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New Nonstandard Method for Measuring Physical Properties of Homemade Polymer Filaments for FFD 3D Printing

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Abstract

The large advance in fused filament deposition (FFD) 3D printing technology is becoming a challenge for the introduction of new materials used in the process. The standard destructive mechanical testing of materials uses large amount of raw filament. As desktop FFD 3D printing becomes an everyday occurrence and 3D printing filament extrusion, a DIY makers practice, establishing a method for physical characterization of parts using only small amounts of homemade filament is of interest. This research is focused on introducing a new nonstandard method for evaluation of 3D printing filament with samples of less than 50 mg material . In this work we test the new method by comparison the results acquired for standard everyday 3D printing filaments. It was found out that the results obtained with this method are in correlation with the results from the standard tests used in everyday practice. This is of interest because it allows fast characterization of exotic filament blends with very small amount of material for research purposes, reducing the costs of production, and the possibility to implement fast changes in the filament blends.

Keywords: 3D printing, filament, material testing

1. Introduction

3D printing in its main concept, functionality and performance is a special, novel and creative additive manufacturing technology that creates objects from digitized models without traditional expensive cutting or casting machines. This allows the creation of practically anything, from 3D printing decorative items, automotive, machining and medical parts, appearing in different fields: biomedicine, aerospace, automotive engineering, civil engineering, food industry and so on [1]. 3D printing is performed throughout different techniques, of which the four most important are: stereolithography (SLA, curing of liquid photopolymer resin with UV light), fused deposition modeling (FDM aka fused filament deposition FFD), selective laser melting (SLM, laser based melting of metal or nylon powder) and selective laser sintering (SLS) [2]. Fused deposition modeling (FDM) is one of the most widely used additive manufacturing processes for fabricating prototypes and functional parts in common engineering plastics [3]. In FDM 3D printing the raw material is the filament most often produced from virgin raw material. These materials properties are standardized depending on the raw material. It is of great interest to introduce homemade polymers for 3D printing in order to be able to experiment and change the final part properties. Furthermore, we consider the interest in recycling plastics and utilizing it for useful purposes in 3D printing. These newly formed polymers, can be enriched with additive elements like metal powders, carbon fibers, cork and so on ensuring different properties. In this paper we present a new nonstandard method for evaluation of the properties of these homemade filaments.

2. Materials and methods

In the FDM process, objects are built layer by layer, leading to their anisotropic mechanical properties. First step is extrusion of the raw material into the printer nozzle and its transformation to semi-liquid state, followed by, deposition on the previous layer, after which the material cools, solidifies and integrates with the surrounding materials. Generally, the properties of parts produced by the FDM technique are apparently dependent on process parameters like extrusion temperature, layer height, printing speed and ambient temperature. When the whole layer is deposited, the platform supporting the object moves down by the height of one layer and the next layer is printed. Standard methods used for investigating the physical properties of 3D printing filaments are mainly destructive and require a big sample or large amount of filaments and time. It is known for PLA and ABS filaments that printing in different angles leads to different properties for the final object. The objects printed in this way can be considered as transverse isotropic materials and their behavior differs for different angles. The uniaxial samples which undergo a uniaxial tensile test, fracture at different points of their body, depending on the angle of printing [1].

In our method the first step of experimental work is the 3D printing of samples, with a 3D printer type PrusaMK3 with a brass nozzle of diameter 0.4 mm. The filaments used in this research are: PLA (polylactic acid), ABS (acrylonitrile butadiene styrene) and PET (polyethylene terephthalate), bronzefill PLA, copperfill PLA, woodfill PLA, TPU shore 98 A and ASA (acrylonitrile styrene acrylate).

The sample (shape and dimensions) is designed in a 3D visual form with the help of the CAD package (SolidWorks). The samples are produced with semi-circular shape with radius of 20 mm and thickness of 1 mm. The width of the sample varies from 1.2 mm to 4.8 mm in steps of 0.6 mm. Experimental samples are divided in three parts depending on layer heights: 100 μm, 150 μm, 200 μm. The step of the width was chosen as 0.6 mm being devisable by all layer heights, resulting always in integer number of layers. It is then exported as a digital 3D object file and subsequently loaded into 3D printer slicing software to generate the G-code which the 3D printer uses to print out each test sample. [4,5]

The printing temperature of used materials varies, respectively: PLA – 215°C, PET – 230 °C, ABS – 255 °C, bronzefill – 215 °C, copperfill – 215-235 °C, woodfill - 190-250 °C and TPU 98A- 240 °C, ASA – 260 °C [6,7].

One layer of the samples is printed by three periodic steps of the nozzle upon the plate resulting in three concentric semicircles in each layer. There is no infill and the geometry of all parts is the same. Printing of samples is done in triplets for each of the polymers (filament types).

Our method uses a mechanical compressibility test to measure the physical properties of the samples. For this we use texture analyzer type TA.XT plus C. The analyzer is modified with a special 3D printed sample holder. This sample holder limits the deformation of the sample only in one plane and introduces a boundary condition at the bottom of the sample holding these locations fixed.

It was observed that compression larger than 2 to 3 mm, depending on material, introduces a plastic deformation in the sample. That's why all measurements are with maximum displacement of 2 mm, being 10% of the total height of the sample.

3. Theory

Most polymeric materials, when exposed to sufficiently small strains, exhibit linear elasticity, which is often referred to simply as elasticity. An elastic material is one which, when externally applied forces are removed, returns to its original dimensions. With a linearly elastic material, the strains and displacements produced are proportional to the applied forces. Such behavior also implies that the strains are small because changes in geometry of the deformed component are of negligible effect on the internal stresses produced by the applied forces.

The general form of a constitutive equation for a linearly elastic material is *stress=parameter×strain.* Since strain is dimensionless, the constant of proportionality has the dimensions of stress. Thus, under uniaxial tensile load, *stress=E×strain* or $\sigma_{xx} = Ee_{xx}$, where E is Young's modulus or the modulus of elasticity of the material. As a result of stress, strains are produced in directions normal to the direction of the stress and these strains are proportional to the

strain in the direction of the stress. Thus the stress σ_{xx} produces a strain $e_{xx} = \sigma_{xx}/E$ in the x direction and strains $e_{yy} = e_{zz} = -\upsilon\, \sigma_{xx}/E$. In orthogonal directions, the negative sign indicating that these strains are of the opposite sense to e_{xx}. The proportionality factor, υ, is called Poisson's ratio and is dimensionless. The elastic constants E and υ apply to both tensile and compressive loading [8].

The above relationships between stresses and strains yield from the assumption that the material is both isotropic and homogenous. This restriction to isotropic homogenous materials leads to a number of important simplifying conclusions. It means that the stress-strain relations do not depend on the coordinate system chosen to describe the problem. For an anisotropic material, six elastic constants would be needed to define each strain, one associated with each of the six independent stress components. With six strain components, a total of thirty-six constants would be required for a complete specification of the constitutive relationships [8,9].

Hooke's law states that for relatively small deformations of a body, the size of the deformation is proportional to the deforming force or load. In this case, the body returns to its initial condition or shape after removal of the deforming force or load.

The deforming force upon solids can be applied in different ways: by stretching, bending, compressing, twisting or squeezing. Mathematically, Hooke's law states that the applied force is equal to a constant k times the displacement or change in length x, or $F = kx$.

The value of k depends on the type of elastic material under consideration, its shape and its dimensions. Hooke's law describes the elasticity of materials only in range in which the force and displacement are proportional. This law also is formulated as $F = -kx$, where now F means the equal and oppositely directed restoring force that causes elastic materials to return to their original dimensions [9].

4. Results and conclusion

The new nonstandard method used for producing samples of above mentioned materials, is very promising. First of all, it ensures production of lots of samples from little amount of raw material. Then, it is cost effective because less labor is needed for realization of measurements and it offers less errors in the 3D printing process.

Starting from the first type of material up to the last one, samples behaved as elastic wires showing linear elasticity. The coefficient of elasticity that comes out from the graphical analysis of the behavior of the samples, depends on the width of the samples but not on the layer height in the printing process. The acquired behavior of the test material for a certain material is shown in Figure 1.

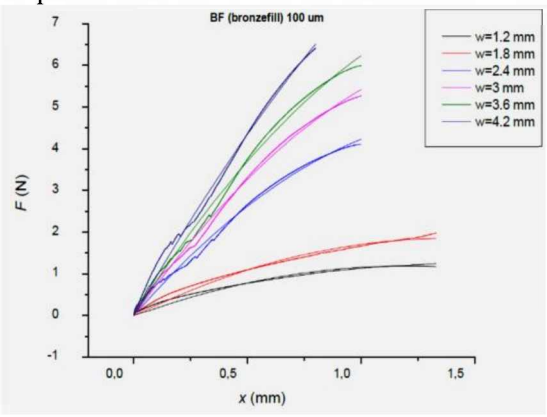

Figure 1

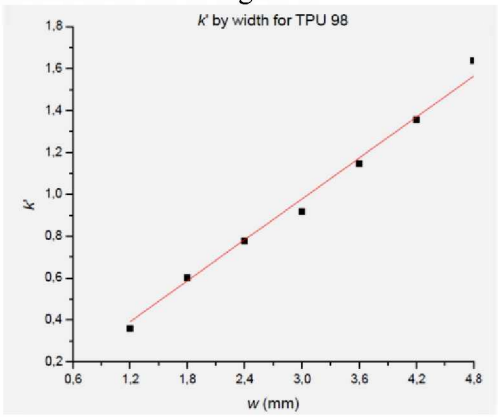

Figure 2

Figure 1. Force displacement curves for bronzefill material depending on the samples' width (w).
Figure 2. Linear dependence of the elastic coefficient on sample width.

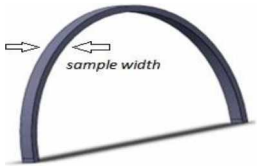

Figure 3. Sample's width

Fitting analysis is done as a polynomial of second order, thus having two coefficients for the fitting equation $y = intercept + B_1 x + B_2 x^2$. The second coefficient has small values compared to the first one ($B_2 x^2 << B_1 x$) thus the dependence is seen as a linear fit with one coefficient.

The linear trend of dependency of the coefficient of elasticity with the width of the sample shown in Figure 2 above may be expressed with the equation $F = k' \cdot w$ where k' is a coefficient for a given material and w is the width.

From here knowing the sample dimensions we can calculate the Young modulus of the tested material and part of the results are shown in Table 1. Here we compare the experimental results with the theoretical values of the standard methods for this materials. Analysis show that the newly proposed method with further optimization can be established as a precise method for evaluation of 3D printing filaments. Comparing to standard method this method uses almost hundredfold less materials. The testing is nondestructive so it can be repeated for comparison or reevaluation of results. Furthermore, results are independent from printing geometry reducing the number of experiments needed to extrapolate the value of the Young's modulus of the material.

Table 1: Young's Modulus values for tested material

Polymer	*E* (GPa) (minimal value)	*E* (GPa) (maximal value)	*E* (GPa) (theoretical value)
ASA	2.00	2.60	2.20
PET G	1.90	2.00	2.00
PLA	3.40	3.60	3.30

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