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INFLUENCE OF PROCESSING FACTORS ON THE TENSILE STRENGTH OF 3D-PRINTED MODELS

VPLIV PROCESNIH DEJAVNIKOV NA NATEZNO TRDNOST TRIDIMENZIONALNO TISKANIH MODELOV

Tomislav Galeta, Ivica Kladarić, Mirko Karakašić

J. J. Strossmayer University of Osijek, Mechanical Engineering Faculty in Slavonski Brod, Trg Ivane Brlić-Mažuranić 2, 35000 Slavonski Brod, Croatia
tgaleta@sfsb.hr

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Since the models produced with three-dimensional printing are not as strong as the ones made with the other rapid prototyping technologies, the main objective of this research was to determine the influence of selected processing factors on the tensile strength and to determine the factor combination that provides the highest strength. Test samples were prepared on a 3D printer with variations in the layer thickness, building orientation and infiltrant type. The secondary objective was to evaluate the application of more affordable alternative infiltrants used instead of genuine infiltrants. The results of the tensile test revealed that the strength of 3D-printed samples comes mainly from the infiltrants, but it may be additionally increased by selecting the best combination of the other two processing factors. The strength of the samples infiltrated with alternative infiltrants was equivalent to that obtained with genuine infiltrants, thus confirming the use of alternative infiltrants.

Keywords: rapid prototyping, three-dimensional printing, tensile strength

Modeli, ki so proizvedeni s tridimenzionalnim tiskanjem, niso tako močni v primerjavi z drugimi tehnologijami hitrega prototipiranja, zato je bil glavni cilj raziskave ugotoviti, kakšen vpliv imajo izbrani procesni dejavniki na natezno trdnost, in kombinacijo, ki zagotavlja največjo trdnost. Vzorci za preizkuse so bili pripravljeni na tridimenzionalnem tiskalniku s spreminjanjem debeline plasti, smeri nalaganja in vrste veziva. Dodaten cilj je bil oceniti uporabo dostopnejših nadomestnih vezivnih sredstev, namesto originalnih. Rezultati preizkusa natezne trdnosti so pokazali, da je trdnost 3D tiskanih vzorcev najbolj odvisna od vezivnega sredstva, mogoče pa jo je povečati z izbiro najboljše kombinacije drugih dveh procesnih dejavnikov. Trdnost vzorcev, ki so bili infiltrirani z alternativnimi vezivnimi sredstvi, je bila enakovredna tisti, pridobljeni z originalnimi vezivnimi sredstvi, kar potrjuje uporabo alternativnih vezivnih sredstev.

Ključne besede: hitro prototipiranje, tridimenzionalno tiskanje, natezna trdnost

1 INTRODUCTION

The models produced with three-dimensional printing (3DP) are not as strong as the ones made with the other rapid prototyping (RP) technologies. Several authors emphasized the issue of the 3DP strength in their researches. Pilipović et al.[1] compared the properties of the samples made with two similar RP procedures: the samples produced with "the stipulated standard 3DP procedure" showed mechanical properties that were inferior to those of the samples produced with the hybrid Polyjet procedure. The results obtained in that paper and frequent customer demands for better tensile properties motivated us to perform further research in order to improve the strength of the models produced on the considered model of 3DP machines. An initiative research was performed and its results were published in a master's degree thesis[2] and in our papers published in conferences.[3,4]

There is a constant effort of the researchers to improve the strength and other mechanical properties of 3DP models. This is evident from the number of recently published papers. Patirupanusara et al. performed studies to enhance the mechanical properties of 3DP specimens on the basis of polymethyl methacrylate.[5,6] Suwanprateeb found that the use of light-cured acrylate resin as an infiltrant can enhance the flexural modulus and the flexural strength of natural-polymer-based 3DP parts to be close to the general use of polymethyl methacrylate resin.[7] Chumnanklang et al. revealed that pre-coated particles would yield a stronger 3DP hydroxyapatite part.[8] Hydroxyapatite is widely used as a medical, highly biocompatible bone-substitute material. Furthermore, several researchers gave their contributions on the subjects closely related to the mechanical properties of 3DP models.[9–13]

The overall work on the enhancement of 3DP mechanical properties can also be noticed on the market. The manufacturers of 3DP systems frequently deliver new enhanced models of printers, together with improved materials, system software or improved alternative spare parts for the existing models. These efforts will reduce the damages to 3DP models that occur during exploration. However, from the 3DP owner's point of view, it should be stressed that most damages occur on green models, i.e., before post-processing and infiltration (**Figure 1**), although customers are usually not informed about such damages. In the previous research[2], the obtained average tensile strength of green samples was 0.95 MPa. However, if the samples were dried in the

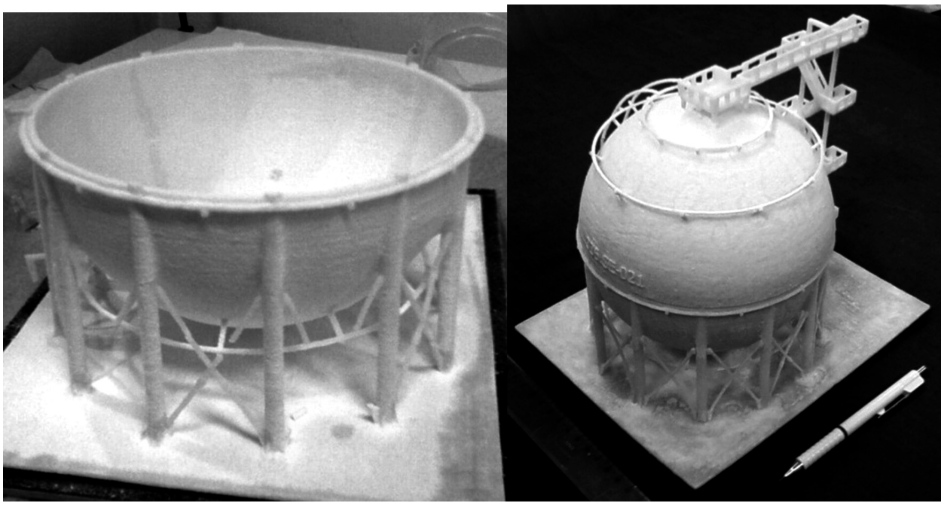

Figure 1: 3DP model of a spherical gas tank – damaged (left) and repaired with infiltration (right)
Slika 1: 3DP-model okroglega rezervoarja plina – poškodovan (levo) in popravljen z infiltriranjem (desno)

oven for at least two hours at 55 °C, the average tensile strength of green samples increased to 1.52 MPa.

Original equipment manufacturers (OEM) constantly make additional efforts to enhance the mechanical properties of the green 3DP model. OEM efforts result in new base materials, printer upgrades and a development of new 3DP machines.

The main objective of our research was to determine the influence of the selected 3DP processing factors on the tensile strength and to determine the factor combination that provides the highest strength. The secondary objective was to evaluate the application of the alternative infiltrants that we used instead of the genuine manufacturer's infiltrants for the considered 3DP system. If the obtained properties are equivalent, the use of the alternative infiltrants can help to reduce the printing costs and to acquire infiltrants from the more available alternative suppliers. For this purpose we carried out a set of experiments on the considered 3DP system.

2 TESTING THE EQUIPMENT AND SAMPLE MATERIALS

The 3D printer, used for these experiments, was model Z310, a product of Z Corporation. It is a low-cost, monochrome 3D printer suitable for the RP education or for small and medium-sized companies. The printer firmware version was 10.158 and the test samples were prepared in printer software ZPrint version 7.5.23[14,15] (**Figure 2**).

The considered 3D printer combines the layered approach of RP technologies and conventional ink-jet printing. It prints a binder fluid through a conventional ink-jet print head into the powder, one layer onto another, from the lowest model cross-section to the highest one (**Figure 3**). After printing, the printed models are dried in the building box (**Figure 4**), then removed from the powder bed, de-powdered with compressed air, dried in the oven and infiltrated for the maximum strength.

There are several base materials, i.e., powder types available for the above mentioned 3D printer. For our

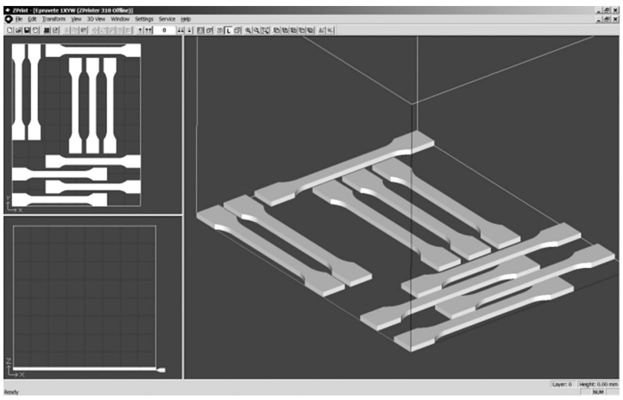

Figure 2: Test-sample build setup in software ZPrint
Slika 2: Razporeditev preizkusnih vzorcev s programsko opremo ZPrint

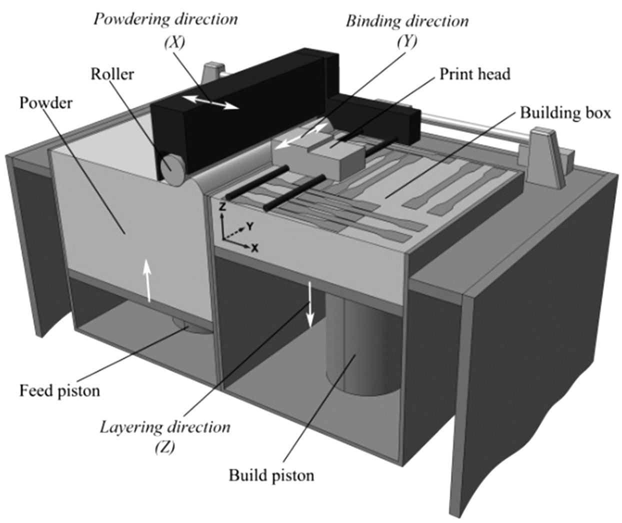

Figure 3: 3D printer main components – a section view
Slika 3: Glavni sestavni deli 3D-tiskalnika – pregled komponent

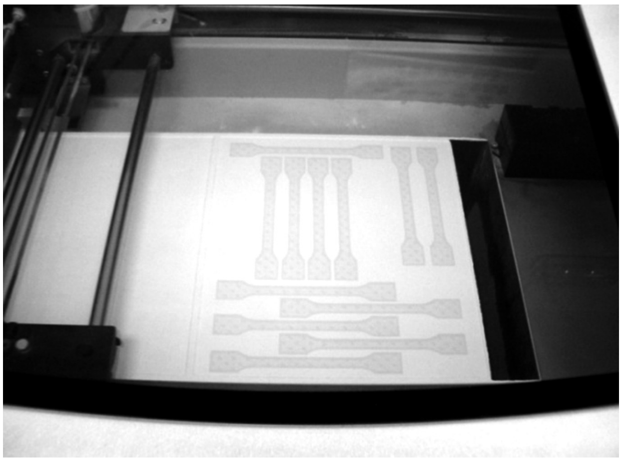

Figure 4: Test-sample 3D printing
Slika 4: 3D-tiskanje preizkusnih vzorcev

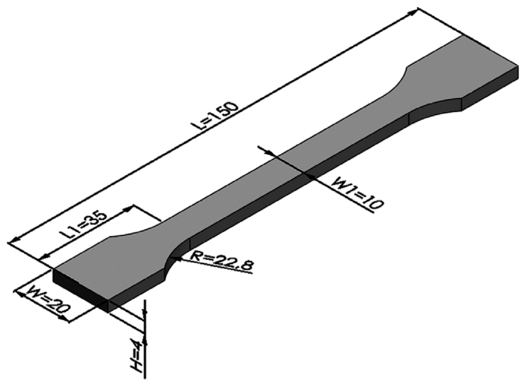

Figure 5: Test sample
Slika 5: Preizkusni vzorec

experiment, we used the plaster-based zp130 powder with an appropriate binder, zb56. The zp130 powder is recommended for the accuracy and for delicate models. It is a mixture of plaster, vinyl polymer and sulphate salt.[16]

All the test samples were dried twice before the infiltration, as recommended in[15,17]: first in the printer's building box for one hour and then, after de-powdering, in the oven for at least two hours at 55 °C.

After drying, the samples were infiltrated with an appropriate infiltrant, taking into account the appropriate combination of the experiment. The applied infiltrants were: cyanoacrylate-based Loctite 406[18]; epoxy-resin-based Loctite Hysol 9483[19] and normal-wax Cera Alba. We applied the alternative infiltrants that are the most similar to the corresponding genuine manufacturer's infiltrants: Loctite 406 instead of Z-Bond[20]; Loctite Hysol 9483 instead of Z-Max; and normal-wax Cera Alba instead of Paraplast X-TRA Wax.[21]

Subsequent to the infiltration, i.e., prior to the tensile-strength test, all the samples rested in room conditions for a minimum of 24 h to obtain the final strength, as recommended for the epoxy-resin infiltrant.[22] We measured the dimensions of the test samples with a digital caliper Lux Profi, model 572587, with a measurement range of 0–150 mm and an accuracy of 0.01 mm.

The tensile test was performed at room temperature on the tensile-testing machine ZMGi 250 made by VEB Thuringer Industriewerk with the jaw-motion speed of 1 mm/min.

3 DESIGN OF THE EXPERIMENT

The models for the tensile tests used in our experiments were those defined with standard ISO 527:1993. The nominal dimensions of the test sample are presented in **Figure 5**. The dimensions measured for the tensile test were: the neck width (W_1) and the height (H). The other linear dimensions like the total length (L) and the width at the end (W) were controlled according to the requirements of the tensile test.

We considered the combinations of the following processing factors: the layer thickness, the building orientation and the infiltrant type. Every combination of the processing factors was denoted with an appropriate unique label made of three characters (**Table 1**).

In the considered ZPrint software version, the layer thickness can be selected from two possible values: 0.1 mm or 0.0875 mm. The first thickness is the default for the printer and it is, therefore, marked with number 1 at the beginning of the label for a particular combination of the factors. Congruently, the second thickness is marked with number 2 in a combination label. The lower layer thickness provides for finer printed models than the higher or coarser layer thickness, with the lower roughness notable especially on the beveled edges and faces.

The sample model can be oriented in any possible direction inside the printer building box. We considered two main directions: the 1st direction denotes the orientation of a sample's largest L dimension towards the building X axis and the 2nd direction denotes its orientation towards the Y axis. Thereby, the samples were aligned at the bottom plane of the building box. In the experiment label for a particular combination of the factors, the mark for the sample orientation is in the second place of the label, expressed with letters X or Y, respectively.

The orientation towards the building Z axis was omitted since it significantly prolonged the printing time: for example, to print five samples oriented with their largest L dimensions towards the building X axis, it takes only 15 min for 39 printed layers; the same time and the same number of layers are necessary when the samples are oriented towards the building Y axis; but when they are oriented towards the Z axis, the process is prolonged to 3 hours and 51 min for 1476 layers.

Although all the other orientations are also available to be combined, additional combinations were omitted in order to reduce the total number of the experiments.

However, if the results of the experiments had indicated a significant influence of the orientation on the tensile strength, additional experiments could have been easily performed.

The type of the infiltrant is marked with the letter at the end of the label for a particular combination of the factors. The letters used for a particular infiltrant type are: W for wax, E for epoxy resin and C for cyanoacrylate.

For every particular experiment, i.e., particular combination of factors in each set, six test samples were printed. During the first tests with the probationary 3D-printed samples, most of the samples tended to slip out of the tensile-testing machine jaws. Therefore, additional rubber pads were inserted between the clamping surfaces in order to ensure a sufficient grip of the machine jaws holding a test sample.

4 RESULTS

The dimensions that have the biggest influence on the test results were measured and analyzed prior to the tests: the test-sample neck width (W_1) and the height (H).

The results of measuring the neck height revealed that most of the samples exceed the limits of tolerance specified with the standard ((10 ± 0.2) mm). A correction to the exceeding dimension can be performed with the afterward processing (e.g., sanding) or this excess can be prevented prior to 3D printing. The prevention can be performed during the model preparation in the printer software with an appropriate anisotropic scale factor as presented in our published research.[23] The measured values of the neck height or thickness of the samples, *H,* are mainly within the limits of tolerance specified with the standard ((4 ± 0.2) mm). The neck width and the sample height multiplied together determine the cross-sectional area A_0 of the test samples (**Table 2**). The cross-sectional area A_0 of the test samples is used later to calculate the tensile strength.

The last two rows in the table contain the calculated values: the arithmetic mean and the standard deviation.

The results of the tensile test are expressed with the values of the breaking force, F_m, and presented in **Table 3**. In the previous researches it was proved that the breaking force of 3DP samples is very close or, often, equal to the maximum testing force[1,2]; consequently, the breaking force values are considered to narrow the focus of the research.

Table 1: Combinations of the processing factors and experiment labels
Tabela 1: Kombinacije procesnih dejavnikov in oznaka preizkusa

Layer thickness	0.1 mm						0.0875 mm					
Infiltrant	Wax		Epoxy resin		Cyanoacrylate		Wax		Epoxy resin		Cyanoacrylate	
Orientation	*X*	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*
Experiment label	1XW	1YW	1XE	1YE	1XC	1YC	2XW	2YW	2XE	2YE	2XC	2YC

Table 2: Neck cross-sectional area (A_0) of the test samples
Tabela 2: Prerez (A_0) preizkusnih vzorcev

	Area A_0/mm^2											
Experiment label	1XW	1YW	1XE	1YE	1XC	1YC	2XW	2YW	2XE	2YE	2XC	2YC
1	41.94	43.60	42.32	43.28	43.42	44.49	43.23	44.13	42.84	43.08	44.27	44.24
2	41.35	43.59	41.69	42.95	44.07	43.52	43.19	43.48	42.70	42.89	43.58	44.95
3	42.28	42.44	41.00	40.59	44.33	42.95	43.73	43.45	43.40	44.61	44.27	44.24
4	41.47	42.50	40.85	41.13	44.51	43.20	43.22	43.58	42.72	44.25	43.58	44.95
5	44.96	42.67	42.42	41.56	43.20	43.66	47.60	44.90	46.46	45.33	49.85	50.80
6	43.93	43.93	42.22	41.71	42.92	43.14	45.63	46.63	45.70	45.39	49.90	50.11
$\bar{x}$	42.66	43.12	41.75	41.87	43.74	43.49	44.43	44.36	43.97	44.26	45.91	46.55
S	1.46	0.66	0.69	1.05	0.65	0.55	1.81	1.24	1.67	1.08	3.09	3.05

Table 3: Breaking force
Tabela 3: Sila ob porušitvi

	Force F_m/N											
Experiment label	1XW	1YW	1XE	1YE	1XC	1YC	2XW	2YW	2XE	2YE	2XC	2YC
1	119	104	237	327	174	177	115	137	366	421	163	223
2	134	154	273	321	154	185	116	126	358	299	214	206
3	100	138	278	256	121	160	121	146	338	483	225	156
4	121	120	230	276	161	143	131	151	380	502	233	123
5	93	112	273	279	137	163	126	105	251	303	208	246
6	133	128	290	295	165	167	101	126	295	332	252	192
$\bar{x}$	116.67	126.00	263.50	292.33	152.00	165.83	118.33	131.83	331.33	390.00	215.83	191.00
S	16.91	18.15	24.16	27.55	19.62	14.54	10.42	16.63	49.19	90.96	30.14	45.00

Table 4: Tensile strength
Tabela 4: Natezna trdnost

Tensile strength R_m/MPa												
Experiment label	1XW	1YW	1XE	1YE	1XC	1YC	2XW	2YW	2XE	2YE	2XC	2YC
1	2.84	2.39	5.60	7.55	4.01	3.98	2.66	3.10	8.54	9.77	3.68	5.04
2	3.24	3.53	6.55	7.47	3.49	4.25	2.69	2.90	8.38	6.97	4.91	4.58
3	2.37	3.25	6.78	6.31	2.73	3.73	2.77	3.36	7.79	10.83	5.08	3.53
4	2.92	2.82	5.63	6.71	3.62	3.31	3.03	3.47	8.90	11.35	5.35	2.74
5	2.07	2.62	6.44	6.71	3.17	3.73	2.65	2.34	5.40	6.68	4.17	4.84
6	3.03	2.91	6.87	7.07	3.84	3.87	2.21	2.70	6.46	7.31	5.05	3.83
$\bar{x}$	2.74	2.92	6.31	6.97	3.48	3.81	2.67	2.98	7.58	8.82	4.71	4.09
S	0.44	0.42	0.56	0.49	0.47	0.31	0.26	0.42	1.37	2.08	0.64	0.89

The typical breakage outlook presents a fragile fracture without the previously observable plastic deformation (**Figure 6**). Moreover, the locations of the breakage are not concentrated in the middle of the sample-neck length but accidentally distributed along the neck length. Such accidental distribution of the breakage location indicates an internal structural inconsistency and its significant influence on the mechanical properties of 3DP models.

The maximum tensile stress (R_m), i.e., the tensile strength is calculated from the results with the following formula:

$$R_m = \frac{F_m}{A_0} \tag{1}$$

5 ANALYSIS AND DISCUSSION

The maximum particular tensile strength of 11.35 MPa was achieved for the 4th sample from the set labeled as 2YE, i.e., the sample was printed with a finer layer thickness of 0.0875 mm, infiltrated with epoxy resin and oriented towards axis *Y*. The particular value is shaded with gray and underlined continuously in **Table 4**.

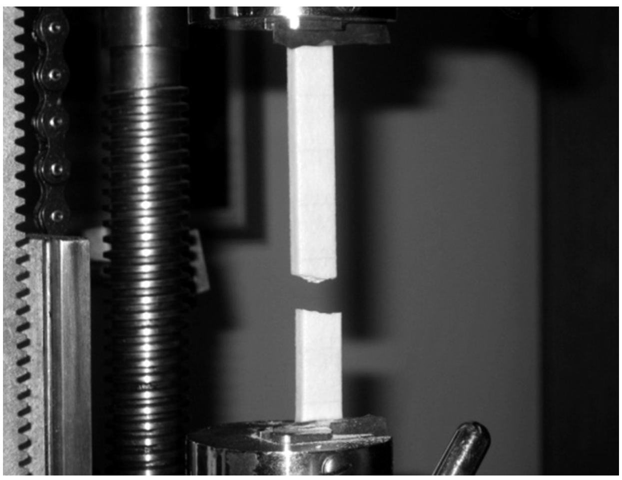

Figure 6: Typical breakage outlook
Slika 6: Značilni videz porušenega vzorca

The minimum particular tensile strength of 2.07 MPa was achieved for the 5th sample from the set labeled as 1XW, i.e., the sample was printed with a coarser layer thickness of 0.1 mm, infiltrated with wax and oriented towards axis *X*. This overall lowest value is shaded with light gray and has a dotted underline in **Table 4**.

An overview of the sorted average tensile strengths, presented in **Figure 7**, reveals the strongest and the weakest experiment sets. The strongest experiment set is the one that includes the strongest particular sample, labeled as 2YE. Although this set also showed the highest standard deviation referring to the significant diversity of the strength values, it has the highest average strength. However, the weakest experiment set was not the one including the weakest particular sample, labeled as 1XW. The weakest average strength was revealed by the set labeled as 2XW, having also the lowest standard deviation.

The samples infiltrated with epoxy resin obtained the highest strength in comparison with the other infiltrant types. Among the epoxy-infiltrated samples, the ones having a finer layer thickness (2YE and 2XE) showed a higher strength than those with a coarser thickness (1YE and 1XE). However, it should be noted that the results for the finer thickness are significantly more dispersed than the results for the coarser thickness: the standard deviation for the 2YE set is 2.08 MPa, for 2XE it is 1.37

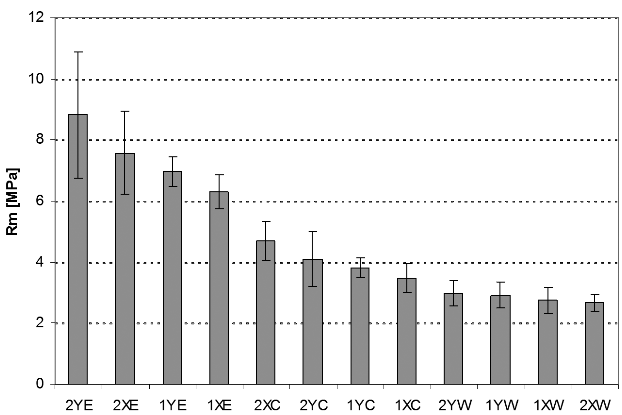

Figure 7: Sorted average tensile strength
Slika 7: Razporeditev povprečne natezne trdnosti

MPa, while for 1YE it is only 0.49 and for 1XE only 0.56. The orientation of the epoxied samples towards building axis *Y* provided a somewhat better strength than those oriented towards axis *X*. The samples infiltrated with cyanoacrylate obtained a medium strength. The cyanoacrylated samples with a finer layer thickness also showed a higher strength than those with a coarser thickness, being similar to the epoxied samples. However, a different orientation of these samples did not cause any obvious difference in the strength.

The waxed samples acquired the lowest strength. The orientation of the waxed samples towards building axis *Y* gave a slightly better strength than the orientation towards axis *X*. The variation in the layer thickness did not show any discrepancy in the strength.

In order to verify the observed principles and relationships between the sample strength and the processing factors, we carried out a factorial analysis of the variance (ANOVA) and summarized the results in **Table 5**. The abbreviations used for the processing factors are: LT – layer thickness; O – orientation; I – infiltrant. ANOVA confirms a major influence of the infiltrant type and a minor influence of the other observed processing factors on the resulting strength of the 3DP samples. The variances in the processing-factor combinations (LT*O, LT*I, O*I, LT*O*I) also indicate a minor influence of the considered combinations on the tensile strength.

Table 5: ANOVA of the tensile strength and the processing factors
Tabela 5: ANOVA natezne trdnosti in procesni dejavniki

Factors	SS	DOF	MS	Var	P	F (0.95))
LT	10.61	1	10.61	14.38	0.00	4
O	2.23	1	2.23	3.02	0.09	4
I	272.47	2	136.24	184.55	0.00	4
LT*O	0.03	1	0.03	0.04	0.85	4
LT*I	7.37	2	3.68	4.99	0.01	4
O*I	3.68	2	1.84	2.49	0.09	4
LT*O*I	1.85	2	0.93	1.25	0.29	4
Error	44.29	60	0.74			

To evaluate the application of alternative infiltrants on our samples instead of the genuine, manufacturer's infiltrants, the results are compared with those obtained for the genuine infiltrants[2] and presented in **Figure 8**. In both researches, the samples were printed with the same model of 3D printer but with different printers. The tensile tests were performed with the same tensile-testing machines.

The genuine epoxied samples show a significantly better average strength when compared to the overall average strength of the alternative epoxied samples. However, it should be noted that only five genuine epoxied samples were tested in the comparative research where the samples were printed with a finer layer thickness, directed towards building orientation *Y* and laid with the narrow side on the bottom of the building box. Therefore, it should be compared with the test involving

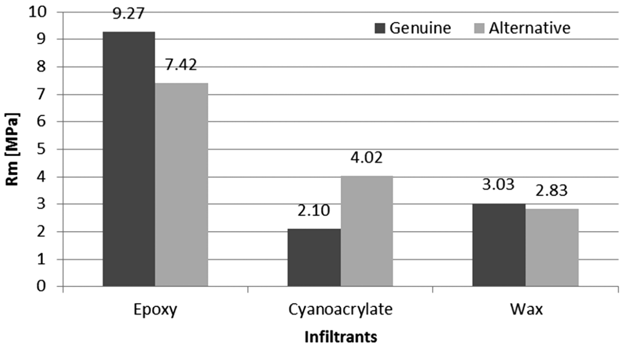

Figure 8: Comparison of the average tensile strengths for the alternative and genuine infiltrants
Slika 8: Primerjava povprečne natezne trdnosti med alternativnim in originalnim vezivnim sredstvom

six appropriate alternative epoxied samples labeled as 2YE, with the average strength of 8.82 MPa (**Table 4**).

The alternative cyanoacrylated samples show a much better average strength when compared to the overall average strength of the genuine cyanoacrylated samples. There were sufficient numbers of samples and combinations of the factors in the two researches for them to be compared: 40 genuine cyanoacrylated samples distributed over 5 distinctive combinations of the processing factors[2] and 24 alternative cyanoacrylated samples used with 4 factor combinations. Since the strength of the cyanoacrylated samples can also be influenced by the residual moisture[24] and the moisture was not measured, we must express some reservation about the results of the comparison between the cyanoacrylated samples.

The genuine and alternative waxed samples reveal almost equal average strengths after a comparison between sufficient numbers of samples (genuine: 50, alternative: 24) and combinations of factors in both researches.

Furthermore, if the results are compared with the previous research published in[1], it can be noticed that the average values of the measured strength correspond to the published values with an evident improvement for the epoxied samples and a smaller decrease for the cyanoacrylated samples than in the previous research. The improvement for the epoxied samples is most likely due to an improved combination of the processing factors used for more samples.

6 CONCLUSIONS

The strength of 3D-printed samples mainly comes from the infiltrants. The results obtained from the conducted experiments clearly confirm a major role of the infiltration type, putting ahead epoxy resin as the strongest one, followed by cyanoacrylate and wax. If the maximum strength is required, as it is common for functional prototypes or molding models, then an additional increase in the strength can be obtained by selecting the best combination of the other two processing factors.

In the case of the infiltration with epoxy resin, to obtain the maximum strength, the model should have a finer layer thickness, i.e., 0.0875 mm. The infiltration with epoxy resin is the slowest one since additional time is necessary for the resin to obtain full strength, usually one day at room temperature or two hours in a heated oven at 70 °C.[24]

Also, the most important dimension of the printed model should be oriented towards building direction *Y*, if possible taking into account the size of the model and the size of the building box. The most probable reason for this is a coincidence between the orientations of axis *Y* and the movement of the printing head – the direction of the binding-material application, so that the direction of the binding-material application coincides with the longitudinal direction of the test-tube orientation along axis *Y*. On the other hand, the orientation of test tubes along axis *X* coincides with the powdering direction, so the application of the binding material is performed transversely to the direction of the orientation of the test tube, so it is expected that the value of the tensile strength is lower. The only exceptions are the cases of 2XC and 2YC, where the average tensile strength is higher in the direction of axis *X*. However, a higher standard deviation of set 2YC implies possible impurities in the powder and post-processing differences.

Although the infiltration with cyanoacrylate provides a clear white color of a 3D-printed model, different from a dim yellow one obtained with epoxy or wax, the experiments did not confirm cyanoacrylate as the best choice when the strength of a model is required. The cyanoacrylate infiltration is the most expensive solution,[25] but it still remains to be the only solution if two or more models have to be joined or mated together after 3D printing, when a large model is divided due to a limitation of the building-box size. A cyanoacrylated model should be 3D printed with a finer layer thickness of 0.0875 mm and the most important dimension of the printed model should be oriented towards building direction X to obtain the highest possible strength.

The infiltration with wax, the cheapest available solution, is also the weakest solution. However, such a low strength can still satisfy customer demands, because many 3D-printed models are produced only for representative purposes without special demands on the mechanical properties. Neither the orientation nor the layer thickness has a significant influence on the resulting strength of a 3D-printed model infiltrated with wax.

The evaluation of the alternative infiltrants, applied instead of the genuine manufacturer's infiltrants, revealed that the obtained levels of the strength are equivalent to those obtained with genuine infiltrants for the considered 3DP system. Therefore, the use of alternative infiltration solutions has been confirmed with respect to the tensile strength.

Although it is possible that some of the presented conclusions are valid for similar machines or even rapid prototyping techniques, all the conclusions should be considered only for the selected 3D printer and the selected materials. New materials and new equipment for 3D printing are developed constantly and may demand new analyses.

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