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Statistical correlation between the printing angle and stress and strain of 3D printed models

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Abstract

In the strides of the most advanced technological achievements, the use of polymers is becoming increasingly evident both in everyday life and in engineering practice. Complex structures made of polymers attract more attention from scientists and researchers, as their application increases in the most diverse fields of science. This phenomenon requires constant improvement of knowledge and technologies for the production of polymeric structures and parts, but it is equally important to establish reliable databases on the behavior of newly-introduced materials under different load conditions. This work is based on the establishment of statistical correlation between parameters of 3D printed models and their mechanical characteristics in conditions of static axial loading.

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Keywords:Rapid prototyping; 3D printing;statistical correlation, stress and strain.

1. Introduction

The constant improvement of the process of constructing machine parts, which has the aim to reduce the costs of production and maintenance, shortening the downtime and time necessary for the development of a new product, while simultaneously increasing productivity and reliability, which often entails the use of new materials. The most commonly used engineering materials of today are metals and metal alloys, ceramics, polymers, etc.

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Polymers, as a relatively new group of materials, require special attention because their domain of application in engineering practice is very diverse, Table 1, Dowling (2013). A polymer is a large molecule (macromolecule) composed of repeating structural units. Although the term polymer sometimes refers to plastics, it actually encompasses a large class comprising both natural and synthetic materials with a wide variety of properties. Polymer materials applied in mechanical engineering are divided into two main groups: duroplasts (duroplastics) and thermoplastics, Jelaska (2012). Polymers most commonly used in the manufacture of machine parts are from the thermoplastic group: polyamide (PA or Nylon), polyoxymethylene (POM) and acrylonitrile butadiene styrene (ABS).

Table 1. Classes, Examples, and Uses of Representative Polymers.

Polymer	Typical usage
Thermoplastics: ethylene structure	
Polyethylene (PE)	Packaging, bottles, piping
Polyvinyl chloride (PVC)	Upholstery, tubing, electrical insulation
Polypropylene (PP)	Hinges, boxes, ropes
Polystyrene (PS)	Toys, appliance housings, foams
Polymethyl methacrylate (PMMA, Plexiglas, acrylic)	Windows, lenses, clear shields, bone cement
Polytetrafluoroethylene (PTFE, Teflon)	Tubing, bottles, seals
Acrylonitrile butadiene styrene (ABS)	Telephone and appliance housings, toys
Thermoplastics: others	
Nylon	Gears, tire cords, tool housings
Aramids (Kevlar, Nomex)	High-strength fibers
Polyoxymethylene (POM, acetal)	Gears, fan blades, pipe fittings
Polyetheretherketone (PEEK)	Coatings, fans, impellers
Polycarbonate (PC)	afety helmets and lenses
Thermosetting plastics	
Phenol formaldehyde (phenolic, Bakelite)	Electrical plugs and switches, pot handles
Melamine formaldehyde	Plastic dishes, tabletops
Urea formaldehyde	Buttons, bottle caps, toilet seats
Epoxies	Matrix for composites
Unsaturated polyesters	Fiberglass resin
Elastomers	
Natural rubber;	Shock absorbers, tires
Styrene-butadiene rubber (SBR)	Tires, hoses, belts
Polyurethane elastomers	Shoe soles, electrical insulation
Nitrile rubber	O-rings, oil seals, hoses
Polychloroprene (Neoprene)	Wet suits, gaskets

In the past, plastic machine parts were considered unworthy substitutions for parts made of metal because they did not have the ability to work under the same operating conditions due to limited strength. However, the development of plastic materials of increased load capacity, the advancement in the technologies for the production of plastic parts and the development of reliable engineering databases have led to successful and increased use of plastic machine parts, EY (2016). Some of the advantages of plastic mechanical parts regarding to metal are: lower density (light mass and low inertia), ability to work without or with minimal lubrication, low friction coefficient, corrosion resistance, etc. Because engineering plastics, as a family, are much younger than engineering metals, their database is not yet complete. In addition, their rapid evolution makes the material selection process more difficult, as it was pointed by Davis (2005). Due to the increasing popularity of polymer i.e. plastic use in engineering a wide range of plastic manufacturing technologies has been developed aimed at increasing the accuracy of a printed object, and accelerating the production process with the acquisition of appropriate mechanical properties and working on the principle of additive manufacturing (AM). In contrast to conventional subtractive manufacturing methods (removing layers of material to reach the desired shape), additive manufacturing is the technology of making objects directly from a Computer Aided Design (CAD) model by adding a layer of material at a time as it is stated in work of the authors Letcher et al. (2015). An overview of the division of additive technologies most commonly applied in rapid prototyping is given in the table 2, www.3dhubs.com. The additive production procedure usually consists of four activities, which is emphasized by Mitrović and Mišković (2017): 1. Creating a 3D model in one of the available commercial softwares (Catia, Inventor, Solidworks); 2. Conversion of 3D models into STL (Stereo-lithographic) format - a compact 3D model is divided into parallel layers of a certain thickness; 3. Defining the 3D printing parameters and 3D model orientation in the 3D printer workspace; 4. Physical prototype production.

Table 2. Additive manufacturing technologies classification.

Additive manufacturing technologies	
VAT photopolymerization	Stereolithography (SLA)
	Digital light processing (DLP)
	Contiuous digital light processing (CDLP)
Material extrusion	Fused deposition modelling (FDM)
Material jetting	Material jetting (MJ)
	Nanoparticle jetting (NPJ)
	Drop on demand (DOD)
Binder jetting	Binder jeting (BJ)
Powder bed fussion	Multijet fusion (MJF)
	Selective laser sintering (SLS)
	Electron beam melting (EBM)
Direct energy deposition	Laser engineering net shape (LENS)
	Electron beam additive manufacturing (EBAM)
Sheet lamination	Laminated object manufacturing (LOM)

FDM is one of the most common methods for manufacturing of plastic models, and it represents an additive process of rapid production by extruding new, dissolved plastic layers of a particular shape, most commonly of PLA (polylactide) or ABS plastic, during a process called 3D printing. Some of the main advantages of applying FDM production process are: relatively cheap production, lightness and speed of production without the need for a mold, a wide range of printing parameters selection- through which the mechanical properties of the printed part are affected, the ability to obtain complex shapes and structures, the elimination of machine and additional finishing processing, etc.

In order to increase the reliability of engineering data on the use of ABS plastic for the manufacture of machine parts, this paper establishes a functional dependence between the printing angle of the 3D printed samples from ABS plastic and the tensile strength of these samples, exposed to axial load in static conditions.

2. Testing samples

The experimental part of the work uses printed samples that are in accordance with the relevant standard EN ISO 527: 2013 (Plastics - Determination of tensile properties). This standard defines the dimensions of samples that are tested by axial loading. The drawing of the sample is given in Figure 1.

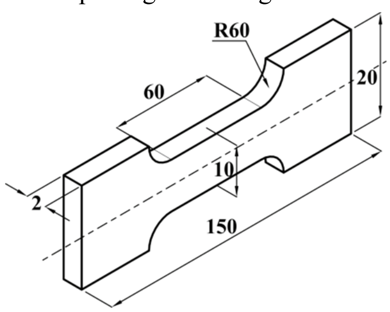


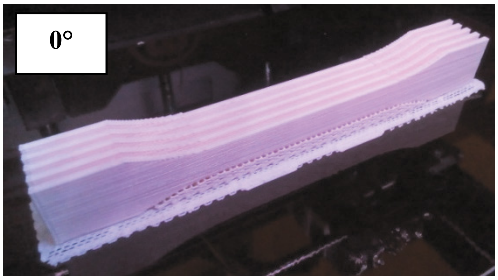
Fig. 1. Dimensions of the testing sample.

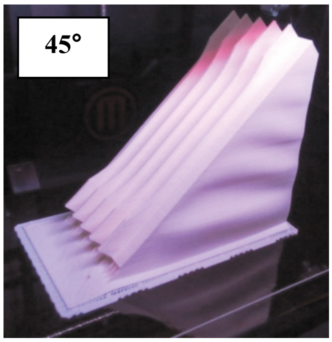
Samples were made by FDM 3D printing process, using the 3D printer Replicator 2X, MakerBot (USA). The material used for the production of samples is industrial strength ABS plastic fiber (diameter 1.75 mm) – purposely developed for the mentioned 3D printer. The printing parameters of the produced samples are shown in the table 3.

Table 3. Printing parameters.

Printing parameters	
Extruder temperature	230°C
Printing platform temperature	120°C
Thickness of the printing layer	0,3 mm
Percentage of the infill	100%
Initial material layer - *Raft*	Yes
Additional supports	Yes
Printing head moving speed	90 mm/s
Raster angle	+45°/-45°

The different printing angles were achieved by different positioning of the model in the printing space. That is, as the extruder always prints horizontal layers of materials that are parallel to the printing platform, by introducing the inclination angle between the plane of the model and the plane of the platform (and therefore the extruder), 3D printing will be made at that same angle. For the purposes of this paper, three different inclination angles of the model were selected, and therefore three different printing angles, i.e. angles of 0°, 45° and 90°, Fig 2.





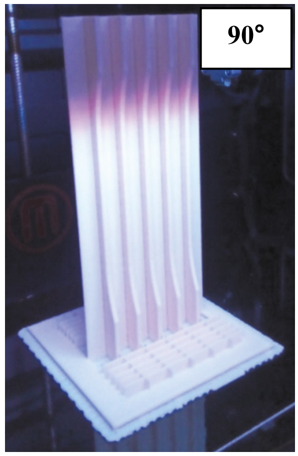


Fig. 2. The appearance of the printed samples.

Samples printed at a printing angle of 0° are denoted with a letter mark *H*, samples printed at a printing angle of 45° are denoted with a letter mark *A* and the ones printed using printing angle of 90° are denoted with a letter mark *V*. Since an axial loading test was envisaged for all the samples, where the direction of acting axial force coincides with the direction of the longitudinal axis of the sample, the samples bearing the mark H had printed layers of the material oriented in the same direction as the axial force, the samples marked V had the printed layers of the materials parallel to the direction of the tensile force, and the samples with the mark A had the angle between the layers of the material and the direction of the axial force of 45°. All the specimens were specially prepared for monitoring using stereo cameras - painted with a white layer, to which black reference points are applied.

For precise geometric measurements of the cross-sectional area of the printed samples, the Hirox 3D digital microscope KH 7700 was used, with an optical magnification of up to 500x, and the possibility of generating a 3D profile of the observed surface. The display of the generated profile of the observed 3D model external surface, at which the print accuracy control is exercised, at a magnification of 200x, is shown in Figure 3. This type of control is also suitable for geometrical specification of printed model surface and can also be used to determine certain parameters of the surface texture. In particular, in this paper, and based on the recorded profile shown in the picture 3, the maximum height of profile (*Rz* parameter) was measured using this optical 3D microscope, and it was determined that the sum of the heights of the largest profile peak height and the largest profile valley depth value (i.e. *Rz*) amounts to 203.6μm. This type of optical control can be also used to control the thickness of the printed layers, i.e. a parameter that is defined at the beginning of the printing process.

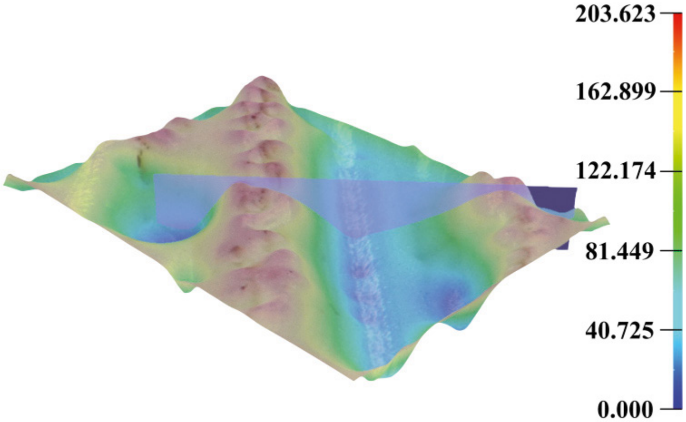


Fig. 3. Generated profile of the external surface of the 3D printed model.

3. Tensile testing

The standard EN ISO 527: 2013 prescribes different testing speeds, with these speeds ranging from 1 to 500 mm/min. For the purposes of this experiment, a testing speed of 2mm/min has been adopted, because it is possible to accurately capture the field of deformation of the loaded samples under the action of the axial force. Also, in accordance with the requirements of the stated standard, all planned experimental tests were carried out in laboratory conditions at room temperature.

The device used for tensile testing is Tinius Olsen H10KS (Norway) benchtop tester with the possibility to generate axial force of up to 5kN. In contrast to the classic tensiometers used in the tests of this type, Aramis 2M, GOM (Germany), a Digital Image Correlation system (DIC) using two digital cameras with a resolution of 1600x1200 pixels and a maximum sampling frequency of 12Hz was used to record the deformation field during the tensile loading. More information on the system and the very principle of operation of this system, which was previously successfully used in similar tests, can be found in the papers Mitrović et al. (2012) and Milosević et al. (2012). The display of the entire installation used for tensile testing and recording of the deformation field during the test is shown in the Figure 4.

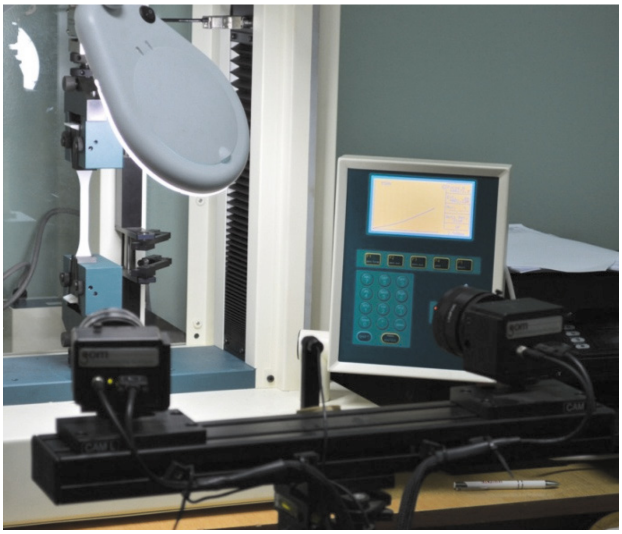


Fig. 4. Tensile testing installation.

4. Analysis of experimental results

For the purpose of obtaining a stress-strain diagram, the samples that were produced and prepared in the manner shown in section 2 were subjected to tensile loading until the occurrence of fracture, using the installation described in section 3. Figure 5 shows one broken sample from each of the three examined groups (marked H, A, V).

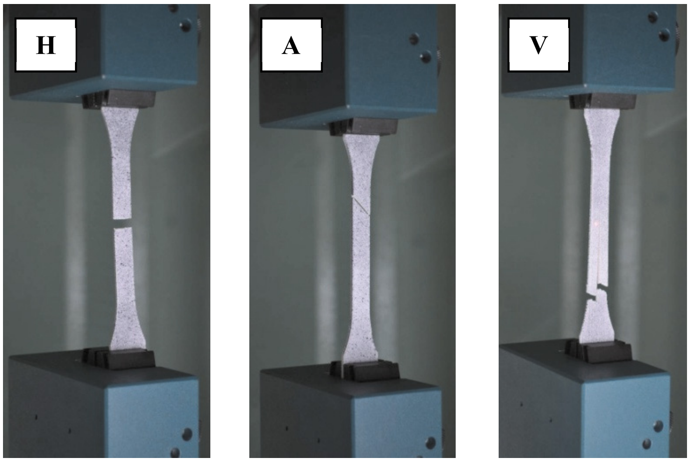


Fig. 5. Display of fractured samples.

The increment of the axial force was measured by the benchtop tester, while the corresponding deformations were obtained by the field of deformation recording. Taking into account the data obtained this way, the stress-strain diagrams for all samples were generated, and are shown in the Figure 6.

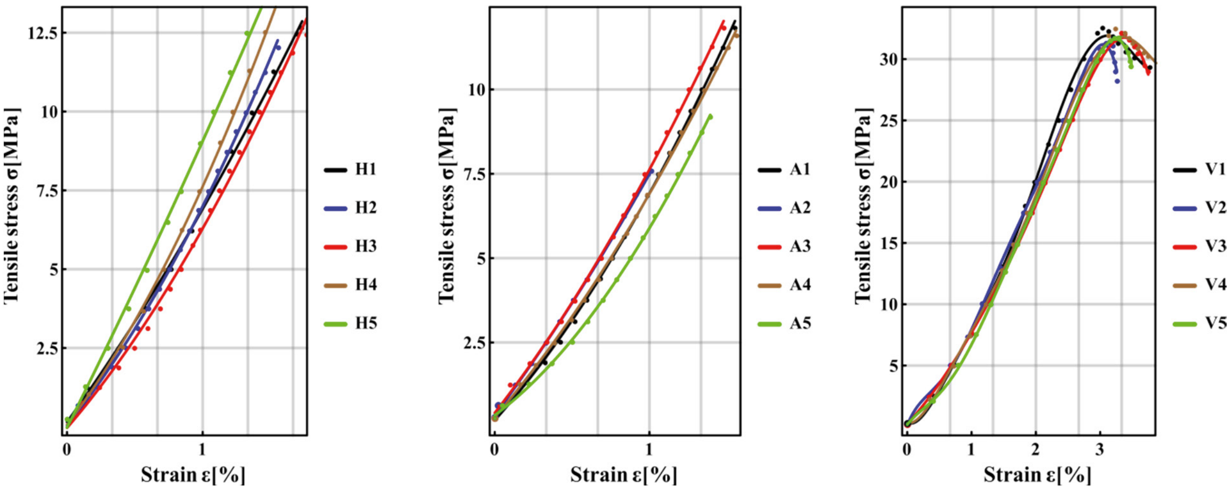


Fig. 6. Stress-strain diagrams for tested samples.

By analyzing the diagrams shown in Fig. 6, it can be concluded that the tensile strength of the samples in which the layers of material are parallel to the direction of the axial force is most favorable (samples marked with letter V). In contrast, the samples in which the layers of the material are perpendicular or inclined at an angle of 45° relative to the direction of action of the axial force have unfavorable tensile strength values. This can be explained by the fact that, in the first case only, the tensile load opposes polymeric fibers that are oriented in the same direction. For other two groups of samples, resistance to tensile loading provide connections between fibers that do not have good bearing properties because plastics consist of macromolecules, frequently in the form of large molecular linear chains in which the atoms are held together by covalent bonds, whereas the bonds between the different linear chains are much weaker, Roesler et al. (2007). Observing the diagrams in Fig. 6, it can also be concluded that there is a certain printing angle, in which the stress-strain curves transforms from the shapes as in the left and middle diagram to the shape of the right diagram. Inadequate selection of the printing angle can even lead to a situation where the values of the tensile strength of the model are found outside of the range which is defined for ABS plastics (25 to 50MPa). The results of the conducted experiment indicate that only in the case of samples made with layers of material parallel to the direction of the axial load (V tubes, 27 - 32 MPa) - the values of tensile strength are in the range mentioned above. It can be also noted that the system for digital image correlation gives credible results when recording the deformation field of the polymers, because the stress-strain diagrams obtained using this method coincide with those who meet in professional and scientific literature, Perez et al. (2014), Letcher et al. (2015).

5. Statistical processing of results

In the continuation of the work, the statistical processing of data shown in Fig. 6 was carried out with the intent to find the appropriate regression model that links the printing angle and the tensile strength and deformation of the plastic models. For the purposes of this statistical analysis, regression analysis was used, with 81 regression models tested, the best of which is shown in Fig. 7. The residuals used to evaluate the statistical correlation error are also shown in the figure 7.

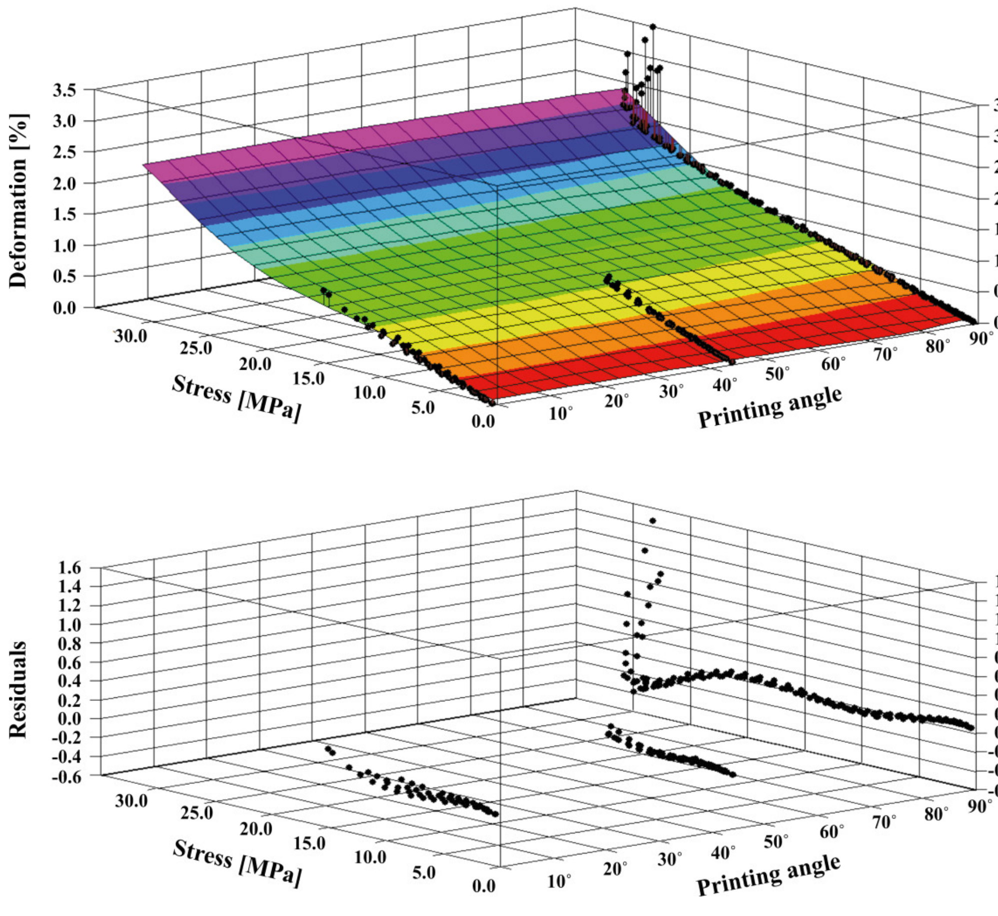


Fig. 7. Graphic representation of the selected regression model with the corresponding residuals

The coefficient of determination for the selected model is R^2 = 0,93, which means that it's expected that 93% of experimental results will match the values calculated according to this statistical correlation:

$$Y = a + b \cdot x_1 + c \cdot x_1^2 + d \cdot x_2 + e \cdot x_2^2 + f \cdot x_2^3 + g \cdot x_2^4 + h \cdot x_2^5,$$

where:

Y – deformation,

x_1 – printing angle,

x_2 – tensile stress.

For a confidence level of 99%, the coefficients from the upper equation have the values given in the table 4.

Table 4. Regression model coefficients.

99% Level of confidence							
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*
5,48E+12	6,22E+10	-1,85E+09	6,90E+11	1,61E+12	-1,56E+11	5,85E+09	-7,27E+07

6. Conclusion

The experiment was carried out as part of a comprehensive project aimed at defining the influence of the printing parameters on the characteristics of the plastic gears. The obtained results are significant because they can be used to define the direction of the material layers of the 3D printed gear in relation to its longitudinal axis in order to achieve the most favorable mechanical characteristics of the plastic model. The reliability of the data obtained is of particular importance as it is a key factor in the application of polymers for making machine parts subjected to loading. They can, for example, find application in the development of safety elements that fail at a certain load level. Advanced methods for geometric control of printed models and recording of the deformation field were used, which were verified by analysis of the obtained results.

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