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ORIGINAL ARTICLE

Experimental analysis of properties of materials for rapid prototyping

Ana Pilipović · Pero Raos · Mladen Šercer

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Abstract Rapid prototyping (RP) can substantially shorten the time and reduce the cost of developing a new product from the initial idea to production. Rapid prototyping can help in recognizing the basic defects whose subsequent correction may prove very expensive, especially if they have already been made when the product is ready for production. There are also many restrictions of RP procedures, primarily in the number of available materials and their properties, which may differ significantly from the properties of end product materials. In this work, based on the stipulated standards of the 3D printing machines (*ZPrinter 310 Plus*) and the hybrid *Polyjet* technique (*Objet Eden 330*), adequate test specimens were made. Furthermore, with adequate equipment, we carried out the analysis of the dimensions, roughness of surfaces, and mechanical properties of prototype test specimens. Then, based on the data obtained by testing of properties, we provided a critical commentary regarding the data stipulated by their producers.

Keywords 3D printing · Hybrid Polyjet technique · Roughness of surface · Mechanical properties of materials

A. Pilipović (✉) · M. Šercer
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Section for Polymer Processing,
Ivana Lučića 5,
10002 Zagreb, Croatia
e-mail: ana.pilipovic@fsb.hr

P. Raos
University of Osijek,
Mechanical Engineering Faculty in Slavonski Brod,
Trg Ivane Brlić Mažuranić 2,
35000 Slavonski Brod, Croatia

1 Introduction

Rapid prototyping (RP) is a procedure of producing models. There are various methods of rapid prototyping. The main advantage lies in the speed of producing physical prototypes as well as almost unlimited complexity of geometry. RP procedures do not require planning during the process, specific equipment for work with materials, transport between workplaces, etc. However, compared with CNC processing, the main drawback of these processes is that they are currently limited to fewer materials. Therefore, CNC machines can be used to process the majority of materials, including metals. Furthermore, the physical objects made by rapid prototyping are used mainly as prototypes or models for other production procedures. The objective of the work was to find out the actual possibilities of RP procedures and materials for achieving maximal precision and accuracy of prototype dimensions.

2 Experiment scheme

The test specimens were made by 3D printing procedures on the *ZPrinter 310 Plus* and by *the Polyjet* procedure on the *Objet Eden 330* machine. The materials used for the test specimens made on the *Objet Eden 330* are *VeroBlack*, *VeroBlue* and *FullCure 720*, while the *ZPrinter 310 Plus* machine uses *zp 102* powder, *zb 56* binding agent and *Loctite 406* and *Loctite Hysol 9483 A&B* reinforcers glue. The technical characteristics of the *ZPrinter 310 Plus* and *Objet Eden 330* can be found in the literature [1, 2].

In determining the dimensions of the test specimens, we used the Mitutoyo digital caliper, with the measurement range 0–150/0.01 mm.

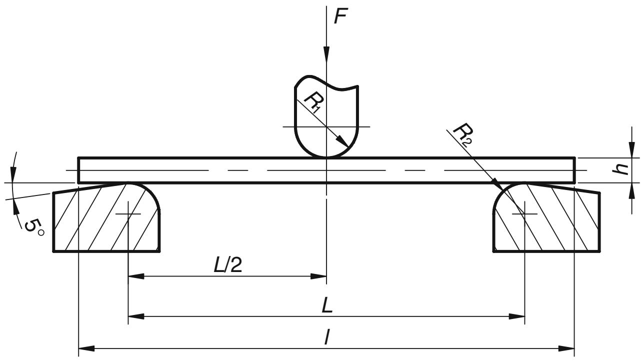

Fig. 1 Shape of test specimen for flexural testing

A Perthometer S8P instrument was used to test the surface roughness. The value of roughness is usually measured regarding the mean reference line of the profile of uneven areas *m*, which divides the profile so that within the measurement length *l* the value of all the squares of profile deviation from that line is minimal. The surface roughness is determined perpendicularly to the direction of production. Measurement is performed at three places (at the beginning, in the middle, and at the end of the test specimen). From the obtained values of the parameters of surface roughness, the arithmetic mean $\overline{x}$ and the estimated standard deviation S have to be calculated and determined. The roughness parameters are determined from the literature [3–6].

To determine the mechanical properties the Messphysik Beta 50-5 tester shall be used. Tests were performed at a temperature of 20°C.

3 Shapes and materials of test specimens

3.1 Shape of test specimen for determining flexural properties [7]

The flexural properties of rigid and semi-rigid polymers in defined conditions are determined according to standard ISO 178: 2001. The tests carried out on test specimens of different dimensions, or those prepared in different conditions may cause results that are not comparable. Other factors, such as testing speed and the condition of test specimens, can also influence the results of flexural testing.

Three-point testing is applied, i.e., the test specimen (Fig. 1) has to be supported by two supports and loaded in the middle by force F, until the test specimen fractures or until the deflection reaches certain values. Table 1 shows dimensions of load, support and test specimens stipulated by the standard.

A minimum of five test specimens are used. The testing speed in the specimens of thickness ≤3.5 mm is 1 mm/min, and for other thicknesses higher speeds are used.

Table 1 Dimensions of loading, support, and flexural test specimen

Loading and supports	Dimensions
Loading radius	R_1=5±0.1 mm
Support radii	R_2=2±0.2 mm — for test specimens of thickness ≤3 mm
	R_2=5±0.2 mm — for test specimens of thickness >3 mm
Test specimen	
Length	l=80±2 mm
Width	b=10±0.2 mm
Thickness	h=4±0.2 mm

Table 2 Dimensions of tensile test specimens

	Dimensions [mm]
l_3 = total length	≥150(1)
l_1 = length of the narrow parallel part	80±2
r = radius	20÷25
l_2 = distance between expanded parallel part	104÷113(2)
b_2 = width at the end	20±0.2
b_1 = width of the narrow end	10±0.2
h = thickness	4±0.2
L_0 = measurement length	50±0.5
L = initial distance between the machine jaws	115±1

(1) for some materials the length has to be increased (e.g., $l3$=200 mm) to avoid fracture or sliding in the jaws of the testing machine
(2) In dependence on $l1$, r, $b1$ and $b2$, but within the tolerance limits

3.2 Shape of test specimen for determining tensile properties [8]

The tensile properties of rigid and semi-rigid polymers are determined according to standard ISO 527: 1993. Table 2 presents the dimensions of the tensile test specimens.

For measuring the elasticity modulus, the testing speed has to be 1 mm/min. Figure 2 shows the shape of the test specimen for tensile testing.

3.3 Materials used in the 3D printing technique and the Polyjet procedure

Test specimens made by the 3D printing technique using the *ZPrinter 310 Plus* machine have been made of *zp 102*

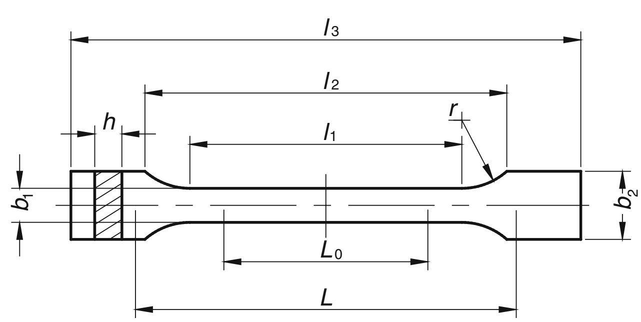

Fig. 2 Shape of test specimen for tensile testing

Fig. 3 Jaws for testing the tensile properties

powder, *zb 56* binding agent and reinforced by *Loctite 406* and *Loctite Hysol 9483 A&B* adhesive. The time necessary for printing test specimens was 31 minutes, and another 45 minutes was required for cleaning and reinforcing. The white test specimens were reinforced by cyanoacrylate *Loctite 406*, whereas the yellowish ones by epoxy resin *Loctite Hysol 9483 A&B*.

The *zp 102* powder is stable, but it should not be combined with acids, strong oxidants, steel, aluminium, copper and zinc. The *zb 56* binding agent is stable, but should not be combined with strong oxidizing or reducing compounds [1]. The *Loctite 406* reinforcing agent is based on low-viscosity cyanoacrylate and rapid crosslinking of polymers. However, reinforcement depends on the basic material, accelerators, and humidity. *Loctite Hysol 9483 A&B* reinforcing agent is a low-viscosity epoxy reinforcing agent. Once it is mixed with the base material it crosslinks at room temperature with minimal shrinkage and forms a transparent adhesive layer at the surface with high flexural toughness. When crosslinking is complete, the epoxy resin is stabilized by many chemicals and solvents [9].

Many more materials are available in the 3D printing technique, and together with their characteristics they are given in the literature [1, 10].

Test specimens produced by the *Polyjet* technique using the *Objet Eden 330* are made of the material produced by the company *Objet*: *VeroBlack* (black test specimens), *VeroBlue* (blue test specimens) and *FullCure 720* (transparent test specimens). The time necessary for the production of all test specimens of a single material is about 70 minutes, with another 10 minutes for cleaning.

FullCure 720 is a transparent acryl photopolymer suitable for rigid models. The advantages of this material include no subsequent machining necessary, tensile strain at

Fig. 4 Jaws for testing flexural properties

break is 20%, good flexural toughness and the possibility of machining, drilling and chroming. *Vero* materials are opaque materials in colour that allow the production of fine details and reduce the need for dying. They have excellent flexural toughness and flexural modulus. *VeroBlack* is a material with high flexural modulus and high stability to humidity, which makes it suitable for many applications. The characteristics of *FullCure 720* and *VeroBlue* materials stipulated by the manufacturer can be found in literature [2].

For other procedures that have not been the basis of this work, the available materials and their characteristics have been given in the literature as follows: stereolithography (SLA) [10, 11], selective laser sintering (SLS) [10, 12], fused deposition modeling (FDM) [10, 11, 13].

4 Experimental system

The prototypes saved in the .stl file format have been produced on the *ZPrinter 310 Plus* and *Objet Eden 330* rapid prototyping machines.

ZPrinter 310 Plus produces models directly from the digital data. The machine is fast and simple and allows fast and inexpensive production of models and functional parts for testing. The machine is ideal for office use [1].

Eden 330 produces fast and accurately 3D prototypes of high quality. It allows application in various industries and reduces the time of production. The models produced by Eden 330 are smooth, durable, with fine details and excellent surface quality [2].

The dimensions of test specimens were determined with the Mitutoyo digital caliper, with a measuring range 0–150/0.01 mm.

A Perthometer S8P instrument was used for testing the surface roughness. The measurements were carried out by probe for external guidance FRW-750. The following are the essential values of the machine:

- Marginal value of GS electrical filter (marginal wavelength for the roughness profile) λ_c=0.8 mm.
- Reference length L_t=5.6 mm.

For determining the mechanical properties the Messphysik Beta 50-5 testing machine is used. The control unit is an EDC 100, with a maximum loading force of 50 kN.

The testing was carried out at the temperature of 18.5°C.

For determining the tensile properties the test specimen is clamped by the jaws of the tensile testing machine

Table 3 Dimensions for determining flexural properties of test specimens

3D Printing							
Loctite 406	l [mm]	b [mm]	h [mm]	*Loctite Hysol*	l [mm]	b [mm]	h [mm]
1	80.84	10.86	4.45	1	80.56	10.62	4.37
2	80.95	10.78	4.38	2	80.66	10.66	4.25
3	80.92	10.84	4.30	3	80.71	10.57	4.35
4	80.91	10.85	4.46	4	80.69	10.70	4.30
5	80.99	10.71	4.33	5	80.66	10.63	4.33
6	80.86	10.76	4.47	6	80.62	10.61	4.28
$\bar{x}$	80.91	10.80	4.4		80.65	10.63	4.31
S	0.056	0.06	0.073		0.054	0.044	0.045
Polyjet technique							
VeroBlack	l [mm]	b [mm]	h [mm]	*VeroBlue*	l [mm]	b [mm]	h [mm]
1	80.12	10.13	4.02	1	80.12	10.08	4.01
2	80.18	10.11	4.02	2	80.10	10.08	4.01
3	80.15	10.12	4.02	3	80.11	10.09	4.02
4	80.12	10.11	4.02	4	80.13	10.09	4.01
5	80.16	10.12	4.03	5	80.10	10.09	4.02
$\bar{x}$	80.15	10.12	4.02		80.11	10.09	4.01
S	0.026	0.009	0.005		0.013	0.007	0.007
FullCure	l [mm]	b [mm]	h [mm]				
1	80.22	10.07	3.97				
2	80.19	10.04	4.03				
3	80.23	10.06	4.01				
4	80.25	10.05	3.98				
5	80.27	10.05	3.98				
$\bar{x}$	80.23	10.05	3.99				
S	0.03	0.012	0.025				

Table 4 Dimensions for determining tensile properties of test specimens

3D Printing									
Loctite 406	l_3 [mm]	h [mm]	b_1 [mm]	b_2 [mm]	*Loctite Hysol*	l_3 [mm]	h [mm]	b_1 [mm]	b_2 [mm]
1	150.87	4.41	10.82	20.91	1	150.57	4.28	10.56	20.59
2	150.91	4.44	10.81	20.91	2	150.53	4.20	10.60	20.62
3	150.10	4.41	10.73	20.82	3	150.61	4.27	10.66	20.68
4	150.87	4.45	10.75	20.83	4	150.65	4.30	10.59	20.62
5	150.77	4.26	10.83	20.95	5	150.51	4.28	10.56	20.68
6	150.90	4.49	10.81	20.80	6	150.55	4.29	10.59	20.66
$\bar{x}$	150.74	4.41	10.79	20.87		150.57	4.27	10.59	20.64
S	0.316	0.079	0.04	0.061		0.052	0.036	0.037	0.037
Polyjet technique									
VeroBlack	l_3 [mm]	h [mm]	b_1 [mm]	b_2 [mm]	*VeroBlue*	l_3 [mm]	h [mm]	b_1 [mm]	b_2 [mm]
1	150.28	4.03	10.08	20.04	1	150.17	4.01	10.01	20.00
2	150.28	4.01	10.04	20.04	2	150.19	4.00	9.98	20.03
3	150.29	4.02	9.99	20.07	3	150.21	4.00	10.00	19.98
4	150.27	4.00	10.06	20.01	4	150.21	3.99	10.00	19.97
5	150.26	4.00	10.12	20.08	5	150.21	4.03	9.97	20.02
$\bar{x}$	150.28	4.01	10.06	20.05		150.2	4.01	9.99	20.00
S	0.012	0.013	0.048	0.028		0.018	0.016	0.017	0.025
FullCure	l_3 [mm]	h [mm]	b_1 [mm]	b_2 [mm]					
1	150.18	3.99	9.99	19.97					
2	150.22	4.01	10.01	20.01					
3	150.19	4.02	10.00	20.02					
4	150.15	4.01	9.99	19.99					
5	150.22	4.00	9.98	19.99					
$\bar{x}$	150.19	4.01	9.99	19.99					
S	0.03	0.012	0.012	0.021					

(Fig. 3) and extended with force *F*, at speed v=1 mm/min, as defined by standard ISO 527:1993. For the testing of flexural properties, the jaws (Fig. 4) differ, since the test specimen has to be supported by two supports and loaded in the middle by force *F*. The testing speed v=2 mm/min.

5 Results of analyzing the rapid prototyping materials properties

5.1 Dimensions and testing of the test specimens surface roughness parameters

Table 3 presents the dimensions of test specimens for flexural testing, whereas Table 4 shows the dimensions of test specimens for tensile testing.

The obtained results of measurement (Table 3) show that the values of the dimensions obtained on *ZPrinter 310 Plus* (*Loctite 406* and *Loctite Hysol*) are greater than on *Objet Eden 330* (*VeroBlack*, *VeroBlue* and *FullCure*). For length l the deviation of 80±2 mm is stipulated, which means that all the dimensions are within tolerance limits, whereas the width b (10±0.2 mm) and thickness h (4±0.2 mm) on *Loctite 406* and *Loctite Hysol* test specimens exceed the tolerance limits. Such deviations occur since the material is rougher (i.e., powder particles), but the assumption is that they will not affect further testing of mechanical properties.

The values of dimensions (Table 4) obtained on *ZPrinter 310 Plus* (*Loctite 406* and *Loctite Hysol*) are greater than on *Objet Eden 330* (*VeroBlack*, *VeroBlue* and *FullCure*), because the *Objet Eden 330* produces layers of 16 µm, and *the ZPrinter 310 Plus* of 89 µm. The length l_3 can be ≥150 mm, so that all dimensions are within limits, whereas thickness h (4±0.2 mm), width b_1 (10±0.2 mm) and b_2 (20± 0.2 mm) both on *Loctite 406* and *Loctite Hysol* test specimens exceed the tolerance limits.

On *Loctite 406* test specimens the arithmetic mean $\bar{x}$ of the mean arithmetic deviation of profile R_a=15.68 µm,

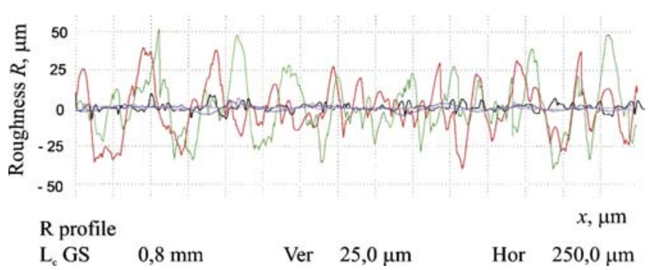

Fig. 5 Surface roughness of all test specimens

Table 5 Flexural properties of *Loctite 406* test specimens

Loctite 406								
	E_f [GPa]	A_0 [mm^2]	F_{max} [N]	σ_{fM} [MPa]	ε_{fM} [%]	S_{max} [mm]	σ_{fp} [MPa]	ε_{fp} [%]
1	2.791	48.33	32.60	14.55	0.684	1.050	14.36	0.75
2	2.505	47.22	30.35	14.09	0.716	1.117	13.04	0.822
3	2.840	46.61	36.00	17.24	0.881	1.399	16.15	0.982
4	2.928	48.39	33.75	15.01	0.678	1.037	14.54	0.743
5	2.616	46.37	29.25	13.98	0.671	1.058	13.43	0.769
6	2.179	48.10	40.50	18.08	0.892	1.363	17.08	0.911
$\bar{x}$	2.643	47.50	33.74	15.49	0.754	1.171	14.77	0.83
S	0.275	0.893	4.093	1.739	0.104	0.166	1.565	0.097

which means that the level of roughness is N10. The surface roughness parameters of *Loctite Hysol* test specimens are somewhat lower than in case of test specimens reinforced by cyanoacrylate. The arithmetic mean $\bar{x}$ of the mean arithmetic deviation of profile R_a=13.99 μm, which means that the level of roughness is N10. Substantial difference is noticed already in *VeroBlack* test specimens. Here the arithmetic mean $\bar{x}$ of the mean arithmetic deviation of profile is only R_a=1.64 μm, which is by 88% lower than R_a *Loctite Hysol* test specimen. The level of roughness is N7. The roughness parameters in *VeroBlue* test specimens are even lower, which can be seen also in Fig. 5. The level of roughness is the same as in *VeroBlack* test specimens N7. *FullCure* test specimens show the best roughness of surface. The mean arithmetic deviation of profile R_a=1.00 μm, which is in comparison with the test specimens made by *3D printing* an as much as 94% lower value. The roughness level of N6 is determined according to R_a. It should also be noted that the surface roughness depends as well on the position of the test specimen in the instrument work area.

5.2 Testing of flexural properties

Test specimens of *zp 102* powder fractured during bending, whereas this was not the case with other materials, so that flexural stress at break σ_{fp} and flexural strain at break ε_{fp} are not calculated for them. *Loctite 406* and *Loctite Hysol* test specimens fractured before deflection stipulated according to standard ISO 178: 2001 of S_c=1.5×h=6 mm, so that the flexural stress at conventional deflection σ_{fC} is not determined for them. The testing was done at a speed of 2 mm/min. Tables 5, 6, 7, 8 and 9 show the flexural properties of the test specimens.

Flexural stress is calculated according to the Eq. (1) [7]:

$$\sigma_f = \frac{3F \cdot L}{2b \cdot h^2} \quad (1)$$

where σ_f [MPa] = flexural stress, F [N] = force, L=16 h= 16×4=64 [mm] = measuring length, b [mm] = width, h [mm] = thickness.

Flexural strain is calculated according to Eqs. (2) and (3) [7]:

$$\varepsilon_f = \frac{6S \cdot h}{L^2} \quad (2)$$

$$\varepsilon_f = \frac{600S \cdot h}{L^2}\% \quad (3)$$

where ε_f [%] = flexural strain, S [mm] = deflection, h [mm] = thickness, L [mm] = measuring length.

Table 6 Flexural properties of *Loctite Hysol* test specimens

Loctite Hysol								
	E_f [GPa]	A_0 [mm^2]	F_{max} [N]	σ_{fM} [MPa]	ε_{fM} [%]	S_{max} [mm]	σ_{fp} [MPa]	ε_{fp} [%]
1	3.230	46.41	33.70	15.95	0.531	0.829	15.95	0.571
2	3.168	45.30	25.85	12.89	0.404	0.648	12.34	0.436
3	2.929	45.98	24.75	11.88	0.511	0.802	10.08	0.558
4	2.534	46.01	28.10	13.64	0.539	0.855	12.01	0.547
5	2.718	46.03	31.50	15.17	0.520	0.820	14.62	0.564
6	3.337	45.41	28.10	13.88	0.524	0.835	12.77	0.538
$\bar{x}$	2.986	45.86	28.67	13.90	0.505	0.798	13.08	0.536
S	0.315	0.421	3.385	1.482	0.050	0.076	1.876	0.05

Table 7 Flexural properties of *VeroBlack* test specimens

VeroBlack							
	E_f [GPa]	A_0 [mm^2]	F_{max} [N]	σ_{fM} [MPa]	ε_{fM} [%]	S_{max} [mm]	σ_{fc} [MPa]
1	2.430	40.72	133.8	78.46	4.856	8.246	68.58
2	2.493	40.64	132.7	77.97	4.848	8.233	68.07
3	2.294	40.68	134.9	79.22	5.067	8.604	68.65
4	2.234	40.64	132.7	77.97	5.082	8.630	66.75
5	2.326	40.30	136.1	80.45	5.161	8.742	68.48
$\bar{x}$	2.355	40.57	134.04	78.81	5.003	8.491	68.11
S	0.105	0.171	1.469	1.048	0.142	0.235	0.791

For the calculation of the flexural modulus, the deflections S_1 and S_2 are used, which correspond to the flexural strain values ε_{f1}=0.0005 and ε_{f2}=0.0025 using Eqs. (4) (5): [7]

$$S_I = \frac{\varepsilon_{fi} \cdot L^2}{6h} \qquad I = 1,2 \tag{4}$$

$$E_f = \frac{\sigma_{f2} - \sigma_{f1}}{\varepsilon_{f2} - \varepsilon_{f1}} \tag{5}$$

where *S* [mm] = deflection, ε_f [%] = flexural strain, *L* [mm] = measuring length, *h* [mm] = thickness, E_f [MPa] = flexural modulus, σ_{f1} [MPa] = flexural stress measured at deflection S_1, σ_{f2} [MPa] = flexural stress measured at deflection S_2.

Test specimens made of *zp 102* powder break at strain ε_{fp} from 0.5 to 1%. Test specimens made of materials *VeroBlack*, *VeroBlue* and *FullCure* did not fracture to deflection S_c=1.5×*h*=6 mm stipulated by the standard, but rather the specimen falls in between the supports at: σ_{fp}= 33.7 MPa, ε_{fp}=17.6 % and deflection *S*=30 mm (Figs. 6 and 7).

Test specimen of powder, binding and reinforced by cyanoacrylate (*Loctite 406* test specimen) shows slightly better properties than with epoxy resin (*Loctite Hysol* test specimen). Its mean value of maximal flexural strength is σ_{fM}=15.49 MPa, compared to *Loctite Hysol* test specimen σ_{fM}=13.9 MPa.

In test specimens made on the *Objet Eden* the best properties are shown by the *FullCure* test specimens. Here the mean value of maximal flexural strength is σ_{fM}= 95.66 MPa. *VeroBlue* material has a somewhat lower value σ_{fM}=86.77 MPa, and *VeroBlack* even lower σ_{fM}= 78.81 MPa.

The analysis of flexural properties (Fig. 8) shows that the best properties belong to the test specimens made of *FullCure* materials. Compared to the properties declared by the producers [2] flexural strength σ_{fM} is somewhat higher, whereas flexural modulus E_f is higher by an average of 100 MPa.

Table 8 Flexural properties of *VeroBlue* test specimens

VeroBlue							
	E_f [GPa]	A_0 [mm^2]	F_{max} [N]	σ_{fM} [MPa]	ε_{fM} [%]	S_{max} [mm]	σ_{fc} [MPa]
1	2.475	40.42	148.4	87.92	5.272	8.975	73.95
2	2.524	40.42	145.1	85.94	4.902	8.346	73.95
3	2.565	40.56	147.4	86.75	5.041	8.561	74.83
4	2.527	40.46	146.2	86.50	4.834	8.229	74.52
5	2.479	40.56	147.4	86.75	4.858	8.250	74.83
$\bar{x}$	2.514	40.48	146.9	86.77	4.981	8.472	74.42
S	0.037	0.071	1.273	0.722	0.181	0.310	0.444

Table 9 Flexural properties of *FullCure* test specimens

FullCure							
	E_f [GPa]	A_0 [mm^2]	F_{max} [N]	σ_{fM} [MPa]	ε_{fM} [%]	S_{max} [mm]	σ_{fc} [MPa]
1	2.628	39.98	158.6	95.93	4.908	8.439	81.63
2	2.596	40.46	164.2	96.67	4.962	8.405	83.43
3	2.639	40.34	155.2	92.10	4.738	8.066	80.09
4	2.754	39.80	159.7	96.79	4.916	8.431	81.79
5	2.798	39.80	159.7	96.79	4.962	8.511	81.79
$\bar{x}$	2.683	40.08	159.48	95.66	4.897	8.37	81.75
S	0.088	0.308	3.22	2.020	0.092	0.175	1.183

Fig. 6 Maximal bending of *VeroBlack* materials

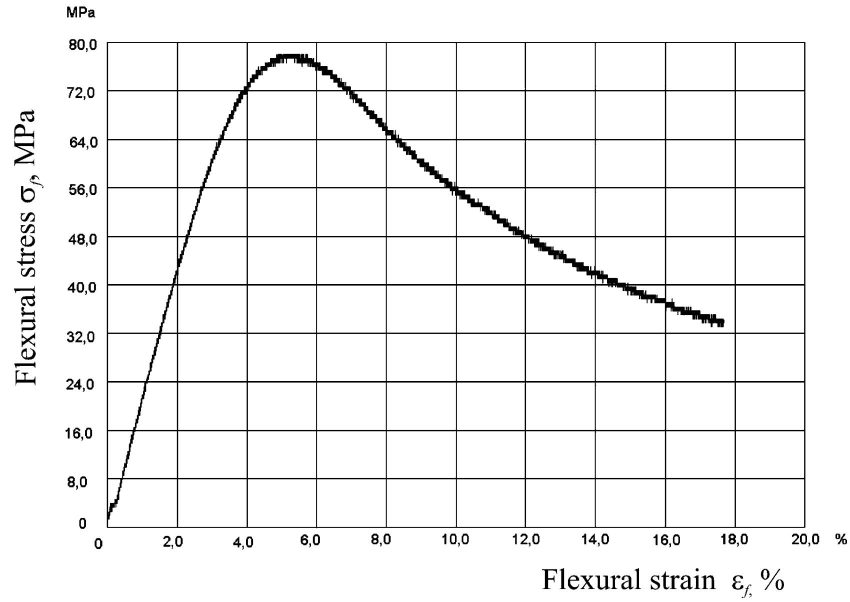

Fig. 7 Diagram of maximum *flexural stress — strain* of *VeroBlack* materials

In case of *Vero* material the producer guarantees in *VeroBlack* the highest flexural modulus. The performed analysis shows that in this group of materials the flexural modulus is the lowest. In case of *VeroBlue* materials the flexural strength σ_{fM} and flexural modulus E_f are between the *VeroBlack* and *FullCure* materials.

The lowest flexural properties are featured by the test specimens of powder made by *3D printing* (*Loctite 406* and *Loctite Hysol* test specimens). In comparison with *FullCure* and *Vero* materials the flexural strength σ_{fM} is very low, as low as σ_{fM}=15 MPa, but the flexural modulus E_f is similar. It should be noted that their properties depend on the hardening agent which has been added to the powder and binding agent. Better properties are featured by the reinforcing agent cyanoacrylate.

5.3 Testing of tensile properties

The testing of tensile properties was carried out at a speed of 1 mm/min.

Tensile stress is calculated according to Eq. (6) [8]:

$$R = \frac{F}{A} \tag{6}$$

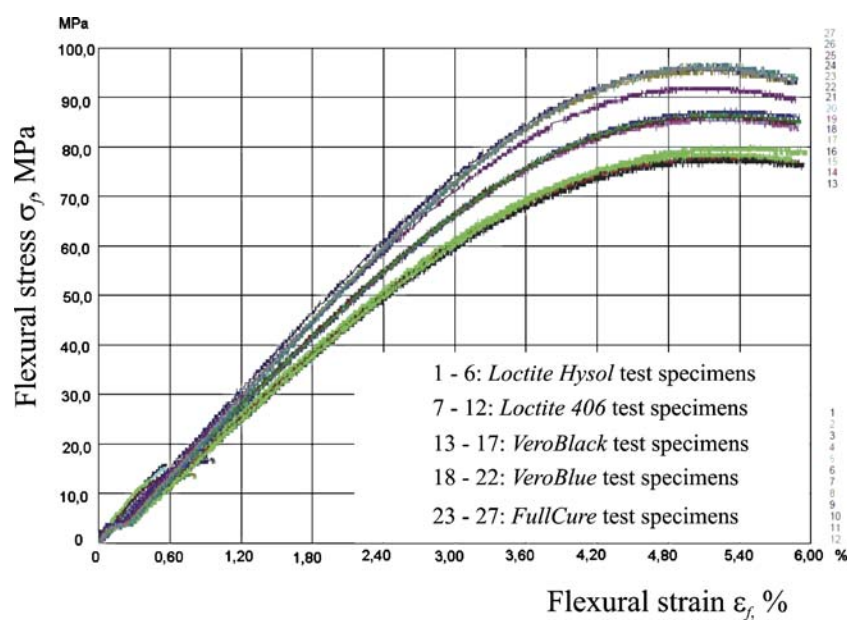

Fig. 8 Diagram of *flexural stress — strain* of all materials

Table 10 Tensile properties of *Loctite 406* test specimens

Loctite 406							
	E [GPa]	A_0 [mm^2]	F_m [N]	R_M [MPa]	R_p [MPa]	ε_K [%]	ε_p [%]
1	3.645	47.72	321.6	6.740	6.693	0.353	0.537
2	2.708	48.00	304.8	6.349	6.349	0.152	0.387
3	3.623	47.32	275.5	5.822	5.798	0.138	0.298
4	4.463	47.84	343.0	7.169	7.169	0.260	0.421
5	3.078	46.14	262.0	5.679	5.630	0.157	0.341
6	2.935	48.54	307.0	6.325	6.279	0.322	0.537
$\bar{x}$	3.409	47.59	302.3	6.347	6.32	0.230	0.420
S	0.638	0.816	29.66	0.557	0.568	0.094	0.100

where R [MPa] = tensile stress, F [N] = force, A [mm^2] = area.

Strain is calculated according to the Eq. (7) [8]:

$$\varepsilon = \frac{\Delta L_0}{L_0} \tag{7}$$

where ε [%] - strain, ΔL_0 [mm] = elongation, L_0 [mm] = measuring length of the test specimen.

Modulus of elasticity in tensile is calculated according to the Eq. (8) [8]:

$$E = \frac{R_2 - R_1}{\varepsilon_2 - \varepsilon_1} \tag{8}$$

where R_2 and R_1 = tensile stress, ε_2=0.0025 = strain, ε_1= 0.0005 = strain.

Tables 10, 11, 12, 13 and 14 present the calculated values of tensile properties of test specimens.

The test specimen of powder, binding agent and reinforced by cyanoacrylate (*Loctite 406* test specimen) features a little better properties than with epoxy resin (*Loctite Hysol* test specimen). Its mean value of maximal tensile strength is R_M=6.347 MPa, compared to *Loctite Hysol* test specimen R_M=5.368 MPa. At the same time the tensile stress at break R_p is higher in *Loctite 406* test specimens (Tables 10 and 11).

Table 11 Tensile properties of *Loctite Hysol* test specimens

Loctite Hysol							
	E [GPa]	A_0 [mm^2]	F_m [N]	R_M [MPa]	R_p [MPa]	ε_K [%]	ε_p [%]
1	3.897	45.20	218.1	4.827	4.827	0.058	0.182
2	2.902	44.52	257.5	5.784	5.784	0.095	0.294
3	2.515	45.52	238.4	5.237	5.212	0.078	0.285
4	2.472	45.54	253.0	5.556	5.507	0.089	0.312
5	2.497	45.30	246.3	5.436	5.411	0.097	0.314
6	2.819	45.43	219.3	4.827	4.827	0.103	0.274
$\bar{x}$	2.641	45.262	242.9	5.368	5.348	0.092	0.296
S	0.203	0.425	15.03	0.362	0.357	0.009	0.017

Loctite Hysol test specimen 1 features very large deviations and is therefore eliminated from further analysis

Table 12 Tensile properties of *VeroBlack* test specimens

VeroBlack							
	E [GPa]	A_0 [mm^2]	F_m [N]	R_M [MPa]	R_p [MPa]	ε_K [%]	ε_p [%]
1	3.612	40.62	1868	45.98	33.00	7.047	7.960
2	2.794	40.26	1826	45.36	33.24	6.090	7.280
3	2.905	40.16	1859	46.29	33.82	6.466	7.630
4	2.796	40.24	1842	45.77	33.25	6.524	7.714
5	2.723	40.48	1875	46.31	34.42	5.610	6.875
$\bar{x}$	2.966	40.35	1854	45.94	33.55	6.347	7.492
S	0.367	0.191	19.94	0.396	0.574	0.535	0.422

In test specimens made on *Objet Eden* the best tensile properties are featured by *FullCure* test specimens. In this case the mean value of maximal tensile strength is R_M=55.09 MPa. *VeroBlue* material has a somewhat lower value R_M=51.53 MPa, and *VeroBlack* still lower R_M= 45.94 MPa. In *VeroBlue* material the tensile stress at break is R_p=38.83 MPa, which means a bit higher than in *FullCure* R_p=38.68 MPa, whereas it is the lowest in *VeroBlack* R_p=33.55 MPa.

The analysis of tensile properties (Fig. 9) shows that the best properties are featured by the test specimens made of *FullCure* materials. Compared to the properties stipulated by the producers [2] tensile strength R_M is a bit lower, whereas the flexural modulus E is approximately the same. Tensile strain at break ε_p (literature 11) is much higher than the one obtained by analysis (ε_p=6.8%).

In *VeroBlue* materials the values guaranteed by the producers almost match with the obtained ones, except in case of tensile strain at break ε_p which is much higher (ε_p= 15–25%) than obtained by the analysis (ε_p=6.63%). *VeroBlack* material has the highest tensile modulus E= 2966 MPa in the group of materials made by *the Polyjet* technique.

Table 13 Tensile properties of *VeroBlue* test specimens

VeroBlue							
	E [GPa]	A_0 [mm^2]	F_m [N]	R_M [MPa]	R_p [MPa]	ε_K [%]	ε_p [%]
1	2.7	40.14	2088	52.02	37.59	5.626	7.019
2	2.726	39.92	2057	51.52	38.96	5.130	6.559
3	2.505	40.0	2049	51.22	41.94	4.347	6.022
4	2.459	39.9	2042	51.18	39.29	4.780	6.375
5	2.699	40.18	2077	51.69	36.35	5.828	7.175
$\bar{x}$	2.618	40.03	2063	51.53	38.83	5.142	6.630
S	0.125	0.127	19.32	0.348	2.097	0.606	0.471

Table 14 Tensile properties of *FullCure* test specimens

FullCure

	E [GPa]	A_0 [mm^2]	F_m [N]	R_M [MPa]	R_p [MPa]	ε_K [%]	ε_p [%]
1	2.561	39.86	2196	55.10	40.0	4.820	6.382
2	2.832	40.14	2210	55.05	36.56	5.904	7.195
3	2.073	40.20	2224	55.33	40.20	4.527	6.465
4	4.174	40.06	2198	54.88	36.41	6.7	7.572
5	2.416	39.92	2200	55.10	40.25	4.717	6.384
$\bar{x}$	2.811	40.04	2206	55.09	38.68	5.334	6.8
S	0.810	0.144	11.61	0.161	2.010	0.934	0.550

The worst properties of tension are featured by the test specimens of powder (*Loctite 406* and *Loctite Hysol* test specimens). Tensile strength R_M and tensile stress at break R_p are substantially lower than in *FullCure* and *Vero* materials (Tables 10 and 11), but the elasticity modulus E in *Loctite 406* test specimens is the highest of all the materials E=3409 MPa. Also, in the case of these properties the reinforcement agent affects the obtained results. Better properties are featured by the reinforcing agent cyanoacrylate.

6 Conclusion

Rapid prototyping allows production of parts of very complex shapes the production of which, until the occurrence of these techniques, had been limited. The rapid prototyping techniques have been developing intensively from day to day. Here, the limiting number is of the available materials and their properties, which substantially differ from the properties of materials of final products. Therefore, it is necessary to know the properties of the prototypes materials.

From the carried out analysis of dimensions, surface roughness and mechanical properties of materials of the prototype test specimens and production procedures the following may be concluded:

The results of measuring the dimensions of test specimens show that the *Objet Eden 330* instrument is more precise in production than the *ZPrinter 310 Plus*.

The surface of test specimens made of *zp 102*powder, *zb 56* binding agent and reinforced by *Loctite 406* cyanoacrylate or *Loctite Hysol 9483 A&B* epoxy resin is rougher than *VeroBlack* and *VeroBlue* material. *FullCure* material shows the lowest value of surface roughness.

The best mechanical properties belong to test specimens made of *FullCure*. For *Vero* material, the producer stipulates that *VeroBlack* has the highest flexural modulus, and still the analysis results show that it is the lowest one. In *VeroBlue* materials the producer's guaranteed values almost match the obtained ones. The worst mechanical properties are from the test specimens made of powder. However, their properties depend on the reinforcing agent which is added to powder or binding. Cyanoacrylate features better properties than epoxy resin.

In the *ZPrinter 310* some parameters may be changed (such as e.g., position of the model in the work space, layer thickness, ratio of saturation by binding etc.), in order to reduce the production time which also influences the properties of prototypes (strength, roughness, dimensions). In the *Objet Eden 330* the position of the model in the work area can be adjusted, as well as the production speed, which does not have any major influence on the properties of prototypes.

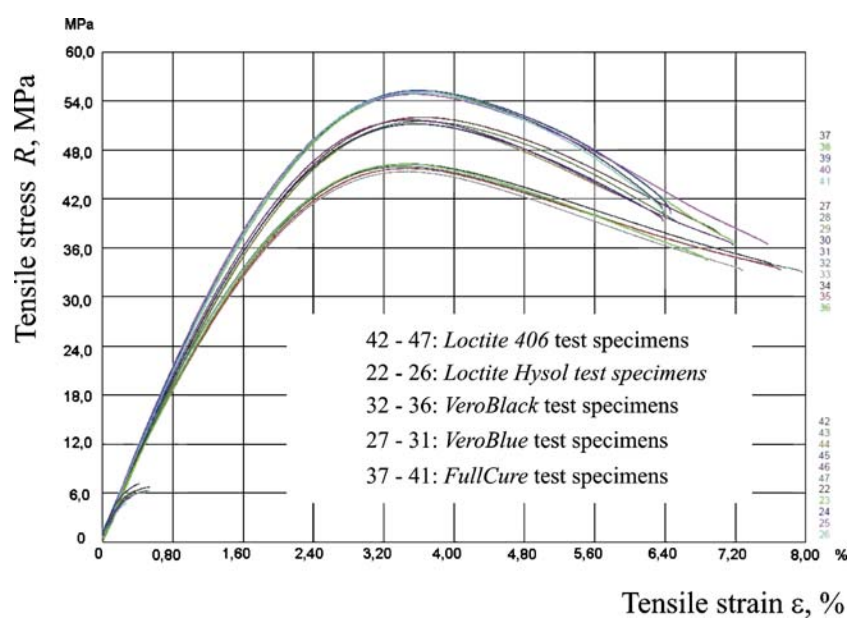

Fig. 9 Diagram *tensile stress — strain* of all materials

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