten positions.

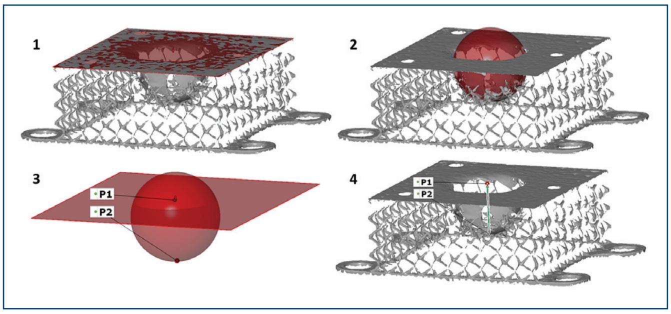

Figure 3. Analysis of dimensions

To evaluate the penetration fitting elements of ideal shape were created (Fig. 3). In the first step the fitting plane on upper side was created. In the next step, an imprint of indenter was selected to create the fitting sphere. Then the center of the sphere was used to create a perpendicular line to the plane (from the first step).

Using the line, the intersection points *P1* (between line and plane) and *P2* (between line and sphere) were founded. In the last step, a distance between points *P1* and *P2* was measured. This process was followed for all lattice structure samples.

3 RESULTS AND DISCUSSION

3.1 AlSi12 Powder Characterization

AlSi12 metal powder from SLM Solution GmbH was used for manu-facturing the samples. The powder was produced using gas atomization technology and the particle size distribution was analyzed for quality verification. For the analysis, Horiba LA-960 laser particle size analyzer was used. Median size of particles is 47 μm, mean size is 49.3 μm and the standard deviation is 17.3 μm. Particle size up to 29.2 μm represent 10% and particle size up to 73 μm represent 90% of particle size distribution (Fig. 4a). According

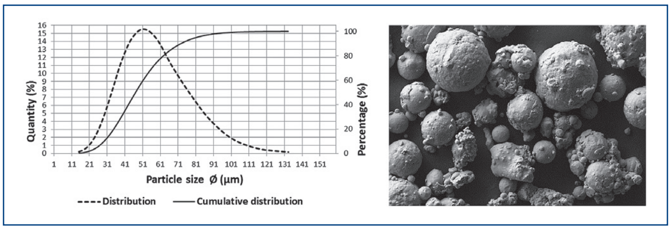

Figure 4. (a) Particle size distribution of AlSi12 aluminum alloy (b) SEM image of metal powder

the powder distribution the layer thickness of 50 μm was used during the experiments. To determine morphology of the powder a Zeiss Ultra-Plus 50 Scanning Electron Microscopy (SEM) was used (Fig. 4b).

3.2 Mechanical Testing

For mechanical testing the impact tester was used (Fig. 2). During the mechanical test, the reaction force in time was measured. In the Fig. 5a, real $F-t$ data record from strain gauges are shown. There are a lot of peaks on $F-t$ data record. That is because the falling head bounces off the sample and falls down again. To determine the impact resistance, only the first peak was used. In the Fig. 5b, the first peak of $F-t$ data record is shown. In the Fig. 6a, the data records for one series of samples (four samples with $d/a = 0.1; 0.15; 0.2; 0.25$) are shown. The time $t = 0$ s is the start of the indenter penetration into the sample. From $F-t$ data record, maximum force was obtained (Tab. 3). After the mechanical testing, all samples were scanned with 3D optical scanner Atos Triple III Scan (GOM GmbH, Germany) and evaluated in GOM Inspect software. Evaluated values are shown in Tab. 3.

The impact tester principle is based on a change of a kinetic energy to the impact energy. For description of the energy conversion, a simplified equation was used:

$$E_P = E_K + E_F \quad (1)$$

$$E_K = E_A + E_T + E_B \quad (2)$$

$$E_P = E_F + E_A + E_T + E_B \quad (3)$$

where $E_P = m \cdot g \cdot h$ is the potential energy, E_K is the kinetic energy of the falling head, E_F is the energy lost through friction in a linear motion, E_A is the absorbed energy in lattice structured sample, E_T is the energy absorbed due to elastic deformation of the impact tester base plate during deformation of the sample and E_B is the remaining energy with which falling head bounces off the sample. It is part of the energy which was not be able to absorb in the sample. Whereas the E_B energy has not been measured or evaluated and E_F is insignificant compared with other components of energy.

Absorbed energy corresponds with deformations of lattice structured panels. Therefore the $F-t$ data records and penetration values from GOM Inspect software were used to determine of the absorbed energy. The measured reaction force was divided by weight of the falling head to obtain negative acceleration a (deceleration) of the falling head in the lattice structured samples. Then equations (2), (3), (4) were used to obtain the absorbed energy E_A.

$$v(t) = \int a(t) \cdot dt \quad (4)$$

$$s(t) = \int v(t) \cdot dt \quad (5)$$

$$E(s) = \int F(s) \cdot ds \quad (6)$$

By numerical integration of $F-s$ data records, $E(s)$ energy was obtained which consists of E_A and E_T energies. The absorbed energy E_A was obtained by integration of the first part of $F-s$ data from $s = 0$ up to penetration value determined by optical measurement (Fig. 6b). The second part of $F-s$ data, from penetration value up to zero value of the reaction force, was integrated to obtain energy (E_T) absorbed by elastic deformation of the impact tester (base plate), as is shown in Fig.6b – green line.

$$E(s) = \int F(s) \cdot ds = E_A + E_T \quad (7)$$

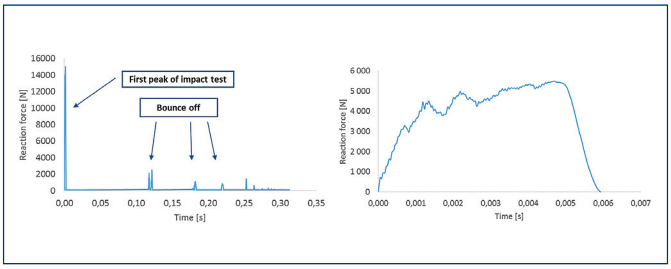

Figure 5. (a) Real F – t data record from impact testing (b) The first peak from F – t data record

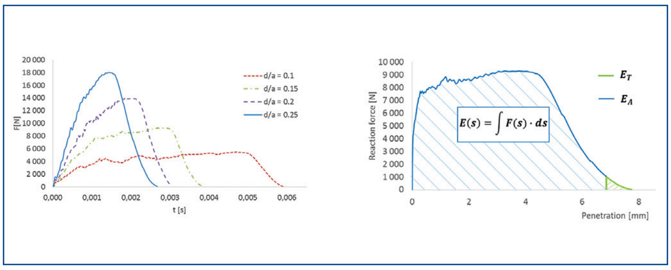

Figure 6. (a) The F – t data records of one samples series (b) Numerical integration of impact energy

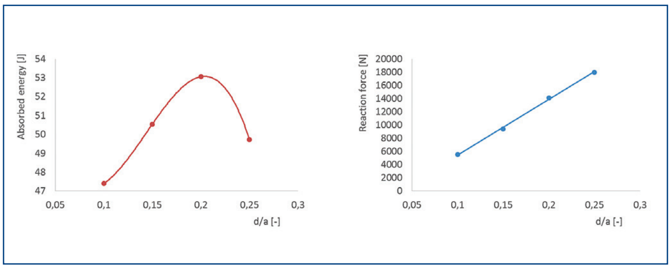

Figure 7. (a) Energy absorbed by the lattice structure (b) stiffness of the lattice structure

The numerical integration was performed in software MATLAB. The obtained values are in Tab. 3. Average values (from four samples) are shown in graph in Fig. 7a.

Measured data							
d [mm]	Name	Reaction force [N]		Penetration [mm]		Impact energy [J]	
0.4	01-01	5844	5538	11,095	11.3	47,35	47,4
	02-01	5268		11,825		46,45	
	03-01	–		11,436		–	
	04-01	5501		11,281		48,40	
0.6	01-02	9013	9419	6,929	6.9	50,09	50,55
	02-02	9888		6,959		50,68	
	03-02	9477		6,969		50,92	
	04-02	9298		6,825		50,49	
0.8	01-03	14371	14096	4,299	4.4	52,74	53,05
	02-03	13906		4,55		53,11	
	03-03	14159		4,35		53,04	
	04-03	13949		4,562		53,31	
1	01-04	18225	17954	3,226	3.3	49,81	49,73
	02-04	17557		3,309		49,89	
	03-04	17990		3,288		49,67	
	04-04	18046		3,214		49,54	

Table 3. Measurement data

4. CONCLUSION

At present, porous materials such as metal foams or honeycomb are used for energy absorption applications. These porous materials are produced by conventional technologies from aluminum alloy. By using additive manufacturing technology, it is possible to produce a lattice structure with exactly defined properties which can be used in special types of industry like aerospace. Thanks to that, the properties of lattice structure, such as stiffness or absorption of energy (amount of absorbed energy, deformation rate, structural failure and depth of penetration) can be controlled.

In this article, sixteen samples of lattice structure from AlSi12 aluminum alloy were tested to obtain the impact resistance and the absorbed energy during the impact testing. The BCC lattice structure samples with ratio d/a = 0.1, 0.15, 0.2, 0.25 were analyzed to find optimal combination of geometrical parameters (*diameter of the trusses; the* *length of the unit cell size*) for maximal impact energy absorption. Initial values for the ratio d/a were selected based on preliminary study in this area ([Shen 2013]).

Using the absorbed energy from numerical integration, *E(s) – d/a* graph was created (Fig. 7a). There interesting regions can be seen from the constructed graph. The first part from *d/a = 0* up to *d/a = 0.1* represent structures with relatively low stiffness. These samples are completely crashed under the indenter (Fig. 8d). The stiffness of this lattice structure is suitable for applications with low impact energy or for applications where low reaction deceleration is necessary and a large deformation is possible. The second part of the graph, from *d/a = 0.1* up to *d/a = 0.2* represent structures with optimal absorptivity (but just in scope of tested impact energy). Although these samples are only partially crushed by the indenter (Fig. 8b, 8c) they absorbed more energy, than the first ones. The third part of the graph with *d/a = 0.2* and higher represents lattice structure with highest stiffness. These samples absorbed only part of impact energy and the rest was bounced off. The stiffness of this lattice structure is suitable for applications with higher impact energy or for application where only small deformation is allowed or high deceleration is required (Fig. 8a). In the graph (Fig. 7a), it is shown that increasing the ratio d/a up to 0.25 does not make sense (*for presented testing parameters – impact energy, shape of indenter*). because the sample is too stiff and already does not absorb energy. Among all experiments, the samples with truss diameter *d = 0.8 mm* absorbed the highest amount of energy.

The results from this article will be used for validation of the prediction an impact resistance of lattice structure with using FEM analysis. In the future, it will be also studied the influence of the indenter (shape, size) and impact energy of falling head on the absorbed energy and ideal d/a ration of lattice structure.

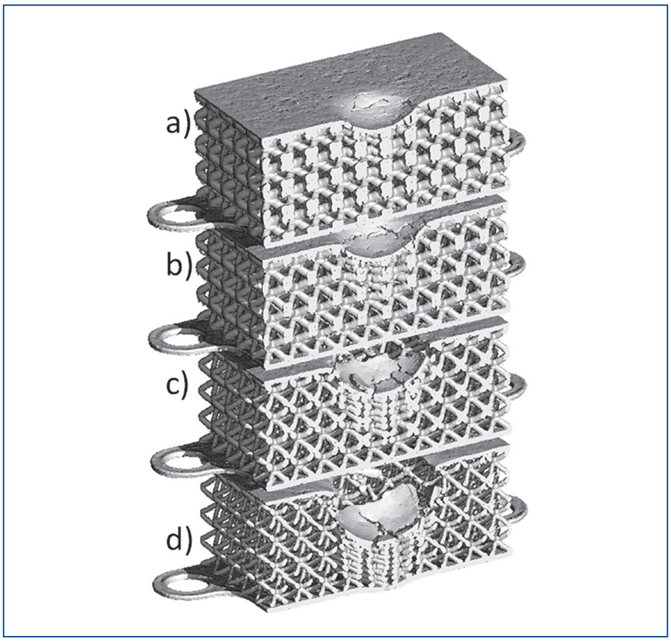

Figure 8. Cross-section of impact samples: a) ∅ 1 mm, b) ∅ 0.8 mm, c) ∅ 0.6 mm, d) ∅ 0.4 mm

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