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Influence of structure on mechanical properties of 3D printed objects

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Abstract

Additive Manufacturing (AM), the relatively young manufacturing technology of layer-based automated fabrication process for making three-dimensional physical objects directly from 3D CAD data set was originally called Rapid Prototyping (RP) when the first commercial process – Stereolitography was entered the market in 1987. This technology is still frequently called Rapid Prototyping. The main objective of research was to determine the impact of sample's structure on the tensile strength of 3D printed samples. Test samples were prepared on a Z Corporation's 3D printer model Z310, with variations of internal geometrical structure. Results of tensile test revealed that the honeycomb structured samples exhibit the highest strength.

Keywords: Additive Manufacturing; Lattice-shaped structures; Rapid prototyping; Tensile strength; Three-dimensional printing

1. Introduction

3D printing or additive manufacturing is a process of making three dimensional solid objects from a digital file. The creation of a 3D printed object is achieved using additive processes. In an additive process an object is created by laying down successive layers of material until the entire object is created. Each of these layers can be seen as a thinly sliced horizontal cross-section of the eventual object. Today, there are many different additive manufacturing techniques with high accuracy and large choices of materials available on the market. The most successfully developed techniques are: Stereolithography (SLA), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), 3D Printing etc. [1,2]

Some of common advantages of existing additive manufacturing techniques are: speed (model building in one day); manufacturing flexibility (almost any geometry can be replicated); high degree of control over part microstructure; wide variety of engineering materials (plastic, metals, and ceramics). They also have some common shortcomings such as: lack of required mechanical properties depending on material combination; lower accuracy (can be improved by additional machining); high computational demands and limited bio-compatibility (important in manufacturing of medical products). Yet, most of listed shortcomings can be successfully avoided in particular case with proper selection of techniques and materials [2].

In our research we have been concentrated on three-dimensional printing (3DP) technique. This process combines a layered approach from RP technologies and a conventional ink-jet printing. It prints a binder fluid through the conventional ink-jet print head into a powder, one layer onto another, from the lowest model's cross-section to the highest (Figure 1). After printing, the printed models are dried in a building box, then removed from the powder bed, de-powdered by compressed air, dried in the oven and infiltrated for maximum strength.

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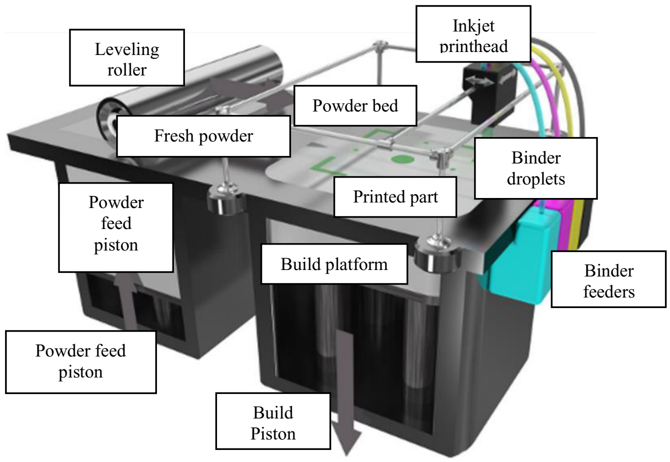


Fig. 1. 3D Printer main components [3]

3D printing technique delivers slightly less details and a rougher surface and it is also less accurate comparing to other AM technologies (e.g. stereolithography, polymer jetting/printing techniques) [4]. The models obtained by 3D printing are not transparent too, but this AM technique is fast and cheap and therefore widely accepted in many areas of application. A comprehensive overview of the capabilities of 3DP processes is presented and evaluated in [4]. It shows the application of 3D printing beyond concept modeling. There are many other studies dealing with various aspects of 3DP processing characteristics, cost evaluation and accuracy, e.g. [5–7].

2. Equipment and materials for experiment

The machine, 3D printer, used for these experiments, was the model Z310, a product of Z Corporation, recently acquired by 3D Systems Corporation. It is a low-cost monochrome 3D printer suitable for RP education or for small and medium sized companies. The printer firmware version was 10.158 and test samples were prepared in printer software ZPrint version 7.10.

There are several base materials, i.e. powder types, available for the above mentioned 3D printer. For our experiment we used a plaster-based powder zp130 with an appropriate binder zb56. The powder zp130 is recommended for the accuracy and for delicate models. It is a mixture of plaster, vinyl polymer and sulphate salt [8]. After drying, the samples were infiltrated with the infiltrant, cyanoacrylate-based adhesive Loctite 406.

In our experiments we used models derived from standard specimens for tensile tests defined in ISO 527:2012 standard. Three different hollow lattice-shaped structures were considered: honeycomb, drills and stripes (Figure 2). Also, one set of standard compact full-bodied specimens were printed and tested as a control set, analogous to control group in randomized controlled trial.

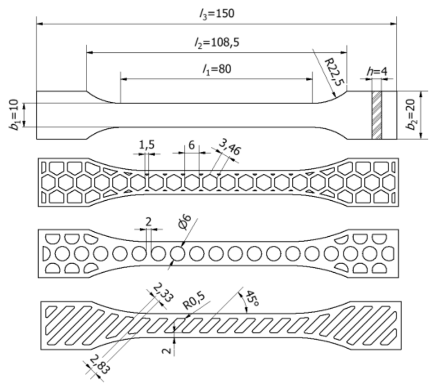
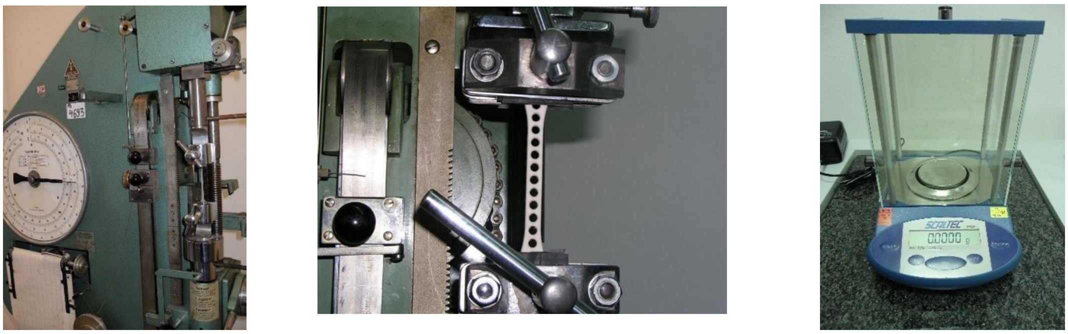


Fig. 2. 3D Sample structure types and dimensions (full, honeycombs, drills, stripes)

The sample model can be longitudinally oriented in any possible direction inside the printer building box. In experiment sample is oriented with largest dimension L towards axis Y and marked on the second place of the label with letter Y. The longitudinal orientation towards the building axis Z was omitted since it significantly prolonged the printing time: for example to print five samples oriented with largest dimension L towards the building axis X it takes only 15 minutes in 39 printed layers; same time and layers are necessary when oriented towards the building axis Y; but when oriented towards axis Z it is prolonged to 3 hours and 51 minutes in 1476 layers. Default printer alignment, when samples are aligned at the bottom of the building box with the face i.e. base determined by the length (L) and width (W) of the sample, were marked with letter W at the end of the experiment label. Raised samples. Full-bodied, compact samples were built also with Y-longitudinal orientation and W-base alignment. Such orientation with the largest dimension of model oriented toward Y axis and the 2^{nd} largest toward X axis is default selection in ZPrint software since it provides the lowes printing time. In order to reduce time needed for printing and to assure same conditions, samples were prepared in one build i.e. in one setup file. Printing layer thickness was 0,1 mm. Universal tensile testing machine (Figure 3-a,b) was used for testing of tensile properties. The testing speed was 5 mm/min. Precision balance Scaltec SPB32 (Figure 3-c) was used for mass determination.



a) b) c)

Fig. 3. Equipment for tensile strength and mass determination

3. Results

The influence of structure on strength of 3D printed models was tested by experiment. Samples were prepared combining three different structures. After preparing, samples were measured and analyzed. Measured values of sample masses and breaking forces are presented in related tables (Table 1 and Table 2). Measured values of full-bodied samples (FYW) we used as control data sets only (Table 1 and Table 2). The last three rows in each of the following tables contain calculated values: arithmetic mean ($\dot{x}$), standard deviation (S) and coefficient of variation (CV). The coefficient of variation (CV) shows measure of dispersion in relation to arithmetic mean of measured data.

Table 1. Measured values of masses

Experiment label	HYW	DYW	SYW	FYW
1	8,48	10,10	10,35	10,72
2	8,63	9,82	10,22	10,63
3	8,99	10,16	8,83	10,55
4	8,74	10,03	8,85	10,57
5	8,53	8,72	10,35	10,96
6	7,01	8,63	10,49	10,46
$\dot{x}$	8,40	9,58	9,85	10,65
S	0,70	0,71	0,79	0,18
CV	0,08	0,07	0,08	0,02

Table 2. Measured values of masses

Experiment label	HYW	DYW	SYW	FYW
1	154	163	131	204
2	160	162	146	198
3	24	196	161	77
4	167	167	169	180
5	171	170	164	188
6	153	156	176	190
ẋ	138	169	158	173
S	56,38	14,06	16,51	48
CV	0,41	0,08	0,10	0,28

Results of tensile test are expressed by values of tensile strength at break (R_p) (Table 3). Tensile strength at break (R_p) is calculated in a way that measured values of breaking force were divided by minimum cross-section area values. Minimum cross-section area for honeycomb, drilled and striped samples amounts consecutive 12,29 mm^2, 16 mm^2 and 16 mm^2.

Table 3. Tensile strengths at break

Experiment label	HYW	DYW	SYW	FYW
1	12,55	10,20	8,16	5,08
2	13,00	10,13	9,14	4,89
3	1,92	12,24	10,06	1,93
4	13,56	10,41	10,55	4,49
5	13,92	10,62	10,27	4,60
6	12,46	9,78	10,98	4,80
ẋ	11,24	10,34	9,86	4,30
S	4,60	0,99	1,03	1,18
CV	0,41	0,10	0,10	0,27

4. Discussion

Coefficient of variation (CV) from tables 2 and 3 shows that in most cases the combination of structure do not vary significantly in relation to arithmetic mean of combination. Thereby, it can be concluded that data sets of breaking force and tensile strength values, are normally distributed.

Maximum particular tensile strength at break (13,92 MPa) was achieved by the 5th sample from the set labelled as HYW (i.e. the sample of honeycomb structure (H) was printed oriented along Y axis and aligned at the bottom of the building box with the base determined by the length and width (W)). This value is shaded with green colour in Table 3. Minimum particular tensile strength at break (1,92 MPa) was achieved by 3rd sample from the same experimental set HYW. This overall lowest value is shaded in yellow in Table 3. The results in this experimental set exhibit the highest standard deviation (S = 4,60) and highest coefficient of variation (CV = 0,41), that both refer to significant dispersing of strength values in relation to their arithmetic mean and therefore an uncertainty of expected returns when taking into account normal distribution of observed data set. With the aim of evaluating a possible advantage of lattice structure, we calculated values of specific tensile strength at break (R_p/m) by dividing values of tensile strength at break by corresponding sample mass (Table 4).

Table 4. Specific tensile strengths at break

Experiment label	HYW	DYW	SYW	FYW
1	1,48	1,01	0,79	0,47
2	1,51	1,03	0,89	0,46
3	0,21	1,21	1,14	0,18
4	1,55	1,04	1,19	0,42
5	1,63	1,22	0,99	0,42
6	1,78	1,13	1,05	0,46
$\dot{x}$	1,36	1,11	1,01	0,40
S	0,57	0,09	0,15	0,11
CV	0,42	0,08	0,15	0,28

As it was expected, considering results of tensile strength at break presented in Table 3, and normally distributed measured values of masses presented in Table 1, maximum (1,78 MPa/g) and minimum (0,21 MPa/g) particular specific tensile strength at break were both achieved in the same data set labelled as HYW. Those values are shaded with green and yellow colour in Table 4.

On first sight the results may be confusing since the compact samples exhibits lower strengths comparing with results obtained by all structured samples. However, it could be explained by internal structure of 3D printed samples. Base powder and binder used in printer to fuse powder, provides only primary or strength of so called “green model”. Such strength is sufficient to handle green model out of the printer for infiltration. Infiltration brings final strength to model. Infiltrant penetrates into the model, but depending on the type of the infiltrant and thickness of the model, it does not penetrate completely through the model. Cyanoacrylate penetrates several millimeters into the model and it should infiltrate almost complete volume of samples. Nevertheless, results of strength tests and look of the cracking reveals structural differences between the core and the surface of the model.

5. Conclusion

When taking into account only structure, the analysis of tensile strength at break showed that honeycomb-structure exhibit the highest strength. Comparing with results obtained by lattice-shaped samples, compact samples proved to be once with lower strengths although compact samples beard the highest breaking forces. Analysis of specific tensile strengths at break revealed that lattice-shaped structure may provide sufficient strength with reduced mass of 3D printed models. Reduced mass combined with retained sufficient strength may significantly reduce 3D printing time and printing costs, enhancing by that the use of 3D printed lattice-shaped models in specific areas like in manufacturing of medical implants. Further research and analysis of the factors that have the significant influence on strength of 3D printed models for different material combinations should be also performed prior to implementation.

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