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The Influence of 3D Printing Direction on the Mechanical Properties of Manufactured Elements

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ABSTRACT

The internal structure of a material is crucial in the design of a number of components, especially those that carry significant loads. Also, the design of such 3D printed components should take into account the type of internal structure of a printed piece. The aim of the study was to evaluate the influence of an internal structure (degree of filling and printing direction) of a 3D printed component on its selected mechanical properties. To carry out experimental research, a set of PLA filament samples was prepared using 3D printing, using a MakerBot Replicator Z18 printer. The test pieces were manufactured in both longitudinal and transverse printing; both the longitudinal and transverse printing were made in two positionings: plane and edge. In this case, four different internal structures were obtained from which static tensile strength and impact tests were carried out. In addition, the samples were made with three different filling options: 100%, 70% and 30%. As a result of the research, it was found that the strength of elements produced by 3D printing from PLA is higher if they are printed in an edge formula, which means that the speed of applying subsequent layers probably plays an important role in building strength.

Keywords: 3D printing, PLA material, mechanical properties.

INTRODUCTION

Polymer components can be manufactured in a number of ways [1]. Among a wide range of modalities, the main ones are as follows:

a) methods which use joining of components: welding [2] and soldering,
b) methods of manufacturing finished, integral components: lamination, pressing (extrusion), casting, coating, injection [3].

It is also necessary to include 3D printing as a manner of obtaining polymer components. This method is based on making an object from a three-dimensional model created in a computer programme. This process involves layering of a plastic material (usually PLA) [4], through a 3D printer specially designed for this purpose, until the final result is a finished component [5]. The history of 3D printing, although printing itself appears to be a relatively recent invention, can be traced back to 1984, when Carl Deckard developed the concept of melting powdered layers of material using either a laser or an electron beam, which in turn led to the creation of 3D printing - SLS - and the opening of one of the first companies producing devices that used this method. 3D printing is now widely used in many areas of life. In industry, it has found use in the creation of templates and prototypes. The objects produced by printers are used in aerospace, medical [6], automotive or even jewellery industries. It is widely used in architecture, where it is used to create land-use mock-ups, with realistic representations of buildings. In medicine, it is most widely used in prosthetics and dentistry [7], and there are also known cases of the manufacture of prosthetic bone elements printed entirely by this method. There are more and more applications for 3D printing and these will increase as the accuracy of the overall process grows [8]. The development of 3D printing is increasing the range of available materials used in this field [9, 10]. The range of available powders, filaments or resins is constantly growing. An increasing availability of new materials makes the selection of a suitable material for printing a given object difficult and requires a great deal of knowledge in the science of materials from the print practitioner [11, 12].

There are 5 main methods of manufacturing components in 3D printing technology:

- FDM (fused deposition modelling), the most common 3D printing method. The construction material is a thermoplastic material wound in the form of a line on a spool. During printing, this material is melted and then spread in layers across the platform, according to the 3D model from which a particular piece is created,
- SLA, (printing with photopolymer resins), is the oldest 3D printing method. The building material in this method is liquid photopolymer resins [13],
- SLS, (sintering of polyamide powder) is the method with the greatest production potential. It involves sintering of powdered polyamide with a focused laser beam,
- PolyJet, (photopolymer resin spraying) is the most precise 3D printing method. The thickness of a single layer in this case reaches 14 micrometres. As with the SLA method, the building material is photopolymer resins,
- DMLS (metallic powder sintering) resembles the SLS method, except that the powdered material is completely remelted rather than just sintered. The building material is usually powdered aluminium and titanium alloys.

One of the most popular 3D printing methods used in scientific work is the first of the above methods - FDM. This method owes its popularity to several key factors such as: low material cost, ease of use, versatility of use and high availability of the material. Printers dedicated to the FDM method are relatively cheap, both in terms of equipment and consumables (filaments). This makes them available to smaller laboratories and research teams. The described technology is easy to use and widely available. Many FDM printers operate on the plug and play (PnP) principle, which makes them attractive to scientists who may not have advanced technical knowledge in the field of 3D printing. Additionally, such machines can use various materials, including thermoplastics with different physical properties, which allows for conducting diverse research. The variety of materials available for FDM printers is very large and includes materials such as: PLA, ABS, PETG, nylon or composite materials. This allows for easy experimentation with different mechanical and physical properties of printed objects. This is confirmed by a number of works in which this type of printing was used. In the works [14, 15] the energy efficiency of the piezoelectric system with microfiber composites (MFC) was analyzed. The tests were carried out in a wind tunnel, and the research object mounted on the beam was a bluff body printed with different filling using the FDM method. This element was not subjected to any processing and was used for tests directly after printing. However, there is a great potential for using the discussed technology to make models of various aircraft. In [16] a printed model of the Alenia Aermacchi M-346 Master aircraft was used, while in [17] the results of tests of a printed model of a hybrid multi-rotor aircraft with autorotation capability in a wind tunnel were presented. Another example is the work [18, 19] in which aircraft models printed in FDM technology were used. In the first case it was the Aduster gyrocopter, and in the second it was the Diamond DA42 aircraft. The aircraft models were subjected to external surface finishing. This is an important aspect in this method of model production. Surface treatment of the research object is also used in other printing methods. The article [20] discusses how surface treatments such as shot peening and electropolishing affect the mechanical properties and durability of components made of Ti6Al4V titanium, which is widely used in metal 3D printing technologies, especially in the aerospace and biomedical industries. The aforementioned work provides a review of research on such processing methods, suggesting that the combination of 3D printing technology and appropriate surface treatment can significantly expand the application possibilities of components made of Ti6Al4V, especially where excellent surface quality and high mechanical properties are required. In [21], the influence of the shot peening process on the corrosion resistance of 17-4PH steel, which was produced by means of 3D printing, was investigated. A significant improvement in corrosion properties was confirmed as a result of surface treatment such as shot peening. In [22], the influence of the ageing temperature in the heat treatment process on the properties of 17-4PH steel produced by the 3D printing method - DMLS (direct metal laser sintering) technology was investigated. The importance of optimizing the heat treatment parameters for obtaining the desired mechanical and corrosion properties was demonstrated. Due to the fact that the printed objects are often subjected to real loads, they must be tested in this aspect. When designing an object for printing, one should be aware of numerous technological parameters that affect the characteristics of the object printed in 3D technology [23–25]. For example, in the article [26] the analysis of mechanical properties of samples produced from traditional 3D printing filaments, i.e. polylactide (PLA), nylon 12 (PA12), acrylonitrile-butadiene-styrene (ABS), polyethylene terephthalate glycol (PET-G) and the same materials with the addition of carbon fiber was presented. The printing was carried out using the fused deposition method (FDM). The authors found that polymers reinforced with carbon fibers have better mechanical properties than unreinforced materials, but the production of samples from modified materials is more time-consuming due to the instability of the production process. The paper [27] presents the influence of the type of filament used and the type and degree of filling of objects printed using the FDM method. Many users of widely popular 3D printers do not take this into account when designing and printing products. Knowing the principles of operation of printers using polymer filaments and having experience in this type of printing, we are aware that the printing direction and the way the object is placed on the printer table are parameters that can have a significant impact on its strength properties. The experimental studies, the results of which are presented in this article, checked whether these parameters are really important and what impact they have on the mechanical properties of the resulting products [28]. Thanks to their conduct, basic knowledge was obtained as to which of the tested parameters are actually important for the mechanical properties of printed objects and which can be omitted in the printing process because they do not affect the key mechanical properties of elements manufactured using 3D printing technology.

Methodology of research

A set of samples was prepared by 3D printing in order to conduct the experimental study. For reliable results, the samples were made from a single spool of PLA filament, on the same printer - the MakerBot Replicator Z18. In this way, it was possible to achieve the greatest possible accuracy in the execution and properties of the created samples. A set of samples printed in different configurations is shown in Figure 1.

Most of the printers available on the market, as well as the one used to print the samples, allow the internal structure to be diamond-shaped. Such a structure – which is very popular in various applications - was used in the sample printing. The internal structure of the samples was varied by different filling levels (30%, 70%, 100%) as well as a different printing direction achieved by varied sample alignment during printing. If the filling increased, the pattern of the internal structure thickened. A depiction of the structure is shown in Figure 2 (30% filling).

The printer uses FDM technology. Owing to its sealed and heated working chamber, it allows good component quality to be achieved [29]. The very samples were printed in four different ways and using different degrees of filling. 120 impact test samples for the testing of impact strength as well as 60 static tensile strength test samples were printed. For impact tests, 40 samples with an internal filling of 30%, 40 samples with a filling of 70% and 40 full samples were printed. Four different types of print were used in each variant (10 samples in each positioning variant). These variants show the distribution of samples on the printer platform after printing. The variants were named: longitudinal

Figure 1. A set of samples printed in different configurations

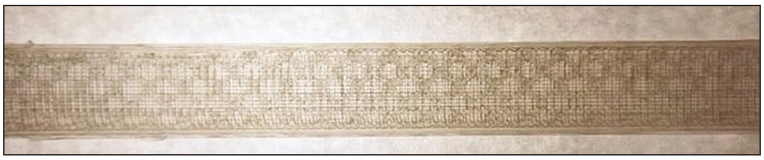

Figure 2. Internal structure of the sample

plane (Fig. 3a), transverse plane (Fig. 3b), longitudinal edge (Fig. 4a) and transverse edge (Fig. 4b). For the static tensile tests, 20 samples were printed in each of the 3 filling types, and in each filling type, as in the case of the impact test samples, 4 variations of positioning on the print platform were used (5 samples each). Thus, for both the impact test and the static tensile strength test, 12 different groups of samples each were obtained. After printing, the samples were properly sorted out and pre-cleaned of excess material from the base layer.

EXPERIMENTAL RESEARCH

Static tensile strength test

The static tensile strength test was conducted in accordance with EN ISO 527-2. In accordance with the standard, type 1B shapes were printed with a length of 150 mm, a width at the ends of 20 mm, a measuring section width of 10 mm and a recommended thickness of 4 mm (Fig. 5). The standard recommends a measuring section length of 75 mm,

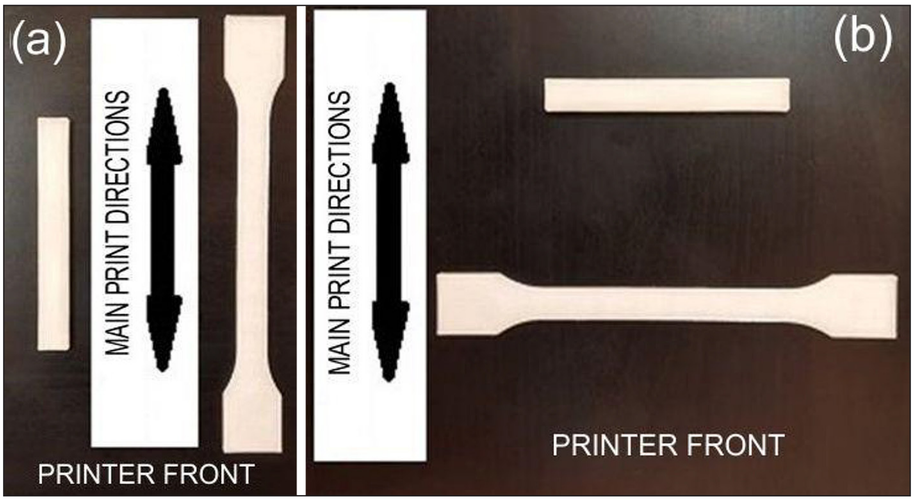

Figure 3. Printing variants of samples used in the tests: (a) longitudinal plane, (b) transverse plane

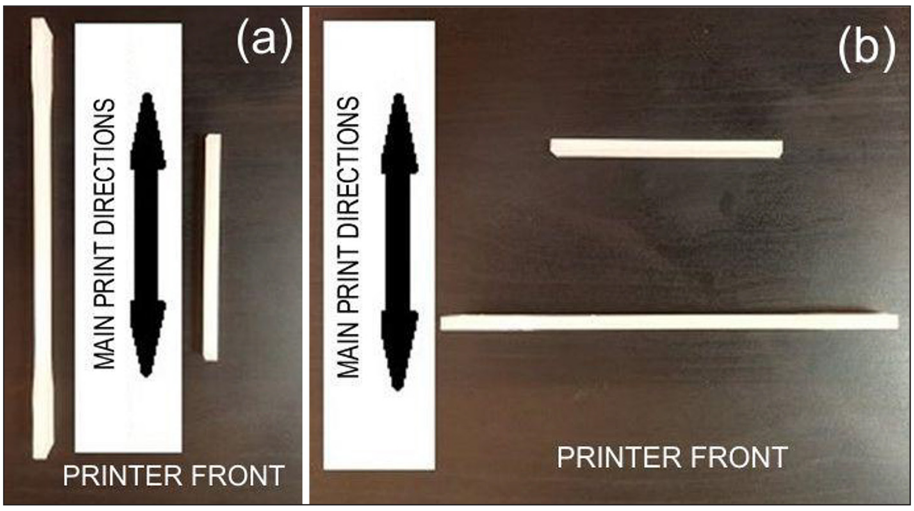

Figure 4. Printing variants of samples used in the tests: (a) longitudinal edge, (b) transverse edge

Figure 5. A sample for tensile strength test

but increasing it improves the accuracy of the test, especially when determining the modulus of elasticity, so in the tested samples it was 90 mm.

The samples were free from cracks, nicks and other imperfections, to the extent allowed by 3D printing technology. A Zwick/Roell Z100 universal testing machine was used for the static tensile test (Fig. 6). The traverse speed during the examination equalled 2 mm/min. In accordance with the recommendations of the research standard, the series number was 5 for each printing variant.

Figure 6. A sample during tensile strength test

The results of tensile tests of the samples are shown in Table 1. As it can be seen (Table 1), in the case of cross-plane printing, the highest average tensile strengths were achieved by 100% and 70% filled samples. The large scatter of results in this group made it impossible to compare the Young's modulus of the tested samples.

In the case of samples printed using the longitudinal in-plane method (Fig. 2a), the highest average tensile strength was also obtained for samples with 100% filling The mean value of Young's modulus was the highest for the samples with 70% filling, which also had the smallest scatter of results.

In the case of transverse edge-printed samples, the highest average tensile strength was obtained for samples with 70% filling. This group (70%) also had the most similar results. The highest mean value of Young's modulus was achieved for the 30% samples, followed by 70% and the lowest for the 100% samples.

In longitudinal edge printing, the highest average tensile strength value was achieved in the group of samples with 100% filling The

Table 1. Static tensile strength test results for different printing variants

Type of printing	Filling (%)	Average tensile strength (MPa)	Average Young's modulus (MPa)	Average elongation at failure (%)
Transverse plane	30	20.2 ± 0.9	109.5 ± 24.8	9.0 ± 1.6
	70	28.0 ± 0.7	110.9 ± 53.0	10.8 ± 1.6
	100	28.1 ± 0.3	116.5 ± 21.5	9.6 ± 0.8
Longitudinal plane	30	21.8 ± 1.5	85.0 ± 25.0	10.1 ± 1.7
	70	28.1 ± 0.3	125.4 ± 19.2	8.1 ± 0.7
	100	30.4 ± 0.8	113.8 ± 27.5	10.3 ± 1.1
Transverse edge	30	27.0 ± 2.6	92.6 ± 8.1	9.8 ± 0.3
	70	32.6 ± 1.4	81.6 ± 15.9	11.6 ± 1.0
	100	31.3 ± 3.0	67.1 ± 7.3	9.7 ± 0.3
Longitudinal edge	30	24.2 ± 2.0	69.9 ± 17.2	10.6 ± 0.8
	70	32.4 ± 2.9	83.8 ± 4.7	13.4 ± 0.8
	100	34.0 ± 2.6	88.7 ± 16.7	12.0 ± 1.1

highest value of mean Young's modulus was also achieved in this group of samples. The highest average elongation at failure was obtained for 70% filling.

As it can be seen, (Table 1) the manner of printing and filling affect the static tensile strength. The highest average tensile strength was achieved for 100% filled samples made in longitudinal edge printing (34.0 MPa) whereas the lowest for 30% filled samples in transverse plane printing (20.2 MPa). The highest average Young's modulus was achieved for samples with 70% filling in the longitudinal plane print (125.4 MPa) and the lowest for samples with 100% filling in the transverse edge print (67.1 MPa). The highest average elongation at failure was recorded in the group of samples with 70% filling for the longitudinal edge print (13.4%), and the lowest for samples with the same degree of filling but a longitudinal plane variant (8.1%).

By analysing the graph of average tensile strength values, it can be seen that, for the 30% filling (Fig. 7), the highest average value was obtained for the samples in the transverse edge print, being equal to 27.0 MPa, while the lowest average strength value was obtained for the samples in the transverse plane variant, equal to 20.2 MPa. The average strength of the transverse edge variant was almost 33% higher than the transverse plane variant of the samples. This may be due to the fact that with transverse edge printing, successive layers were applied with a shorter gap time (due to the shorter path of the head movement) than in the case of plane printing and this allowed the structure to blend together better.

For samples with 70% filling (Fig. 8), the highest tensile strength was also obtained for the transverse edge print, and the lowest one also for the transverse plane variant. These amounted to 32.6 MPa and 28.0 MPa, respectively. In this case, the samples in longitudinal edge printing, on average, showed 16% higher strength than samples in transverse plane printing.

In the case of solid samples (Fig. 9), the highest strength was characterised by samples in the longitudinal edge variant and the lowest by samples in the transverse plane variant. The average strength results in this case were 34.0 MPa and 28.1 MPa, respectively. The longitudinal edge samples for the solid print showed 21% higher tensile strength than the samples in the transverse plane print. The differences appear to be due to

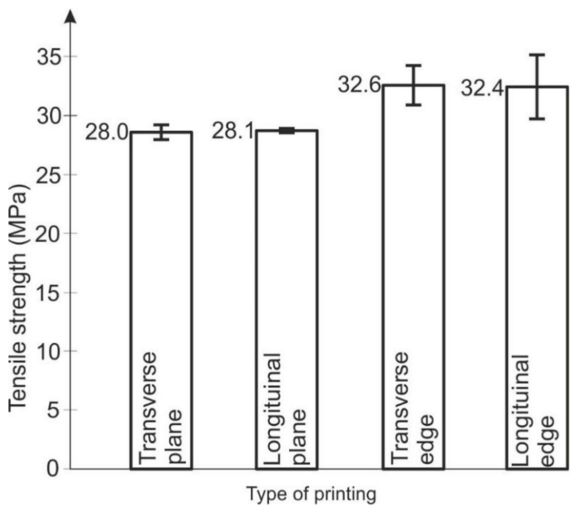

Figure 8. Average tensile strength of samples with 70% filling

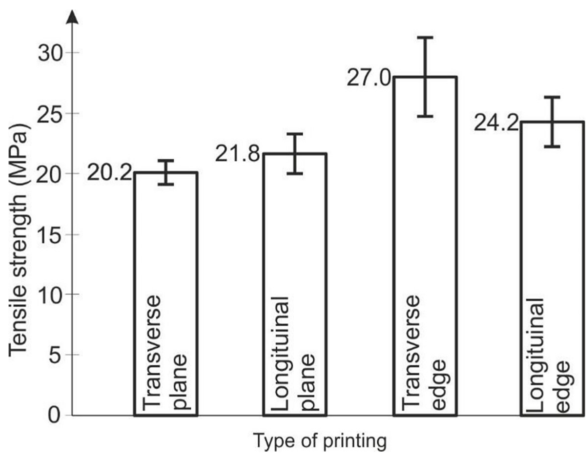

Figure 7. Average tensile strength of samples with 30% filling

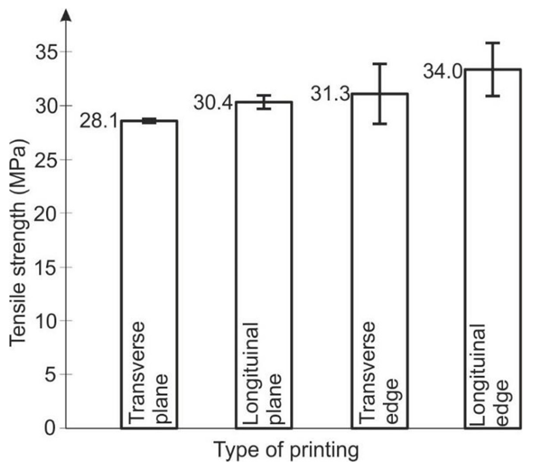

Figure 9. Average tensile strength of samples with 100% filling

the fact that with transverse edge printing, the time between layer-by-layer application is much shorter than the time the print head has to travel in the case of transverse plane printing. The plastic in the first case (probably still in the plastic state) shows a better bonding capacity, which has a positive effect on the formation of a strong structure.

Impact strength testing

Impact tests were carried out using a Galdabini Impact 25 pendulum hammer, with a maximum pendulum energy of 7.5 J. The test was conducted using the Charpy method.

The impact strength test was performed in accordance with EN ISO 179-1 standard. The tests were performed with a plane impact. The principle of the test is based on placing the sample in the form of a beam between supports and then releasing the pendulum, which strikes the sample with maximum energy (7.5 J in the test). The samples had no visible imperfections and were made with the precision depending upon capability of the printer. The type of fittings used for the test are, according to the standard, number 1, 80 mm long, 10 mm wide and 4 mm thick (Fig. 10). Each series was composed of 10 pieces for each printing variant. Due to the brittleness of PLA, the samples broke completely on impact. This type of damage is referred to as 'C' in the standard. The average values, as well as the individual sample results themselves, were recorded to two significant digits.

In the group of transverse edge-printed samples, the highest value of average impact strength was obtained for samples with 100% filling. The smallest scatter of results was characterised by samples with 70% filling.

For samples made in longitudinal edge printing, the highest average impact strength value was also obtained for samples with 100% filling The lowest average impact value in this print variant was obtained for the 70% filled samples, however, the results in this group were the most recurrent. In the group of longitudinal plane-printed samples, the highest average value of impact strength was obtained for samples with 70% filling As it can be observed, for samples in cross-plane printing, the highest average impact strength was also obtained for samples with 70% filling.

Based on a comparison of the average impact strength values in the different filling groups and print variants, the highest average impact strength value was obtained for the longitudinal edge print with 100% filling. The lowest value of the average impact strength is shown by the material in cross-plane printing with a filling of 30%. The smallest scatter in the results was obtained for the samples made in the cross-edge printing with 70% filling.

In the group of all print types with 30% filling (Fig. 11), the highest average value was achieved for longitudinal edge printing and was equal to10.70 kJ/m^2. The lowest average impact value in this filling group was 5.97 kJ/m^2 for the transverse plane printing. This means that samples in longitudinal edge printing, on average, showed 79% higher strength than samples in transverse plane printing. This may be due to the fact that the bands of material in longitudinal edge printing were applied perpendicularly to the direction of load application and in transverse plane printing, parallel to the direction of load application.

For all types of samples with a filling of 70 % (Fig. 12), the highest average impact strength result was obtained for the transverse edge-printed samples and was equal to 10.62 kJ/m^2. The lowest average impact strength result was again recorded in the cross-plane printed sample

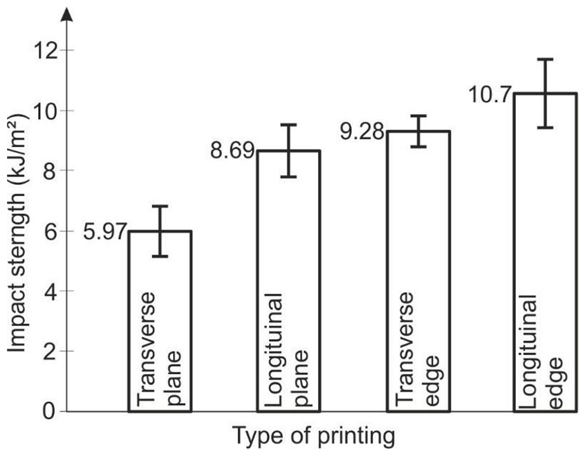

Figure 11. Average impact strength value for samples with 30% filling

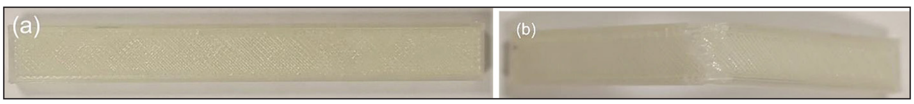

Figure 10. A sample for impact strength test: (a) before test, (b) after test

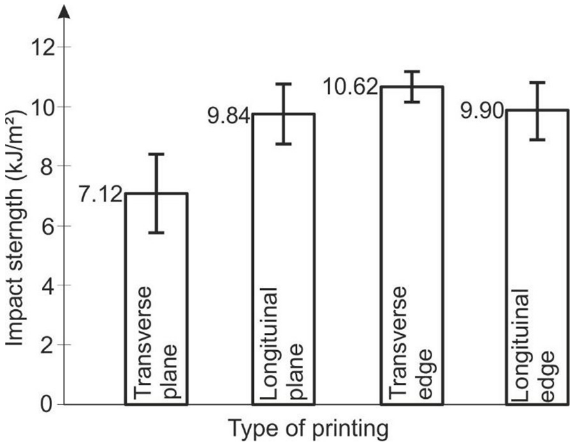

Figure 12. Average impact strength value for specimens with 70% filling

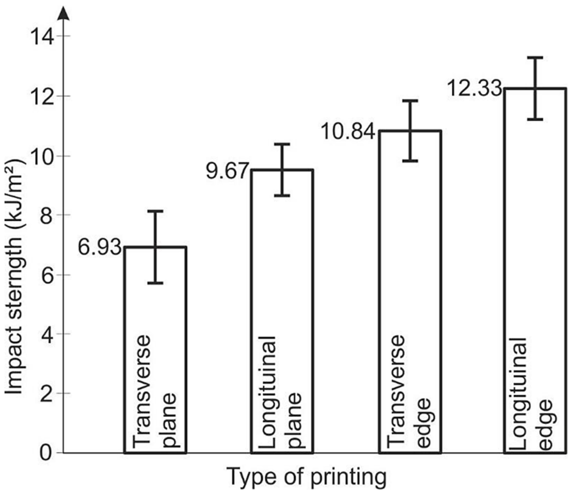

Figure 13. Average impact strength value for samples with 100% filling

group and was equal to 7.12 kJ/m^2. The average impact strength of the highest impact strength samples was 49% higher than that of the lowest impact strength samples.

In the group of 100% filled samples (Fig. 13), the highest average impact strength was obtained for longitudinal edge printing and reached 12.33 kJ/m^2. The lowest average impact strength value was again recorded in the cross-plane printed sample group and was equal to 6.93 kJ/m^2. Samples in longitudinal edge printing were, on average, 78% stronger in this comparison than samples in transverse plane printing. Of all the samples tested, the highest average impact strength value was achieved for longitudinal edge printing with 100% filling and was 12.33 kJ/m^2, while the lowest was achieved for transverse plane printing with 30% filling, being equal to 5.97 kJ/m^2. The difference in impact strength in this case was 106.5%.

The impact strength test results confirm that the infill level has an impact on the impact strength of PLA printed parts, and that the impact strength decreases with decreasing infill level, although the experiments conducted are not consistent in this respect in all cases. The lowest impact strength of the samples obtained in the transverse plane printing indicates that the quality of the connection of adjacent material paths is most important if the applied load affects the separation that occurs in the impact strength test. During the load application, the sample undergoes a deformation that initiates the separation of adjacent material paths on the tensile side of the sample. Therefore, it seems worthwhile to analyze the printing parameters in detail in order to improve the quality of the connections of adjacent material paths.

CONCLUSIONS

Based on the findings of the conducted research, it can be concluded that the internal structure of 3D printed elements affects their strength; both static tensile strength and impact strength. Elements with a higher degree of filling are characterized by greater strength, although this is not an expected rule and this phenomenon requires further research.

An important observation is that the way the sample is oriented during printing has a significant effect on the mechanical properties of the produced part. The strength of parts 3D printed from PLA is higher when printed along the long edge, which means that the adhesion of successive layers plays an important role in building strength, as seen in the results obtained for transverse plane samples, which have impact strengths that are at least 30% lower than samples printed in other configurations. The obtained results can serve as a guide for practical printing applications.

Based on the tested parts made of PLA material, it can be concluded that the strength of 3D printed parts is difficult to estimate unequivocally and largely depends on how they are arranged on the printer platform. To confirm the obtained results, samples made of a different type of material should be tested.

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