ORIGINAL PAPER

ACCURACY OF SLA AND MATERIAL MORPHOLOGY USED IN ARCHITECTURE

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Abstract. *Stereolithography (SLA), Digital Light Processing (DLP), and Fused Deposition Modeling (FDM) technologies have evolved a lot in the last decade, making 3D printers more and more accurate, faster, and at more and more affordable prices. The precision of the parts obtained through these technologies has reached the order of microns, and the materials used by these technologies are increasingly versatile, from classic PLA, ABS, PEEK plastics, reinforced plastics with metal particles or wood particles, respectively different types of photopolymerisable resins. The software used by SLA, DLP, and FDM technologies is numerous and very sophisticated because it allows the manufacture with very great precision of 3D prototypes, identical to the designed 3D model, through modern additive manufacturing techniques. These 3D printers are used to make three-dimensional parts that can be used in different industries such as: aeronautical and aerospace, automotive, tooling, electronics, robotics, medicine, architecture, and design. The quality and mechanical strength of the prototypes obtained using 3D printers are very good, these technologies permit to realize of very fine lattice structures of the parts. In this article were realized different SEM, EDS and Mapping analysis for simple and composite photopolymerisable resins, and PEEK materials to determine the morphological structure, the qualitative and quantitative chemical composition, and the distribution of chemical compounds in the structure. The objective of the work consists of the design and 3D printing of a functional prototype in the architecture field to determine the processing precision and to compare the optimal processing variant depending on the type of additive manufacturing process, material, and desired precision.*

Keywords: *photopolymerisable resins; stereolithography SLA; SEM analysis; lattice structure; architectural design.*

1. INTRODUCTION

Additive Manufacturing (AM) technologies of prototypes are fundamentally different from material removal processing technologies (cutting, electroerosion, laser processing) and material redistribution processing technologies (casting, injection, forging, molding, extrusion) by the fact that the parts are obtained by adding material as much as necessary and where necessary. [1-5]

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The specificity of these additive manufacturing processes is their ability to make complex three-dimensional parts and objects, starting from a computed aided design (CAD) file (using different software Solidworks, Inventor, Catia, Onshape), without the need to use machine tools or any additional tools or molds. The main peculiarities of AM technology are the great flexibility and design freedom that can be achieved. [6-8]

The basic element of additive prototyping technologies is the "section".

The parts are quantified in sections and made using a repetitive construction process, section by section, reducing a three-dimensional problem to a flat one. This dimensional reduction leads to a decrease in the accuracy and quality of the surfaces due to the scale effect.

The FDM (Fused Deposition Modeling) is the most widely used additive manufacturing technology due to its simplicity and affordability. It is used in modeling, and prototyping but also in production applications [9,10].

FDM printing technology consists of passing a filament of plastic material through an extruder that heats it to its melting point, then applying it uniformly (by extruding) layer upon layer with high accuracy to physically print the 3D model according to the CAD file (stl. file or g-code file).

The thermoplastic material is heated until it reaches a semi-liquid state, then it is extruded through a nozzle of small diameter and is deposited in layers with a thickness of several tenths of a millimeter.

The deposition is carried out with the help of a modeling head equipped with one or two extrusion nozzles. The raw material used from a physical point of view is in the form of a filament with a diameter of approximately 0.2; 0.4; 0.8; 1.75; 2.85 or 3 mm. The essential element of the FDM process is maintaining, inside the heating-extrusion head, a temperature corresponding to the pasty state of the material.

The advantages of FDM technology are very user-friendly, silent, and safe office technology [1,11].

a)

b)

Figure 1. a) Architectural and b) design parts manufactured by SLA technology

Usable objects and parts can be produced, the palette of materials being quite wide. The price of 3D printers (kits and assembled models) as well as consumables (rolls with plastic filaments) is extremely affordable. FDM manufacturing technology features ease of use. The disadvantages of this process are the slow construction speed in the case of complex geometries, the possibility of the existence of non-uniformly printed areas (non-glued layers), low impermeability, poor resolution and accuracy for small parts and fine details (microns).

Applications of the FDM process consist of making durable parts and subassemblies for functional testing, conceptual design, presentation and marketing models, detail parts for food or medical applications, plastic subassemblies for high temperature applications, very small series productions.

Stereolithography is an additive manufacturing technology, known as a manufacturing process by solidifying the raw material in a liquid state due to photopolymerisation. Stereolithography was the first process that allowed the generation of a physical model, using model data, directly from the computer. The parts solidify in the presence of the laser, at low laser powers (5-10 W) [1-4].

This technology allows the creation and manufacture of models, prototypes and parts layer by layer, using for solidification, the process of selective photopolymerisation, a process that is activated by a light beam and forms bonds between unsaturated molecules forming polymer chains [5-7].

The desired 3D model is initially sliced into cross sections. For each layer, the laser beam traces a cross-section of the partial pattern on the surface of the liquid resin. Exposure to ultraviolet laser light solidifies the model drawn on liquid resin resulting in a solid built (3D printed) layer that is added to the previous built layer.

After the pattern has been drawn, the platform descends a distance equal to the thickness of a single layer, typically between 0.05 mm and 0.15 mm.

The accuracy of the printed parts is very good, the finish of the printed surfaces is very good, the printing speed is good to very good, as is shown in Fig. 1. Materials used are photo-sensitive polymers as: liquid resins, transparent resins, wax-based polymers, composite resins with ceramic materials (newly developed).

Once the part is fully fabricated, additional post-processing such as backing material removal, chemical bath and UV drying can be performed. Since the entire cross-section is designed in a single exposure, the construction speed of a layer (section) is constant regardless of the complexity of the geometry. Regardless of whether a simple part is printed or 10 complex parts simultaneously, the printing speed remains constant. SLA technology costs are superior to FDM. In the case of SLA technology, the accuracy of the printed parts is very good. The finish of the printed surfaces is very good. Print speed is good (for multiple objects and complex geometries).

The advantages of SLA technology are fine and precise printed surfaces (use in the jewelry industry, dental technology, electronics), fairly resistant prototypes for processing, diverse range of resins including biomedical materials (certified for use in the medical field) and transparent resins (prototypes in the industry packaging), stable printers with few moving parts. [1-5]

SLA technological advantages are the prototyping of parts with complex and highly detailed geometries, very fine and precise printed surfaces, large part construction sizes, the printed parts can be used as a master mold for the industries of injection molding (injection molding), thermoforming, casting metals and parts resistant to high temperatures. [1-7]

SLA technological disadvantages consist of average resistance to mechanical processing, unsustainability over time, long exposure to the sun damages parts that become brittle and brittle, requires troublesome post-processing operations (with potentially dangerous chemicals). All both technologies, FDM and SLA are used in architecture, in the automotive, aeronautical, aerospace, tooling, medical [5], robotics fields and for industrial design to realise 3D parts with complex forms and very fine details. [8-11]

The purpose of this research was to establish the steps necessary to print the architectural parts and determine the morphological structure for photopolymerisable resin used in SLA (Stereolithography) technology according to processing precision, manufacturing time, software, costs, materials used, and post-processing treatments.

In this article, were realized comparisons concerning the microstructure characterization and chemical analysis of two types of photopolymerisable resins (simples and composite) and PEEK (Polyether ether ketone) material and was determined the possibility to obtain lattice structure with fine details, by SLA.

2. MATERIALS AND METHODS

The experimental research of this paper consists in the design of the Cretulescu castle, using the software SolidWorks 2019, and being saved as STL. file, as in Fig. 2. The 3D printer used for this research was Formlab 3D printer (Formlabs, Somerville, Massachusetts, USA), presented in Fig. 3.

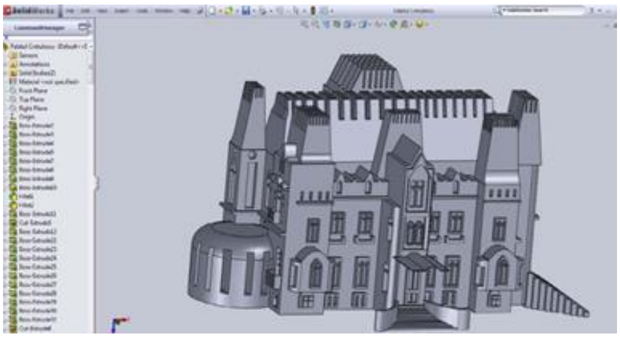


Figure 2. STL. file of the castle part.

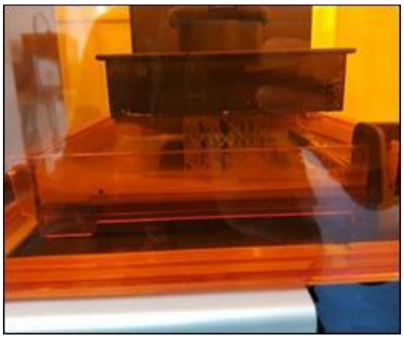


Figure 3. The SLA process for the castle.

The Formlab Form2 3D printer (Fig. 3) is a modern, state-of-the-art printer that produces parts with an accuracy of 25-300 microns. It is equipped with a low-power laser (P=250 mW and λ=405 nm). The software used is Preform. The file types used are STL, OBJ or FORM [12].

The Preform software was used to prepare the 3D printing of the landmark, as in Fig. 4. The landmark will have 1159 layers, the printing duration will be 4 h and 12 min and around 148.7 ml of photopolymerisable resin will be consumed.

The material used was a white photopolymerisable resin, with special mechanical resistance, used for the manufacture of prototypes and models in the field of architectural design that require high complexity and fine details. The mechanical properties of this material are given in Table 1, and the chemical properties are presented in Table 2. [1-8].

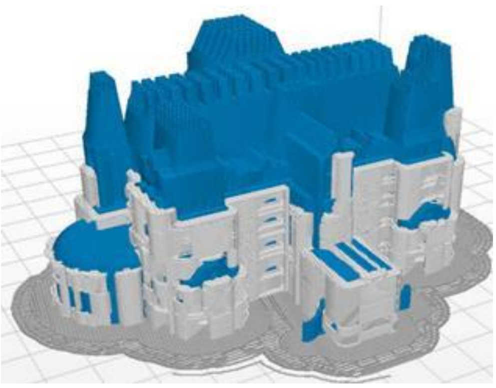


Figure 4. The STL file of the castle, using the PreForm software

Figure 5. 3D printed piece through SLA technology

In Fig. 5, is represented the 3D printed castle prototype, with the dimensions (194x158x116 mm). After 3d printing process, the supports are removed and the piece is cleaned with isopropyl alcohol and for improving the mechanical properties, the part is introduced in the UV furnace, at the temperature comprised between 190-220°C, for 30 minutes.

Table 1. The mechanical properties of the gray photopolymerisable resin used in SLA technology [8].

	METRIC		METHOD
Tensile Properties			
Ultimate Tensile Strength	35 MPa	61 MPa	ASTM D 638-14
Tensile Modulus	1.4 GPa	2.6 GPa	ASTM D 638-14
Elongation	32.5%	13%	ASTM D 638-14
Flexural Properties			
Flexural Stress at 5% Strain	39 MPa	86 MPa	ASTM D 790-15
Flexural Modulus	0.94 GPa	2.2 GPa	ASTM D 790-15
Impact Properties			
Notched IZOD	not tested	18.7 J/m	ASTM D 256-10
Temperature Properties			
Head Deflection Temp. @1.8 MPa	not tested	62.4ºC	ASTM D 648-16
Head Deflection Temp. @0.45 MPa	not tested	77.5ºC	ASTM D 648-16
Thermal Expansion (-30 to 30ºC)	not tested	78.5 um/m/C	ASTM D 831-13

Table 2. The chemical properties of the photopolymerisable resin used in SLA technology [8].

Mechanical Properties	**24 h weight gain [%]**	**Mechanical Properties**	**24 h weight gain [%]**
Acetic Acid, 5%	0.75	Hydrogen Peroxide (3%)	0.75
Acetone	10.77	Isooctane	0.02
Isopropyl Alcohol	1.56	Mineral Oil, light	0.35
Bleach, ~5% NaOCl	0.65	Mineral Oil, heavy	0.27
Butyl Acetate	0.84	Salt Water (3.5% NaCl)	0.64
Diesel	0.08	Sodium hydroxide (0.025%, pH= 10)	0.72
Diethyl glycol monomethyl ether	2.38	Water	0.83
Hydrolic Oil	0.16	Xylene	0.42
Skydrol 5	0.54	Strong Acid (HCl Conc)	8.21

For the FDM manufacturing, it was used a hybrid 3D printer, Zmorph 2.0 SX, 3D printer, and Voxelizer software.

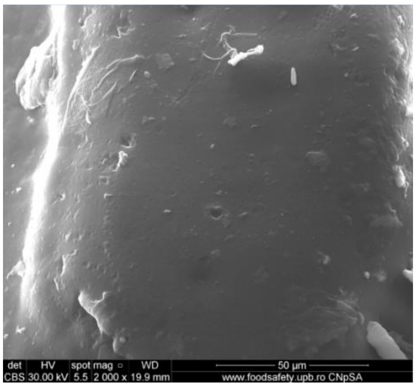
A scanning electron microscope (SEM) (Hitachi TM3030 Plus, Tokyo, Japan) coupled to an energy dispersive X-ray spectrometer (EDS), Bruker's Quantax 70 (Bruker, Billerica, MA, USA) was used for the surface morphology and elemental composition investigation. The EDS measurements were done for the two different types of photopolymerisable resins simple and composite manufactured by SLA and PEEK manufactured by FDM. To obtain images of surface morphology and elemental composition, mixed images of backscattering and secondary electrons of the surface morphology were acquired for each specimen.

3. RESULTS AND DISCUSSION

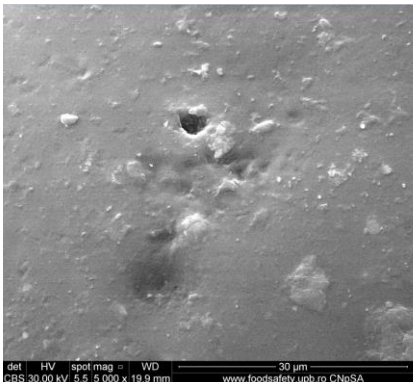
3.1. SEM ANALYSIS OF PHOTOPOLYMERISABLE RESINS AND PEEK USED IN ADDITIVE MANUFACTURING

The photopolymers resins manufactured by SLA technology are used in aeronautical and aerospace industry, automotive industry, tooling industry, medicine (dentistry, orthodontics, surgery), in the jewelry industry, architecture, and for the interior design, etc.

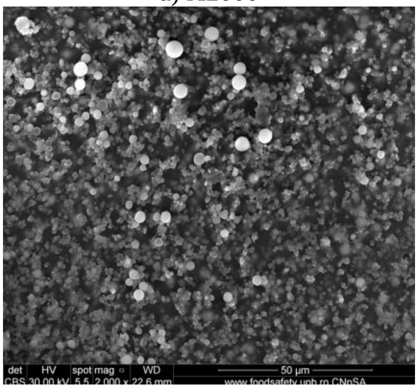
In Fig.6, it is presented the morphological structure of simple and composite photopolymerisable resins used in SLA technology, remarking the thin and uniform structure of this material. For the simple resins can observe the thin surface with rare fine porosities in the structure, as in Fig.6 a) and b). The sample of the composite photopolymerisable resin presents a smooth structure of resin with microns grains order, having the diameters comprise between 1.75 – 4.23 µm, as in Fig.6 c) and d) [1-7].



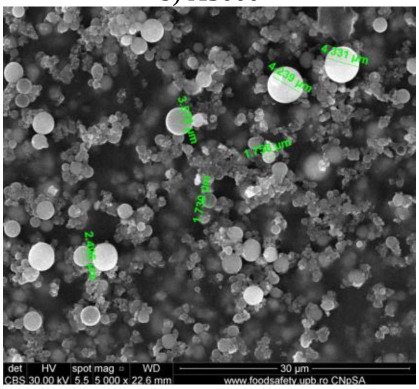
a) X2000



b) X5000



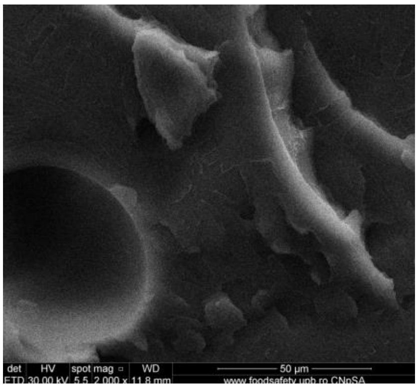
c) X2000



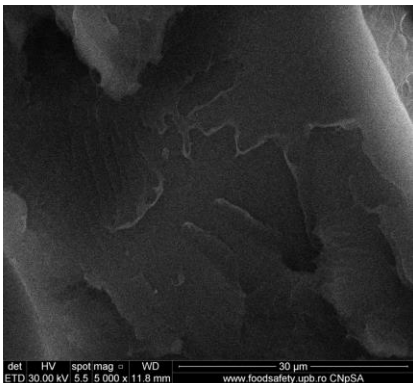
d) X5000

Figure 6. SEM analysis of photopolymerisable resin used in SLA technology (x2000; x5000).

In Fig. 7 a) and b) is presented the morphological structure of PEEK material used in FDM (Fused Deposition Modeling) technology and can remark that presents roughness and porosities.



a) X2000



b) X5000

Figure 7. Morphology structure of PEEK used in FDM technology (x2000; x5000).

Fig.8 shows qualitative and quantitative concentrations of chemical elements for the simple photopolymerisable resin, presenting the next chemical composition: 79.95 [wt.%] C, 20.02 [wt.%] O, 0.021 [wt.%] P.

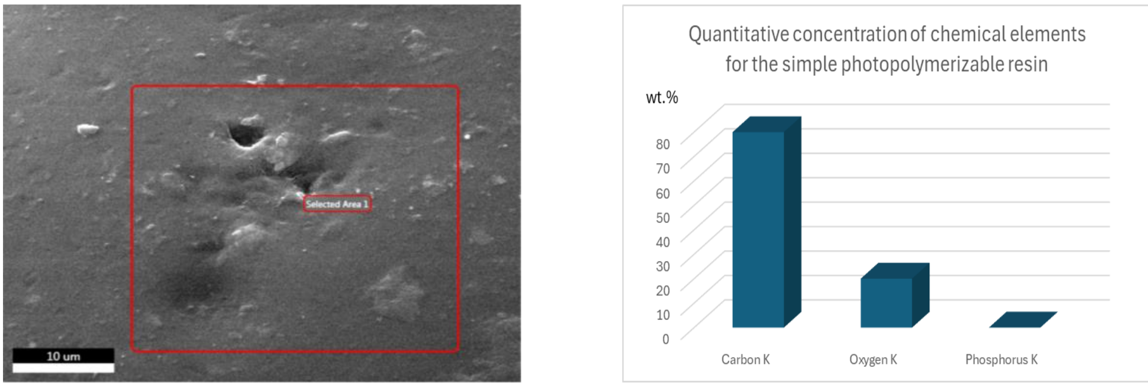


Figure 8. The qualitative and quantitative concentration of chemical elements for the simple photopolymerisable resin.

In Fig.9 can remark the EDS analysis for composite photopolymerisable resin, presenting the next chemical composition: 55.69 [wt.%] C, 32.57 [wt.%] O, 6.47 [wt.%] Si, 4.49 [wt.%] Al, 0.31 [wt.%] Ca, 0.26 [wt.%] K, 0.19 [wt.%] P.

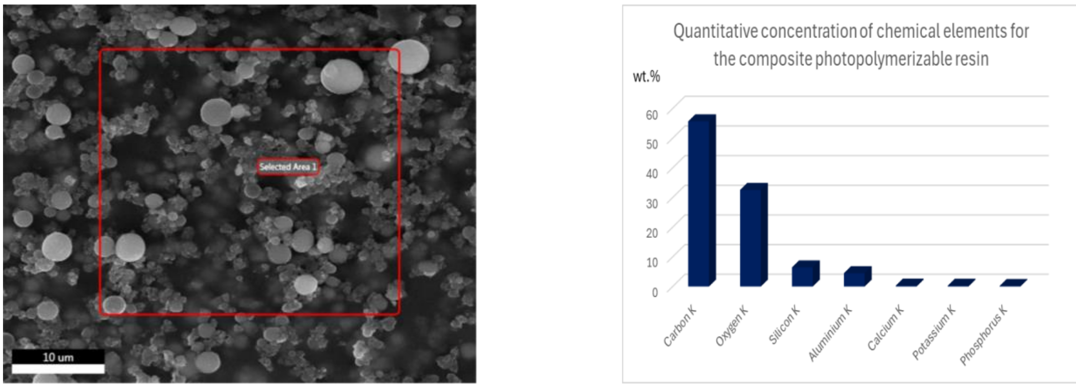


Figure 9. The qualitative and quantitative concentration of chemical elements for the composite photopolymerisable resin.

The qualitative and quantitative concentration of chemical elements for the PEEK material is presented in Fig.10, as: 79.46 [wt.%] C, 20.35 [wt.%] O, 0.19 [wt.%] Cl.

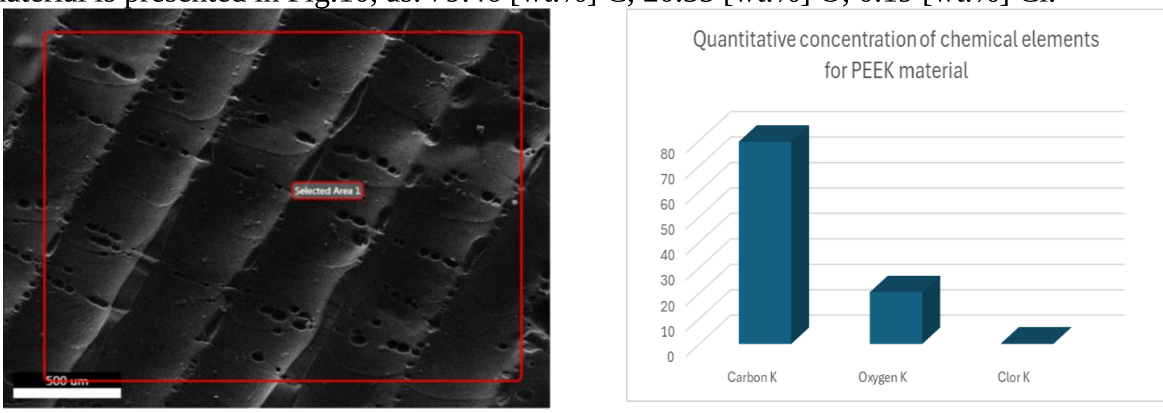


Figure 10. Qualitative and quantitative concentration of chemical elements for the PEEK material.

In Fig.11, is presented the mapping analysis for the simple photopolymerisable resin and can remarck the uniform distribution of the chemical elements in the sample structure (C, O, Cl).

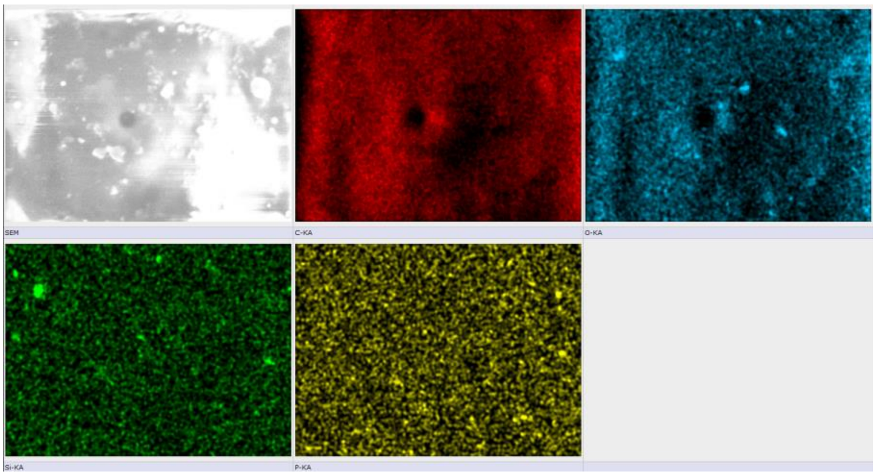


Figure 11. Mapping analysis of simple photoșolymerizable resin.

The mapping analysis of composite photopolymerisable resin from Fig.12, shows the uniform distribution of the grains (Al_2O_3-grain size 1-10 microns, and SiO_2 – grain size 55-75 nm) in the photopolymers resins, K and C present ununiform distribution on the surface sample, the results being similar to those in speciality literature.

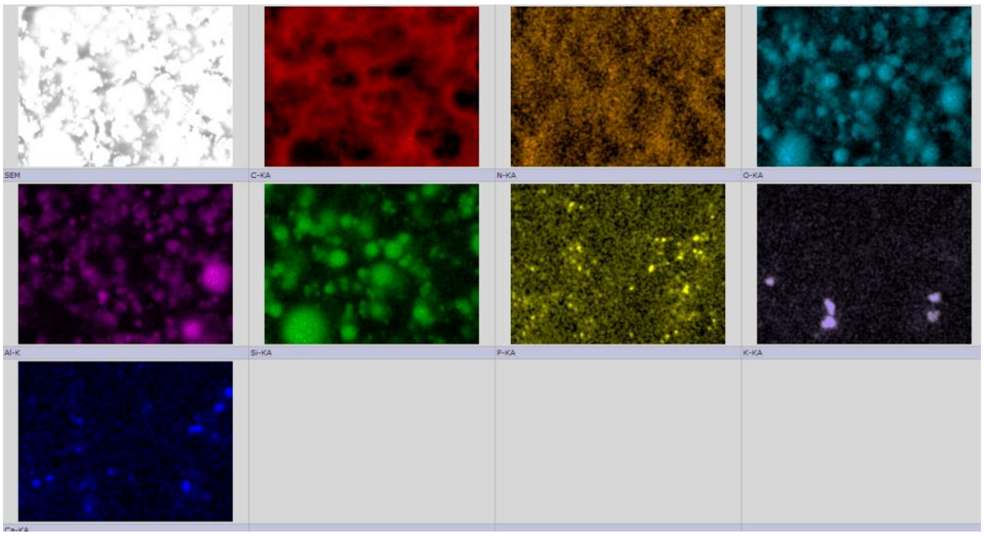
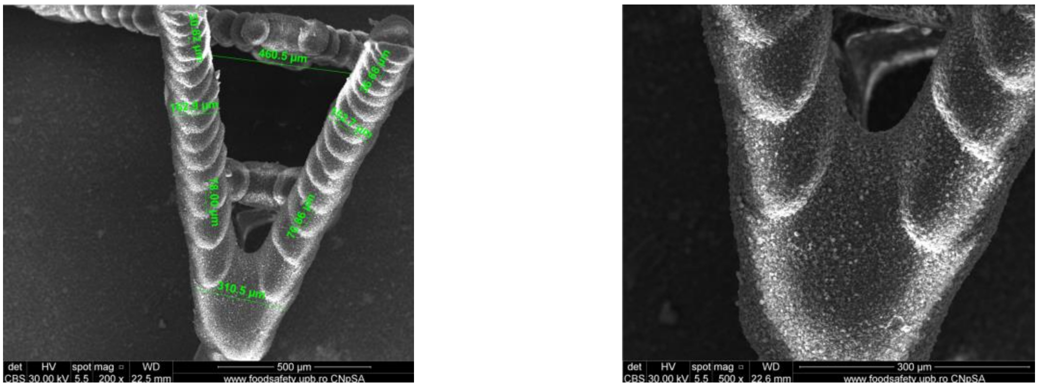


Figure 12. Mapping analysis of composite photopolymerisable resin.

3.2. LATTICE STRUCTURE DETAILS OBTAINED BY SLA

The lattice structure details is presented for the castle prototype in Fig.13 a), the layers of the composite photopolymerisable resin are from microns orders, between 30.82 – 78 µm. It can remarck the fine lattice surface with complex geometries of the sample as in Fig.13 b).



a) X200 b) X500

Figure 13. SEM analysis of the finest details obtained on the castle model.

4. CONCLUSIONS

Stereolithography produces large models with high precision and a superior roughness surface in rapport with FDM technology. The SEM analysis shows that the resins photopolymerisable prototypes do not present porosities due to the quality of 3D printing made with Formlab 3D printer. The FDM technology, grace of the dual extruder can realize composite material part (using 2 different filaments), and with gradual composition, and used various plastic filaments (PLA, ABS, PET, PEEK, HIPS, etc.)

The scanning electron microscopy analysis of the PEEK material and the photopolymerisable resins were realized, establishing the qualitative and quantitative chemical composition, and the morphological structure and the mapping analysis established the uniform distribution of the chemical compounds. In the case of composite resins, can remark that permit a better surface roughness, because of the powder grains that permit a smoother transition from one layer to another.

Stereolithography (SLA) produces the most advanced plastic 3D printing models across the widest range of applications. The details and complexity are beyond traditional modelmaking means, making SLA 3D printing the ideal way to produce complex and large-scale context models.

The SLA technology is recommended for the manufacture of landmarks with smooth and uniform surfaces and for the complex surfaces and fine details as for the architectural models. The photopolymerisable resins permit to manufacture 3D architectural parts with high complex geometries and fine details, and using different colors, that allow to obtain different interesting combinations with gradual color.

The parts manufactured by SLA technologies require a post-processing treatment in a UV furnace, at a temperature of 200^oC, for half an hour to improve the mechanical properties. The accuracy of the 3D parts manufactured by SLA process is from microns order. The SLA generally uses traditional photopolymerisable resins or reinforced resins with different nanocomposite particles that are used to manufacture functional prototypes with complex surfaces and fine details of the micron orders, depending on the desired mechanical properties.

In this paper was researched the lattice structure, manufactured by SLA, using composite photopolymerisable resins (photopolymers resins mixed with Al_2O_3 and SiO_2 grains of nanometres order), and can remark the complex and fine details obtained, of microns teens order.

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