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3D SURFACE MODELLING ASPECTS FOR 3D PRINTING

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Abstract: *The "Rapid Prototyping" term does not include all recent applications of this technology but represents the principles of additive manufacturing process. Additive manufacturing is a process through which a solid object of any shape is created, starting from a 3D virtual model, by adding successive layers of material in a horizontal plane. The article is divided into six parts describing: the 3D printing process, geometric modeling of the objects relating to the 3D surface type, equipments, materials used in 3D printing, conversion of files and experimental results. A study on 3D printable geometrical surfaces through the material extrusion process is included in the present article. The 3D surfaces were modeled using different modeling applications, design software and an application for digital animation software. The five types of 3D surfaces are: NURBS surface, POLY surface, SUBDIVS surface, SOLID object and MASH surface. The objects have been printed on a 3D* "Ultimaker –2" *printer. Polylactic Acid filament was used to print the objects. The article also refers to 3D design and printing constraints generated by the machine work load limitations and the extruded material.*

Key words: *3D printing*, *FDM, modeling, extrusion, geometry.*

1. INTRODUCTION

Nowadays the same process is defined differently by various companies in the field.

For example, what "Stratasys" calls – Fused Deposition Modeling (FDM), "3D Systems" call it Jet Printing Plastic and "RepRap" call it Fused Filament Fabrication (FFF).

According to ASTM (American Society for Testing and Materials), responsible for grouping standard terminologies of additive manufacturing processes in seven main types, the three abovementioned methods can be included in the "Material Extrusion" category.

The standardized terminology for additive manufacturing processes is [1]:

- Photo polymerization;
- Powder Bed Fusion;
- Material Extrusion;
- Material Jetting;
- Binder Jetting;
- Sheet Lamination;
- Directed Energy Deposition.

This paper is intended as a comparative study of 3D surfaces and 3D objects modeled by different processes in different 3D graphics programs.

The work contains some experimentation resulting from printing these surfaces.

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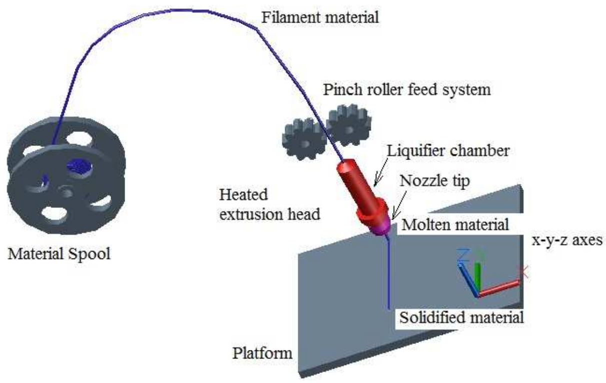


Fig. 1. Schematic of Extrusion-Based Systems.

2. EXTRUSION-BASED SYSTEM

The extrusion method functions under the following principle: the extrusion material (filament input) is brought into a semi-solid state and forced through a nozzle to form a filament with a narrower diameter than the diameter of the input filament that will rapidly solidify after the extrusion.

The input filament will be liquefied in a liquefaction chamber placed before the nozzle.

The temperature in the liquefaction chamber is set so that the filament changes its state.

The diameter of the filament resulting from the extrusion will remain constant if the movement of the nozzle on the surface is set to a constant speed.

Figure 1 shows the extrusion system and its components.

Liquefaction of the material is carried out in a tank which is attached to a nozzle such that the molten material to flow and adhere to the already deposited material prior to solidification.

This process is similar to conventional polymer extrusion processes.

In this case the extruder is mounted in vertically position on a plotting system.

In the scientific literature it is considered that there are a number of key features that are common to any extrusion-based system [2]:

- loading of material;
- liquefaction of the material;
- application of pressure to move the material through the nozzle – extrusion;
- plotting according to a predefined path and in a controlled manner;
- bonding of the material to itself or secondary build materials to form a coherent solid structure;
- inclusion of support structures to enable complex geometrical features.

The primary process entails extrusion of highly viscous materials through a nozzle. The material flows as a Newtonian fluid in most cases [3].

3. GEOMETRIC MODELING

Albert Einstein said, "Imagination is more important than knowledge." Three dimensional geometric modeling develops computer skills identical to those developed for the effective implementation of physical models [4].

In designing 3D solids (Fig. 3) it can be started from a drawing done in 2D (Fig. 2) or a 2D sketch. Solid modeling is the technique of creating three-dimensional solid by using a combination of solid primitives.

Numerous modeling techniques exist, as well as many modeling formats. Point modeling, edge loop modeling, box modeling and paint modeling are a few of the polygon modeling techniques. Polygon proxy modeling is a variation of subdivision modeling.

NURBS surfaces are used extensively in industrial design, manufacturing, and the automotive industry. A modeling based on NURBS-type primitives, Fig. 4, is the easiest but not the most advanced.

The NURBS curves are curves which can be created by translating the points that make up the curve and can give it a sinuous shape. Generally, the NURBS curves are used to create the surface outlines to be then rotated around an axis in order to create a final surface and for fine modeling of the surface [5].

A modeling based on polygon primitives (Fig. 5) is the most commonly used in modeling characters for computer games. In this case, the polygon surfaces are so limited that the game can run in real time. The polygon surfaces give a sculpture look to the object modeled. A modeling based on subdivided primitives is the finest, Fig. 6. This combines the modeling techniques with NURBS and polygon-type primitives.

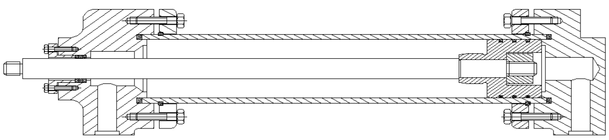


Fig. 2. 2D drawing.

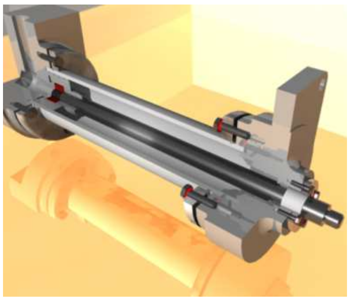


Fig. 3. 3D solids.

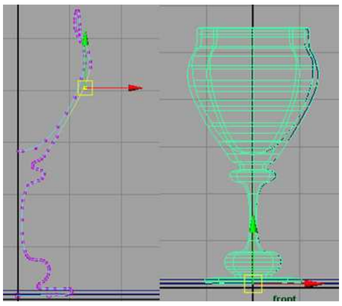


Fig. 4. Modeling by NURBS primitives.

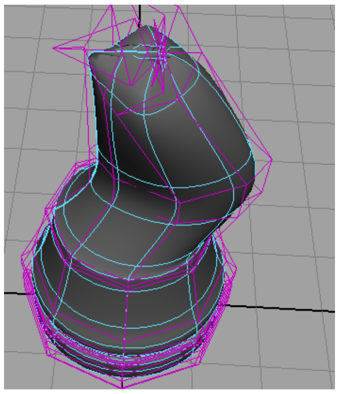


Fig. 5. Modeling by polygon primitives.

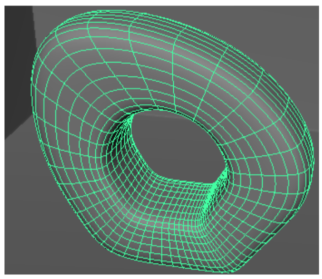


Fig. 6. Modeling by subdivided primitives.

Fig. 7. 2D drawing.

These surfaces have edges and faces similar to polygons, shapes which give the object a smooth surface.

The featured models have been created using different surfaces, the object being hollow.

Object type, solid models are easier to create for the designer but imply a different structure in modeling.

Solid objects are created either from existing outlines (Fig. 7) that are given a series of commands to generate solid shapes (Fig. 8), or from primitive solid shapes (Fig. 9) that will change with commands of union, subtract or merge with other solid shapes.

Elementary spatial geometric shapes are basis for modeling any object whatever its complexity [6].

These elementary spatial geometric shapes, also called primitives of 3D modeling, are geometric models preset for CAD applications.

If a designer can create a very complex shape (Fig. 10) and the used CAD program allows its modeling, the spatial shape is limited to a time by both the product function and its manufacturing technology [7, 8].

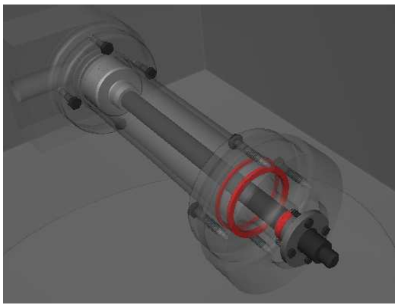


Fig. 8. Solid object.

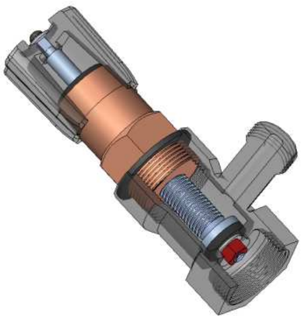


Fig. 9. Combination of the two solid objects.

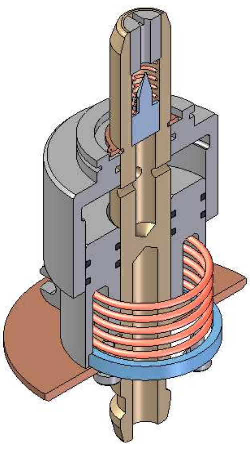


Fig. 10. Complex shape.

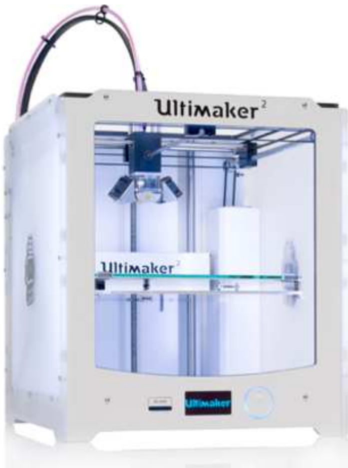


Fig. 11. Ultimaker^2 – 3D printer [9].

4. EQUIPMENT AND MATERIALS USED IN TESTS

Printing filaments used to be limited to PLA, but today there is a wide range of different materials on the market [10]. PLA (Polylactic Acid) filament was used to build the objects in experimental part of this article.

Extrusion temperature in the experimental parts was 200 ^{o} C, no rafts were used, while the extrusion speed was kept at 50 mm/s.

These were constant parameters throughout the experiment. Print surface: heated glass bed.

The Ultimaker was founded in the Netherlands by active RepRap advocates and developers, Erik de Bruijn, Siert Wijnia and Martijn Elserman. The first Ultimaker kits shipped in early 2011 [11].

The machine (Fig. 11) developed 3D printing of various surfaces is Ultimaker^2. The Ultimaker was the only printer with feature a Bowden-style extruder, where the filament drive mechanism is separated from the extrusion nozzle.

As a result, engine weight that makes advance filament does not add to the weight of the print head [11]. A low-mass tool head is ideal for fast prints.

The electronics components have been redesigned and updated in time [11].

Review unit included also UltiController, an add-on that allows you to adjust temperature and print speed, print from an SD card, monitor constructions, and implementation of maintenance operations independently of a computer [11].

Those from Ultimaker can print in ABS or PLA, machines provided they are designed to print PLA material type. These machines are equipped with heated building platform designed specifically to print ABS materials [11].

The technical characteristics of the printing filaments used in the experimental research are: filament diameter 2.85 mm and filament diameter after extrusion 0.4 – 0.3 mm.

5. EXPORT FOR SLICING

The transfer of the geometric models presented in this article was performed using .stland .obj file types, exported from graphic software.

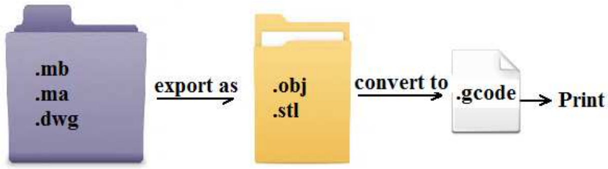


Fig. 12. Export and convert.

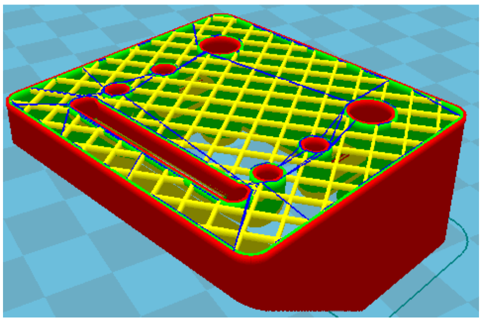


Fig. 13. Forming layers.

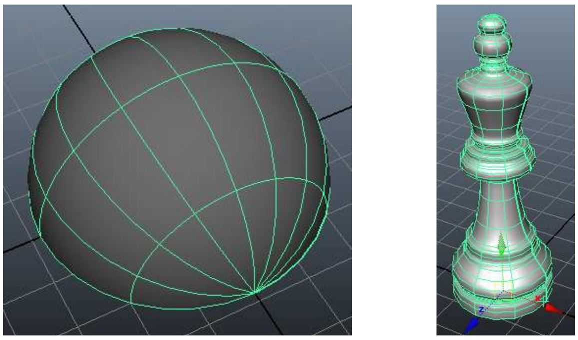


Fig. 14. NURBS surface.

The .stl or .obj file types were converted to .gcode using Cura software provided by Ultimaker.

The simplest way to print a model is to export it as a Stereolithography (.stl) file from and convert it to .gcode, using Cura, Skeinforge or Slic3r (Fig. 12).

Layer formation is closely related to the diameter of the extruded filament to be deposited in successive planes, parallel to each other (parallel to the construction platform) and perpendicular on the flow direction of the extruded material (Fig. 13).

The path of the extrusion top can be observed in the current layer (Fig. 13).

6. THE RESULTS OBTAINED FROM 3D PRINTING

In order to analyze the different printed surface types, diverse surfaces were generated using various methods from a range of applications that were transferred to the 3D printer in .obj format or .stl format:

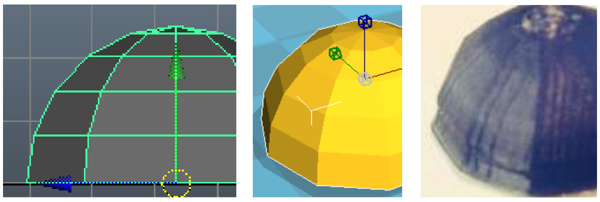
- NURBS surface is shown in Fig. 14 (NURBS – Non-Uniform Rational B-splines − use a method of mathematically describing curves and surfaces that are well suited to 3D applications);
- POLY surface (Figs. 15, 16, and 17) with different subdivisions for surface (polygon surfaces are a network of three or more sided flat surfaces called faces that get connected together to create a poly mesh;

The printing process characteristics for the piece presented in Fig. 15 are: printing time – 15 min; 0.25 m of used filament; the resulting piece weighs 2 g; the work piece dimensions are $w \times d \times h$: 20 mm × 19 mm × 10 mm; the radius of the object in a CAD application – 2.5 mm; subdivisions axis of surfaces: 10; subdivisions height of surface: 10.

The printing process characteristics for the piece presented in Fig. 16 are: printing time – 16 min; 0.26 m of used filament; the resulting piece weighs2 g; the work piece dimensions are $w \times d \times h$: 20 mm × 20 mm × 10 mm; the radius of the object in a CAD application – 2.5 mm; subdivisions axis of surfaces 20; subdivisions height of surface 20.

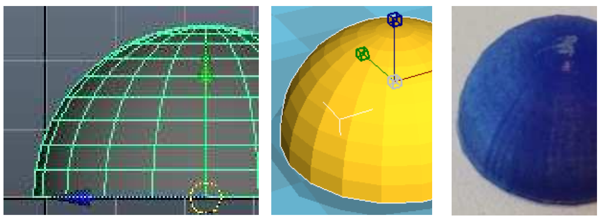
The printing process characteristics for the piece presented in Fig. 17 are: printing time – 16 min; 0.26 m of used filament; the resulting piece weighs 2 g; the work piece dimensions are $w \times d \times h$: 20 mm × 19.9 mm × 10 mm; the radius of the object in a CAD application 2.5 mm; subdivisions axis of surfaces 30; subdivisions height of surface 30.

- SUBDIVS surface (Figs. 18 and 19) with different subdivisions for surface (Subdivision surfaces are a hybrid surface type that possess characteristics of both NURBS and polygonal surfaces);



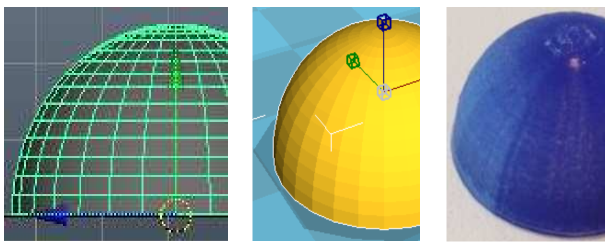
a b c

Fig. 15. POLY surface with 10 subdivision of surface: *a* – CAD model; *b* – .stl model; *c* – finite piece.



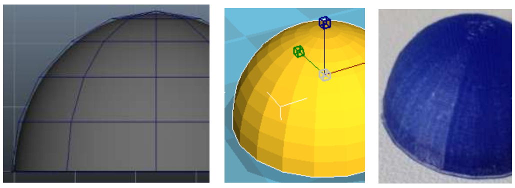
a b c

Fig. 16. POLY surface with 20 subdivision of surface: *a* – CAD model; *b* – .stl model; *c* – finite piece.



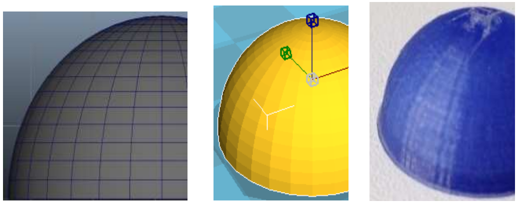
a b c

Fig. 17. POLY surface with 30 subdivision of surface: *a* – CAD model; *b* – .stl model; *c* – finite piece.



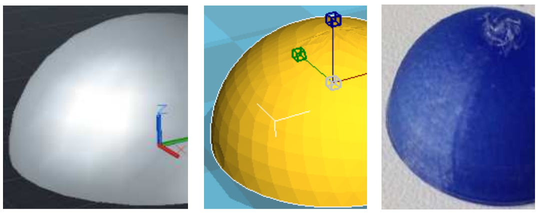
a b c

Fig. 18. SUBDIVS surface with 10 subdivision of surface: *a* – CAD model; *b* – .stl model; *c* – finite piece.



a b c

Fig. 19. SUBDIVS surface with 30 subdivision of surface: *a* – CAD model; *b* – .stl model; *c* – finite piece.



a b c

Fig. 20. SOLID object: *a* – CAD model; *b* – .obj model; *c* – finite piece.

The characteristics of the printing process for the finite piece from Fig. 18: printing time – 16 min; 0.26 m of filament used; the resulting piece has 2 g; workpiece dimensions are $w \times d \times h$: 20 mm × 20 mm × 10 mm;

The characteristics of the printing process for the finite piece from Fig. 19: printing time – 16 min; 0.26 m of filament used; the resulting piece has 2 g; workpiece dimensions are $w \times d \times h$: 20 mm – 19.9 mm × 10 mm;

- SOLID object (Fig. 20);

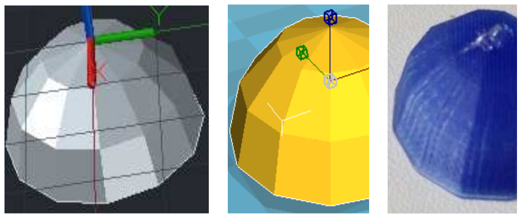
The characteristics of the printing process for the finite piece from Fig. 20 are: printing time – 17 min; 0.15 m of filament used; the resulting piece has 1 g; workpiece dimensions are $w \times d \times h$: 20 mm × 20 mm × 10 mm; radius of object in CAD application is 20 mm.

- MESH surface (Figs. 21, 22, 23 and 24);

The printing process characteristics for the finite piece from Fig. 21 are: printing time – 11 min; 0.15 m of filament used; the resulting piece has 1 g; workpiece dimensions are $w \times d \times h$: 19.9 mm × 19.9 mm × 9.9 mm; radius of object in CAD application is 20 mm.

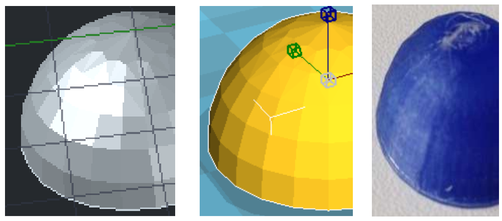
The characteristics of the printing process for the finite piece (Fig. 22) are: printing time – 11 min; 0.14 m of filament used; the resulting piece has 1 g; workpiece dimensions are $w \times d \times h$: 18.3 mm × 18.3 mm × 9.5 mm; radius of object in CAD application is 20 mm.

The characteristics of the printing process for the finite piece in Fig. 23 are: printing time – 11 min; 0.14 m of filament used; the resulting piece has 1 g; workpiece dimensions are $w \times d \times h$: 18.6 mm × 18.3 mm × 9.6 mm; radius of object in CAD application is 20 mm.



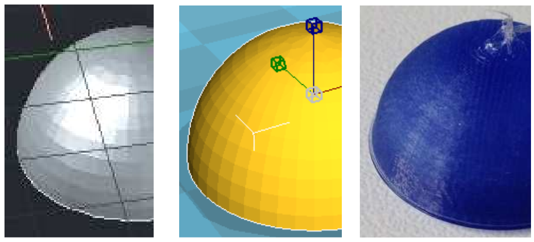
a b c

Fig.21. MESH surface: *a* – CAD model; *b* – .stl model; *c* – finite piece.



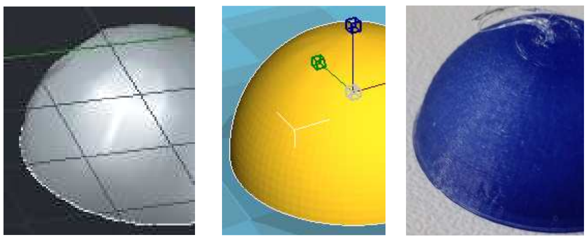
a b c

Fig. 22. MESH surface with 1 level of mesh smooth: *a* – CAD model; *b* – .stl model; *c* – finite piece.



a b c

Fig. 23. MESH surface with 2 level of mesh smooth: *a* – CAD model; *b* – .stl model; *c* – finite piece.



a b c

Fig. 24. MESH surface with 3 level of mesh smooth: *a* – CAD model; *b* – .stl model; *c* – finite piece.

Fig. 25. Supporting structure.

The characteristics of the printing process for the finite piece from Fig. 24: printing time – 11 min; 0.14 m of filament used; the resulting piece has 1 g; workpiece dimensions are $w \times d \times h$: 18.6 mm ×18.3 mm × 9.5 mm; radius of object in CAD application is 20 mm.

7. CONCLUSIONS

Starting from experimental research results presented above, the characteristics of the printing process were synthesized in Table 1, where: t – printing time; l – length of filament used; G – piece weight; w, d, h – workpiece dimensions; Ra – roughness of piece.

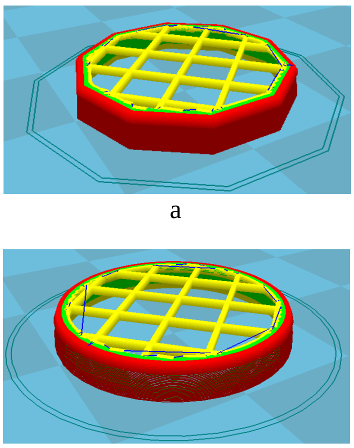
From the experimental data it can be seen an error in the volume varies depending on the type of surface model. Surface roughness depends on the smoothing of the surface results in the 3D geometric modeling.

To convert the .stl or obj. format to .gcode format, the user must position the pieces on the platform so that the piece is created with regard to the exclusion of any support structures Fig. 25.

Table 1

Characteristics of the printing process

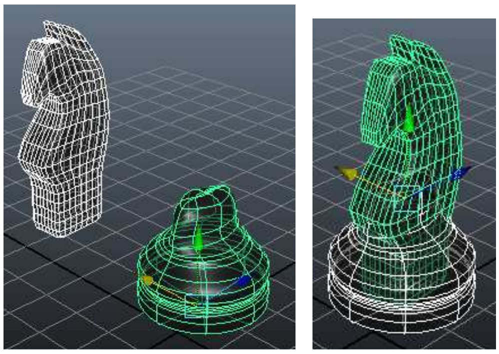
Surface	*t* [min]	*l* [m]	*G* [g]	*w* × *d* × *h* [mm]	*Ra* [μ]
NURBS (Fig. 14)	–	–	–	–	–
POLY (Figs. 15–17)	15	0.25	2	20×19×10	25
	16	0.26	2	20×20×10	12.5
	16	0.26	2	20×19.2×10	12.5
SUBDIVS (Fig. 18)	16	0.26	2	20×20×10	25
	16	0.26	2	20×19.2×10	12.5
SOLID (Fig. 19)	17	0.15	1	20×20×10	12.5
MESH (Figs. 20–23)	11	0.14	1	19.9×19.9×9.9	25
	11	0.14	1	18.3×18.3×9.5	25
	11	0.14	1	18.6×18.3×9.6	12.5
	11	0.14	1	18.6×18.3×9.5	12.5



a

b

Fig. 26. Perimeter of the layers: *a* – poly surface; *b* – subdivs surface.



a b

Fig. 27. POLY surface with 30 subdivision of surface: *a* – individual objects; *b* – overlapping objects.

However, if support structures are needed, their number should be minimal so that their removal does not affect the external appearance of the piece.

Most appearance flaws arise from curve surfaces estimation errors caused by the layers fabrication method.

The piece finishing time depends on the surface type. The smoother is the exterior surface, the longer it takes to be finished because the layers' perimeter increases (Fig. 26).

The format .stl or mesh converted pieces require post-processing operations. The piece in Fig. 20 is closest to a smooth surface, without major flaws.

Simultaneously overlapped objects, converted from a CAD file cannot be printed (Fig. 27).

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