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MECHANICAL PROPERTIES EVALUATION OF THE SAMPLES MADE BY SLM, WITH TREE-LIKE FRACTALS INTERNAL STRUCTURE

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Abstract: *Additive manufacturing is in continuous development due to its distinct advantages such as manufacturing parts with complex geometry, various materials, light weight properties and enabling rapid prototyping. The purpose of this study is to determine mechanical properties of various test samples manufactured by Selective Laser Melting (SLM) and modeled using fractal patterns as internal structures. The design of the samples is modeled following biomimicry concepts using tree-like fractal structures (in different configurations) as internal structures of the part. The tested parts were manufactured using SLM made of tool steel 1.2709 powder. The specimens were tested for compression, bending, and tensile tests. Furthermore, Finite Element Analysis (FEA) was used to describe the deformations and stress distribution in the fractal structures. The experimental results were compared with the FEA results only in linear domain (for elasticity) to determine some properties of the fractal structures. For compression and bending the maximal load can go up to 1600 N, while for traction up to 10000 N. Each fractal configuration has an influence on the applied load and equivalent stress from the FEA.*

Key words: *Selective Laser Melting, Tree-like fractals, Mechanical testing, Finite Element Analysis.*

1. INTRODUCTION

Selective Laser Melting (SLM) is a technology that belongs to Additive Manufacturing, which showed rapid growth in the past years. This technology uses metal powder to create parts layer by layer. Different types of metals can be used, such as: aluminum, titanium, steel, nickel and many more alloys can be mixed to create parts with different mechanical properties [1]. SLM is mostly used in automotive and aerospace industries, but the medical field also benefits from SLM. Different implants and prothesis may be manufactured, due to the possibility of creating complex designs and lightweight parts [2]. Tool steel is one of the commonly used materials in SLM, with many applications in molds, casting dies, tools, and others, due to its high strength and absorption [1-4].

Multiple studies show the mechanical properties of tool steels and their influences, such as heat treatments, building orientation of the part, surface quality, microstructure and others, each under different conditions [4-8].

In the last years, more nature inspired elements were introduced in designing parts, due to the possibility to create complex geometries and internal structures with additive manufacturing resp. SLM [9]. In this work, a bio inspired fractal structure is proposed to be tested in different configurations. Fractals are repetitive structures and can be found in nature under multiple forms, from snowflakes to plants, trees and even in anatomy (e.g., lungs, blood vessels etc.). The samples presented in this study contain tree-like fractals, which have the basis on modeling with homogenous transformation matrices [10].

The aim for this study is to test the tree-like fractal structures for compression, bending and traction. The samples are SLM manufactured from tool steel 1.2709. A comparation between the obtained results and the existing literature for tool steels is made to determine similarities. Besides the mechanical testing, Finite Element

Analysis (FEA) is applied on the samples and the results are compared with the experiments. Having the evaluation of the mechanical properties, tree-like fractals can be used as internal structure in future application for lightweight.

2. EXPERIMENTAL DESIGN

2.1 Sample design

The samples were designed for compression, bending and tensile tests. The fractal structures defined in Fig. 1., are modeled for different test with the following dimensions and propagation rules:

- All fractal structures for this tests, have struts of 0.7mm.
- Compression sample:
  - Angles $\alpha_i = 35°$ (70° between two struts);
  - First branch length $L_1 = 8$ mm;
  - Length of the next branches $L_i = L_{i\text{-}1}\cdot 0.7$ (70% of the previous length);
- Bending and tensile sample:
  - Angle $\alpha = 35°$ (70° between two struts);
  - First branch length $L_1 = 2.5$ mm;
  - Length of the next branches $L_i = L_{i\text{-}1}\cdot 0.8$ (80% of the previous length);

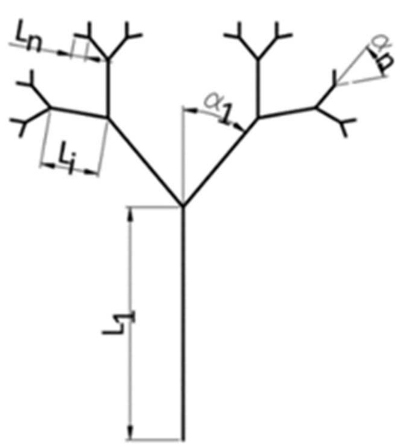
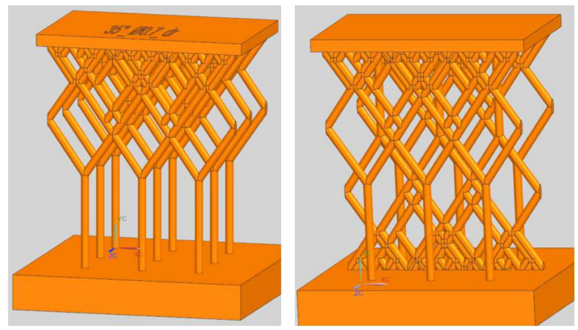


Fig. 1. Tree-like fractal structure dimensions

Figure 2 shows two models designed for compression. Each sample had 9 fractals (which were slightly modified to the printing conditions), distributed in three rows, with 5 mm between them. One sample had the second row of fractals upside down (Fig.2. b.), denoted in the future as SJ. The second compression sample where all fractals are oriented in the same direction is denoted as S. The total height of the sample is 23 mm.



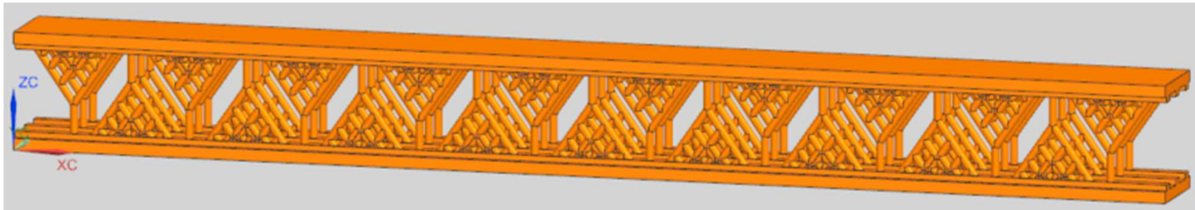
a) **b)**

Fig. 2. Compression design samples: a) All fractals up (code S); b) Having upside down fractals (code SJ);

For the bending and tensile test samples the fractals were distributed in different configurations, as shown in Fig. 3. Following notations have been used to identify the models of the samples:

- Bending
  - SJ – each second fractal is oriented upside down (Fig. 3.a);
  - S – on each side of the samples 6 fractals are oriented with the branches on top, while in the middle, 7 fractals are up-side down (Fig. 3.b);
- Tensile
  - SJ – each second fractal is oriented upside down (Fig. 3.c);
  - SJ-1- fractals are oriented in the same direction on the first row, and in the second row, the fractals are up-side down (Fig. 3.d);

For bending, the samples contain three rows, with 3 mm distance of 19 fractals, the samples have a length of 100 mm and are 8 mm wide. For the tensile samples, the fractals are distributed in two rows, with 1 mm distance and 11 fractals are in one row, the total length of the samples in 90 mm and width is 3 mm. The distance between two fractals is 5mm on all samples.



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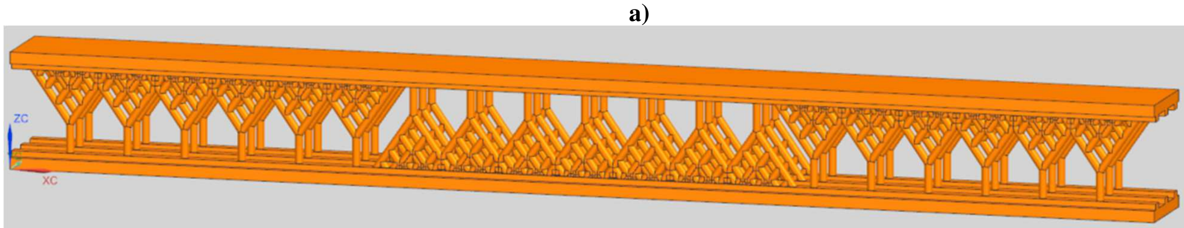

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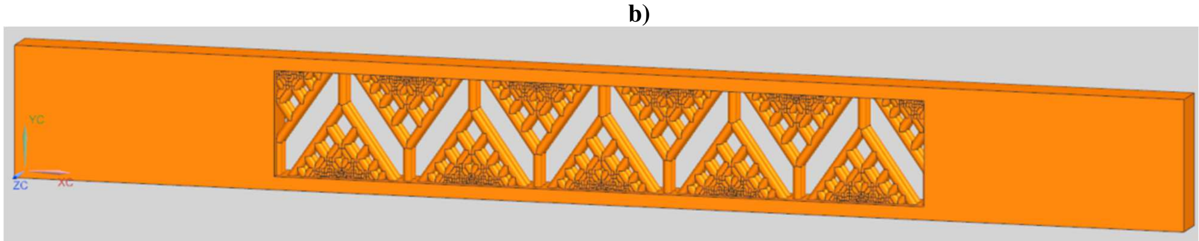

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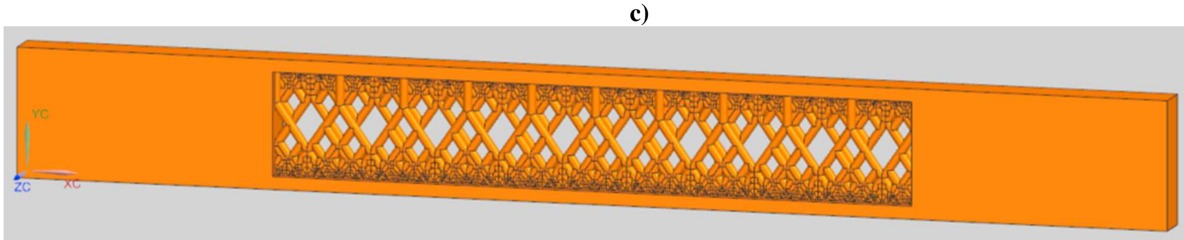


d)

Fig. 3. Samples design for: a) Bending tests (code SJ); b) Bending test (code S); c) Tensile tests (code SJ); d) Tensile test (code SJ-1);

2.2 Manufacturing

The samples were manufactured from tool steel powder 1.2079 / Maraging 300 a martensitic steel, on a Renishaw AM400 machine. The material 1.2709 used is from Böhler Edelstahl and its composition is presented in Table 1. In QuantAM the samples were prepared for printing, using the STL format of the CAD models. The process parameters used for printing the hatches were the following: laser power 200 W, exposer time 80 µs, a focus of 5 mm, and a point distance of 65 µm. The layer thickness was 40 µm. These parameters are based on previous testing and have the appropriate values for good quality on this machine. No heat treatment was applied on the samples. The postprocessing operation was only to eliminate the support structures and to smoothen that surface.

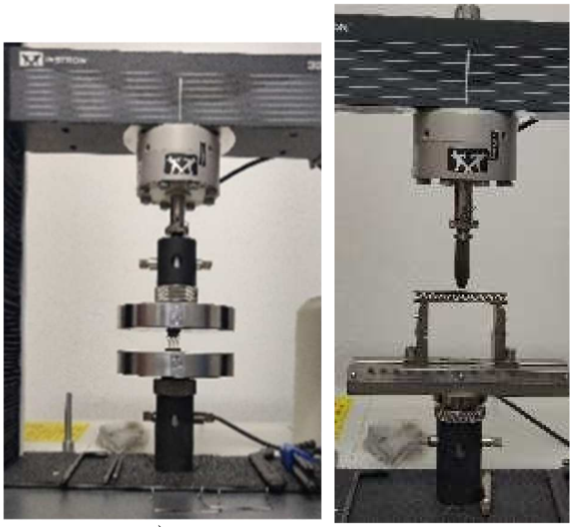
2.3 Measurements

After manufacturing, the samples dimensions were measured on Keyence VHX - 6000 microscope and the roughness of the fractal-trees was scanned with Alicona – Infinite Focus, after the standards ISO 4287 and ISO 4288.

Table 1

Chemical composition tool steel – 1.2709 (Böhler)

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Ti	Co
Min.	-	-	-	-	-	-	4,5	17	0,8	8,5
Max.	0,03	0,1	0,15	0,01	0,01	0,25	5,2	19	1,2	10,0



a) b)

Fig. 4. Instron 3366 set-up for: a) Compression; b) Bending;

The compression and bending tests were undertaken using an Instron Universal testing machine 3366 with a maximum load of 10 kN. A preload of 20 N was applied and the moving rate is 2 mm/min. It proceeded until the maximum of the force was reached on the sample and then began to decrease. The testing set-up is represented in Fig. 4.

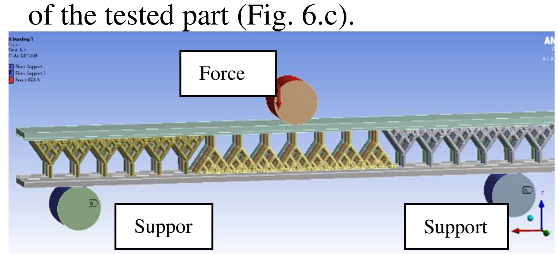
For the tensile tests the machine Instron 8801 was used, which has a maximum load of 100 kN presented in Fig. 5. In this case, the moving rate was also 2 mm/min but the preload was 50 N. The force was applied until the first crack appeared in the sample.

Fig. 5. Instron 8801 set-up for tensile test

2.4 Finite Element Analysis

The CAD models for the samples were analyzed using ANSYS software. To have a close approximation of the laboratory experiment the following experimental design parameters were used:

1. The ANSYS analysis was performed only on the linear domain (of Young's modulus) of deformation which was approximated from the laboratory tests (using the strain to displacement curves).
2. An assumption was made that the Young's Modulus of the fractal structures manufactured with SLM will be lower in value than the actual material (due to material imperfections after SLM). This behavior is documented in other work [11]. This implies that:
    a. The areas of the parts without fractals were kept at the documented value of steel 1.2709 Young's Modulus (160 GPa) [7] whereas the value of the Young's Modulus for the fractals was determined using divide and conquer strategies starting from the documented value of Young's Modulus.
    b. Multiple simulations were performed until the relative error between the results (experimental and simulations) was below 10%.
3. Meshing resolution was set to 5 (out of a maximum value of 7 in ANSYS) for all simulations.
4. For the bending test 3 cylinders were added in the model (Fig. 6.a), two of them constrained as fixed support (simulating the testing equipment supports) and the third one applying a force at the middle of the part (simulating the press).
5. For the compression test the lower surface of the part was defined as fixed support and the force was applied on the upper surface (Fig. 6.b).
6. For the tensile test the fixed support and the force were applied to the sides (left and right) of the tested part (Fig. 6.c).



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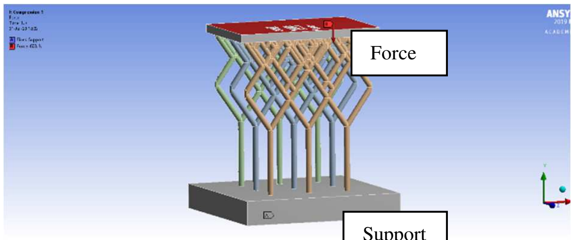

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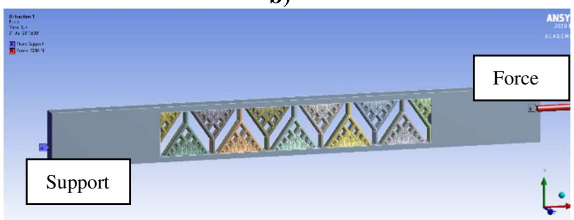


c)

Fig. 6. FEA simulation definition: a) Bending; b) Compression; c) Tensile test;

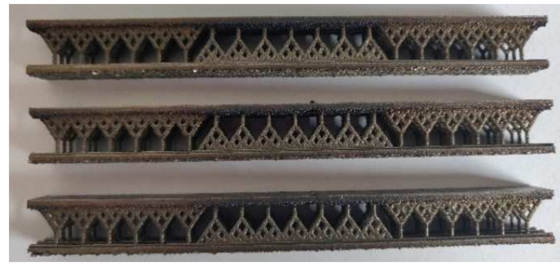
3. RESULTS

3.1 Manufactured samples

The CAD designed models were manufactured with SLM and then measured on Keyence and Alicona. The printed samples are presented in Fig. 7. Three samples of two models were designed for bending and tensile testing, while for compression two samples were printed.

The measurements showed little deviations from the CAD model to the printed sample. It can be seen that at the compression samples, the fractal structure on the sides are not perpendicular to the top platform, but have a deviation about 2° (value measured on Keyence microscope). For the bending and tensile samples, no major deviations were found. The strut diameters tend to be slightly bigger than the CAD model, this is due to the roughness on the fractal trees. The roughness measured with Alicona on different segments of the fractals are presented in table 2.

a)



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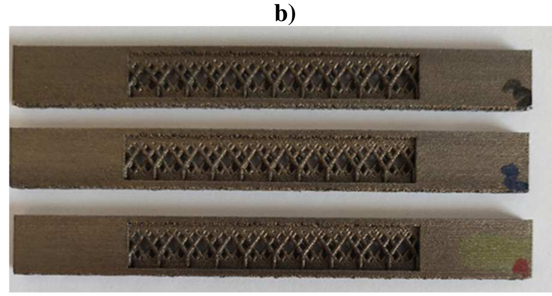

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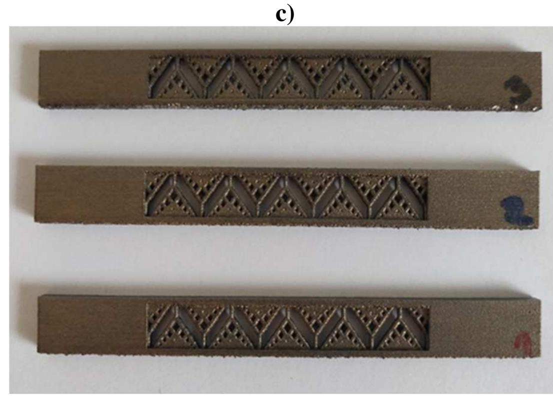

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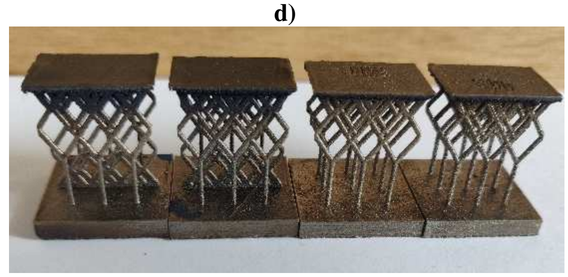


e)

Fig. 7. SLM printed samples for: a) Bending (code SJ); b) Bending (code S); c) Tensile code (SJ-1); d) Tensile (code SJ); e) Compression code SJ and S;

Table 2

Roughness on tree-like fractals structures of the samples

Test	Sample code	Ra [μm]
Compression	S	16,04
Bending	S – up	18,71
	S - upside down	26,50
Tensile	SJ-1 – up	26,18
	SJ – up	23,36
	SJ - upside down	28,45

3.2 Compression

The maximal load that resulted after the compression tests is 1271.86 N and was applied on the SJ-sample, where the middle row of fractals is upside down. In Fig. 8 the correlation between the applied force and deformation for all samples is presented. It can be seen that at the samples with fractals only in one direction, model S, the force reaches 1128.75 N and the deformation of the struts is starting earlier. Fig. 9 presents how the fractals bend after the tests. The first strut respectively the first branch of the fractal tree is bulking the same way after the compression test, in both of the samples, regardless of the fractal orientation.

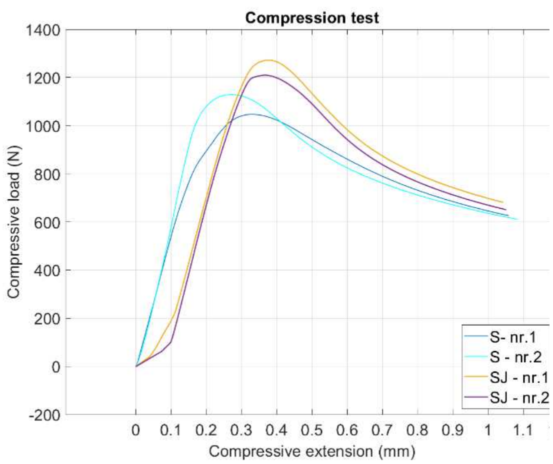
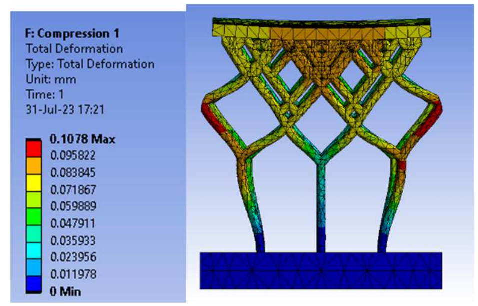


Fig.8. Compression load and extension

Fig. 9. Sample after compression test

Taking in consideration the linear domain of the deformation, in FEA a force of 600 N was applied on top of the compression samples. The fractal Young's Modulus value was estimated at 72 GPa, whereas the thicker parts were kept at the nominal value for steel 1.2709 (160 GPa). Fig. 10 shows the S sample simulated in ANSYS. The calculated relative error between experimental and simulated results for deformation at a load of 600 N was about 6.7 %. The maximum stress in sample S at the first strut of the fractal (Fig. 10.b) was simulated at around 296 MPa.



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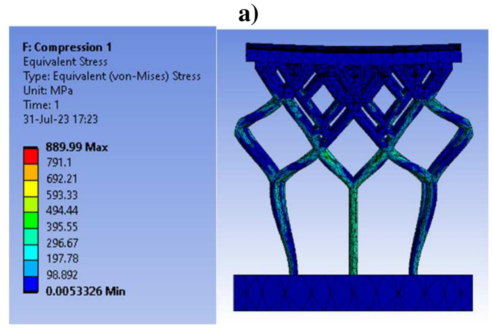
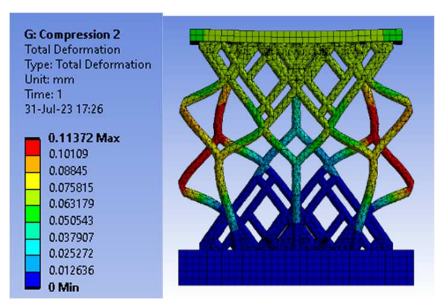


b)

Fig. 10. S sample analysis: a) Total deformation; b) Equivalent von-Mises stress;

Fig. 11 shows the SJ sample simulated in ANSYS. The calculated relative error between experimental and simulated results for deformation at a load of 600 N was about 1.6 %. The maximum stress in sample SJ (Fig. 11.b) was simulated at around 392 MPa at the first strut, then the stress is distributed to the next branches.



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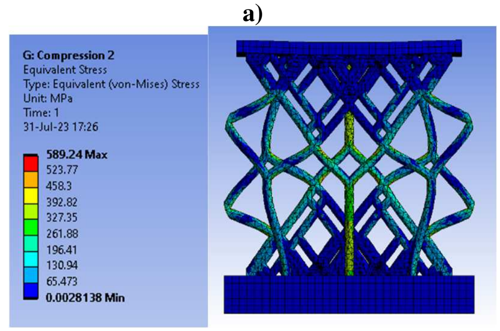


b)

Fig. 11. SJ sample analysis: a) Total deformation; b) Equivalent von-Mises stress.

3.3 Bending

For the bending tests, the graphic between the force and the displacement is presented in Fig. 12, for both types of samples, S and SJ, three specimens each. After the bending testing, it results that the sample SJ, where each second fractal is upside down have a smaller resistance, since the applied force reaches a maximum of 1480 N, while the sample S can go up to 1700 N. Still, at these samples (S) two of the specimens (1,2) record fractures that are represented in the graphic form Fig. 12. by the spikes on the curve. This can be also seen in Fig. 13 and can be influence by the differences of angle deformation and fraction at the fractals in the sides of the sample. On specimen 1 on the sides the inclination angle between the first strut and the base platform, after bending was 0° to 8°, while on the other side it was 40°. The same angles on the specimen 3 were measured and had values of 20° on both sides.

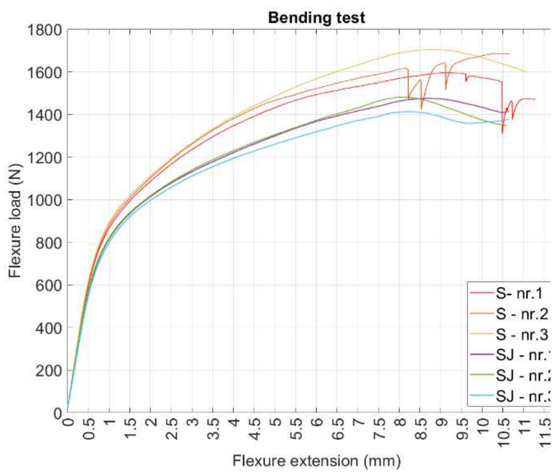
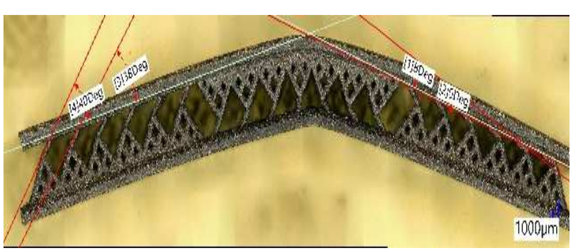


Fig. 12. Flexure load and extension

The samples SJ (Fig. 14) did not register big deviations between the specimens and all specimens have the angle inclinations between the first strut and the base between 36° and 42°, as measured on Keyence.



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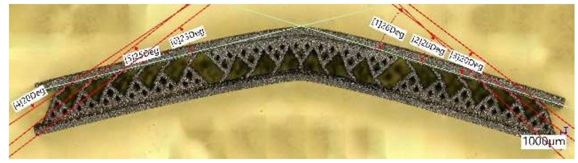

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Fig. 13. Sample S after bending test: a) Specimen 1; b) Specimen 3.

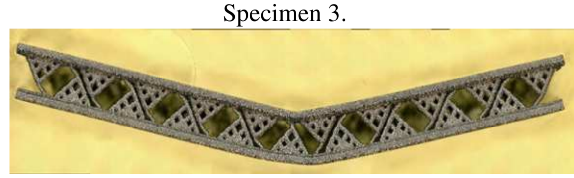
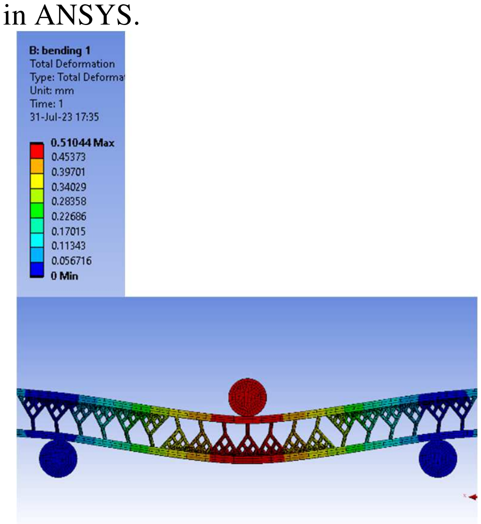


Fig. 14. Sample SJ after bending test

In FEA, considering again the linear domain of deformation, a force of 600 N was applied on the test part. Fig. 15 shows the S sample simulated in ANSYS.



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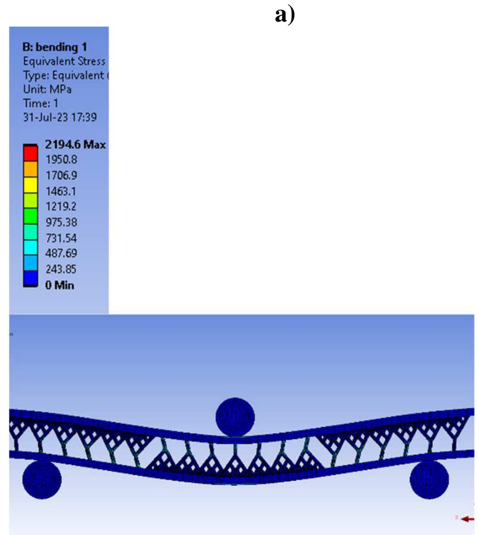


b)

Fig. 15. S sample analysis: a) Total deformation; b) Equivalent von-Mises stress.

The fractal Young's Modulus value was estimated at 120 GPa, whereas the thicker parts were kept at nominal value. The calculated relative error for deformation between experimental and simulated results at a load of 600 N was about 4.1 %. The stress in sample S for the fractal structure (Fig. 15.b) was simulated at around 975 MPa and is present at the first strut and the beginning of the bifurcation. For the SJ sample the relative error was calculated 6.7 % and the maximum stress was around 950 MPa for the fractal structure.

3.4 Tensile

Fig. 16 represents the curve formed of the load and displacement for the two kinds of tensile samples. The first sample (SJ) showed a maximum (break) load of 7473 N. The three SJ samples behaved similarly in the traction test.

A maximum load of 10500 N was reached by the second sample (SJ-1) and again the samples behaved very similarly during testing. Fig. 17 shows different samples after the traction test highlighting where the sample break.

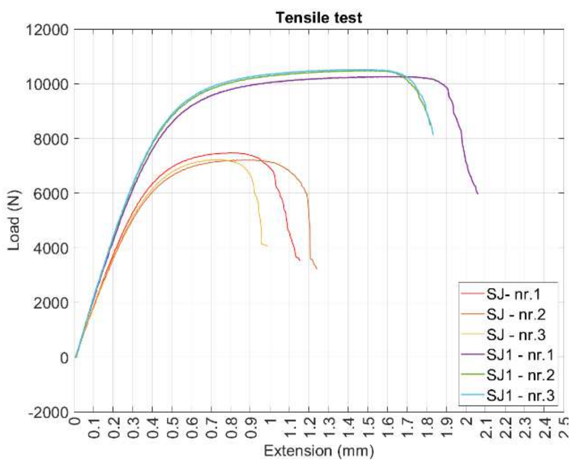


Fig. 16. Tensile load and extension

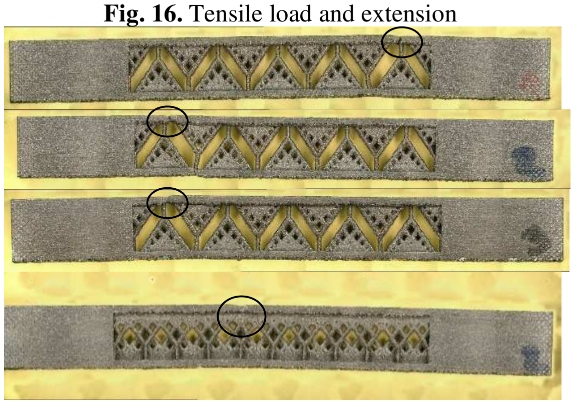
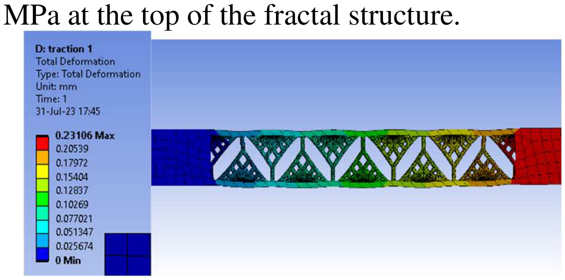


Fig. 17. Samples SJ after tensile testing

In FEA, considering again the linear domain of deformation, a force of 4000 N was applied on the test part (SJ). The fractal Young's Modulus value was estimated at 120 GPa, whereas the thicker parts were kept at nominal value. Fig. 18 shows the SJ sample simulated in ANSYS. For the SJ sample the relative error for displacement was calculated 6.8 % and the maximum stress was around 800 MPa at the top and base of the fractal structures (Fig. 18.b). For the SJ-1 sample a force of 6000 N was applied (the values for Young's Modulus was the same as for the previous example). Fig. 19 shows the simulations results. The relative error for was 2.3 %, and the maximum stress was around 1214 MPa at the top of the fractal structure.



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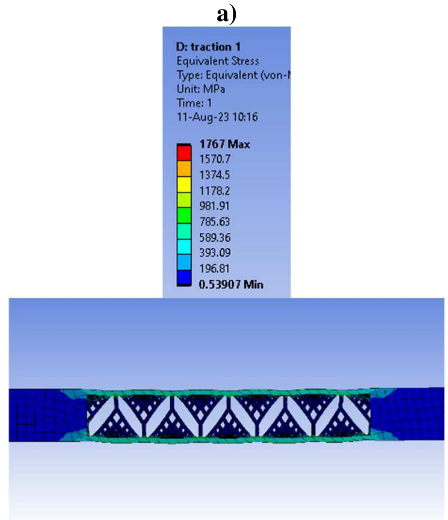

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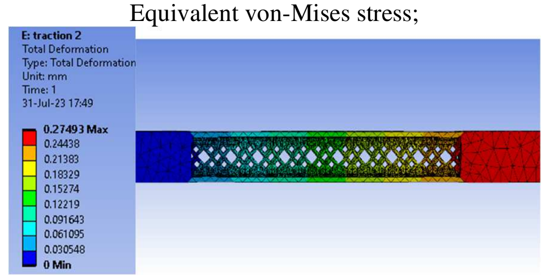
Fig. 18. SJ sample analysis: a) Total deformation; b) Equivalent von-Mises stress;



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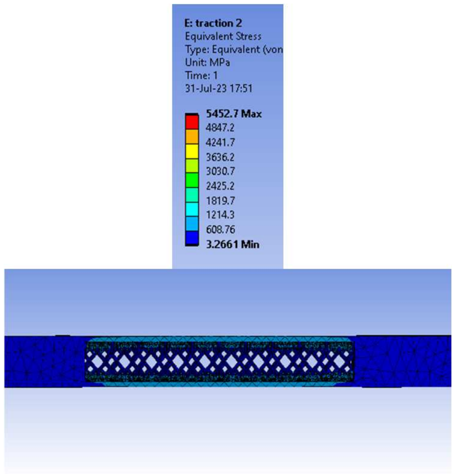

b)

Fig. 19. SJ-1 sample analysis: a) Total deformation; b) Equivalent von-Mises stress.

4. DISCUSSION

For compression tests, the results showed that the samples SJ, which had the middle row upside down, is more resistance, the compression force was higher with 143 N than S samples, even if the bulking effect appeared on both models of samples (SJ and S). For bending tests, the SJ-sample reported a smaller resistance to the applied force, but the fractals did not break, as at the S samples, where a higher force could be applied, but some of the fractal branches bend so hard, they broke (see Fig. 13). The fracture of the fractal trees in the S samples can be recognized also in the graphic (Fig. 12) due to the spikes recorded during the experiment. The same behavior, of lower resistance was found for tensile test, the samples which contain the model of each second fractals upside down (SJ-model) were not so resistant in comparation to the SJ-1 which is reported in the graphic from Fig. 16.

Finite Element Analysis was applied to the samples to validate the laboratory testing. It is important to note, that the comparation between the simulation and experiment is made only in the linear domain of the deformation. As presented in the results, the relative error on the displacement after the force was applied is under 10%. With the simulation the equivalent stress could be also predicted and the tension in distribution in the fractal is noticed. Having this information could lead to future design optimization. Also, these segments with accumulated stress where the segments were the sample broke. By establishing the simulation now and maintaining a low relative error, in the future the samples and parts containing fractal tree-like structures printed by SLM could be simulated and the mechanical properties could be predictable.

Compared to the literature, the samples with fractals reached an experimental tensile stress of 650 MPa, while the tensile stress in standard samples of tool steel 1.2709 reached up to 1200 MPa, without heat treatment [7-8]. The flexure stress obtained for the plate samples in [3], printed with three energy densities, was between 3000 and 4000 MPa. These values are higher than the flexural stress obtained for the S and SJ samples, manufactured with fractals structures infill (1500MPa, medium value, obtained after bending test). The differences between the results could be due to the fractal infill, which has a smaller area in section than the samples from the literature, but also due to the different tool steel material and printing conditions.

5. CONCLUSION

This article presented an approach to study the mechanical properties of samples, designed with tree-like fractals, manufactured by SLM.

Three mechanical tests were achieved, bending, compression and tensile tests (each test with samples having different fractal geometries). For compression the SJ samples can resist at a force of 1200 N, while for bending and tensile testing the samples S respectively SJ-1 recorded a higher resistance at the applied force and a smaller stress value, showing that the fractal geometries on each of the three tests behaved differently. A preliminary conclusion of these tests is that the geometry of the tree-like fractal structures used as internal structures, has significant influence on the mechanical properties of the part.

For future work, more configurations of the fractal tree are necessary, to study the influence of the structure parameters (angles, strut diameters and lengths of the branches) on mechanical properties of the final part. Although the focus was parts with fractals as internal structures this approach could be applied for studying other SLM parts.

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EVALUAREA PROPRIETĂȚILOR MECANICE A EPRUVETELOR FABRICATE PRIN SLM, CE CONȚIN FRACTALI DE TIP COPAC CA STRUCTURI INTERNE

Rezumat: Fabricația aditivă este în continuă dezvoltare datorită avantajelor acesteia, precum fabricarea pieselor cu geometrii complexe, utilizarea diferitelor materiale, proprietăți pentru reducerea greutății dar și facilitarea prototipării rapide. Scopul acestei lucrări este de a compara proprietățile mecanice a diferitelor epruvete fabricate prin Topire Selectivă cu Laser (SLM) și modelate utilizând tipare de fractal ca structuri interne. Proiectarea epruvetelor este realizată după conceptul de biomimetică, utilizând structuri de fractal de tip copac (în diferite configurații), ca structuri interne ale pieselor. Piesele testate au fost fabricate prin Topire Selectivă cu Laser, din pulbere de oțel de scule 1.2709. Epruvetele au fost testate pentru compresiune, încovoiere și tracțiune. Mai mult, s-a utilizat și Analiza cu Element Finit (FEA) pentru a descrie deformările și distribuția stresului în structurile de fractal. Rezultatele experimentale au fost comparate cu rezultatele FEA, doar în domeniul linear (pentru elasticitate) pentru a determina proprietăți ale structurilor de fractal. Pentru compresiune și încovoiere, forța maximă aplicată poate ajunge până la 1600 N, pe când pentru tracțiune până la 10000 N. Fiecare configurație a fractalilor are o influenta asupra forței aplicate si a distribuției stresului din FEA.

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