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TESTING MATERIALS USED FOR 3D PRINTING

Badania materiałów stosowanych do druku 3D

Abstract: *The paper addresses issues related to 3D printing in repairing military equipment. It quoted a short story on the invention of the 3D printer and the development of printing technology. The significance of knowledge of the materials employed in 3D printing is discussed in the further part. To this end, the authors reviewed selected strength-related tests (tensile strength, in particular), to determine their application possibilities. Test samples were prepared based on a Polish standard and the material provided by two manufacturers. The tests were conducted using a Zwick Roell Z100 machine. The obtained results were presented as graphs. The paper is concluded by a short summary and an indication of further research.*
Keywords: 3D printing, 3D printing materials, material strength, strength testing

Streszczenie: *W artykule poruszono kwestię druku 3D w naprawie sprzętu wojskowego. Przytoczono krótką historię drukarki 3D oraz rozwoju technologii druku. W dalszej części omówiono znaczenie znajomości materiałów stosowanych w druku 3D. W tym celu przedstawiono wybrane badania wytrzymałościowe, głównie wytrzymałość na rozciąganie, w celu określenia możliwości ich zastosowania. Próbki do badań wykonano w oparciu o polską normę i materiał dostarczony przez dwóch producentów. Badania zrealizowano na maszynie Zwick Roell Z100. Otrzymane wyniki przedstawiono graficznie na wykresach. Na zakończenie dokonano krótkiego podsumowania oraz wskazano kierunki dalszych prac.*
Słowa kluczowe: druk 3D, materiały do druku 3D, wytrzymałość materiału, badania materiałowe

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1. Introduction

Spatial printing technology finds many applications in everyday life and in industry. Its development was initiated by Charles Hull, who invented a 3D printer that printed using stereolithographic technology. Stereolithography became commonly used at the end of the 1980s. It was then when research commenced focusing on similar spatial printing technologies, namely, FDM (*Fused Deposition Modelling*), invented in 1988 by Scott Crump, founder of Stratasys and SLS (*Selective Laser Sintering*). Yet another 3D printing (3DP) technology was patented several years later. It is similar to 2D ink jet printers [1-4].

3D spatial printing utilizes several types of materials and technologies for creating object. The key elements that distinguish a print type are the material used for the model, quality (execution accuracy), and the operating range of temperatures for the device and the medium that shapes the form (e.g., laser or extruder) [5-6].

However, the application of individual materials requires vast knowledge of their capabilities, resistance to various operating loads and conditions, in particular. To this end, it is recommended to conduct appropriate strength tests aimed at identifying the resulting object's mechanical properties. Due to the relatively wide range of tests and the limited possibilities to present them herein, the authors chose only those that seem to be rather most important [7-9].

2. Test specification

Test samples were prepared according to the Polish standard EN ISO 527-1 and ISO 179-1: 2000 (Fig. 1).

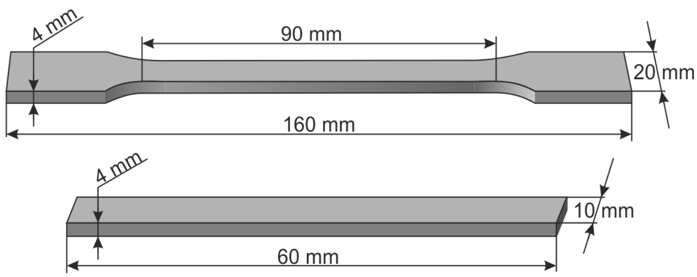


Fig. 1. Prepared test samples (using CAD software)

Sample sizes were unified relative to the entire range of the tested material. In the case of minor dimension differences, corrections were introduced in the strength testing devices. Samples supplied by third-party producers were printed based on a model developed in the

CAD environment (Fig. 1), which enabled testing materials of comparable dimensions. The first and largest test material group comprised samples produced on a Z18 Replicator printer using PLA. The printing material was supplied by two manufacturers: MakerBot and 3D GENCE - manufactured for Navi Tracer Polska Sp. z o.o.

Tensile strength test samples were produced in several printing variants relative to the test assumptions included in the test algorithm. The factors distinguishing individual PLA material groups included:

- material manufacturer,
- infill type,
- infill percentage,
- sample printing orientation.

Printed test samples exhibited two infill types, namely, hexagonal and linear. The impact of the infill on the properties of the printed material was tested.

Another criterion affecting individual samples was the infill percentage of the sample. FDM printing on a MakerBot printer provides users with an option to control the material percentage share in filling internal sections of printed bodies. Material percentage share may be preset with an accuracy increment of almost one percent (i.e., 1% - 100%) – Fig. 2.

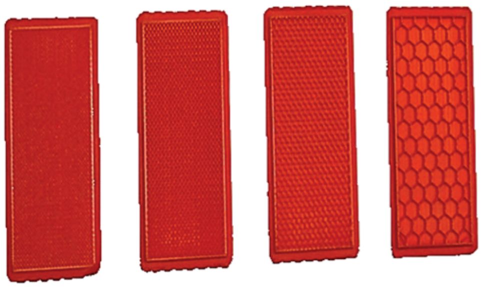


Fig. 2. Material percentage share (hexagonal infill), from left to right: 70%, 50%, 30%, 10%

Tests involved using samples with a percentage infill ranging from 10% to 100%, with 10% increments and with a hexagonal infill type. To limit the number of test materials, samples with linear infill were prepared with an infill percentage of 10, 50, 70 and 100%. The comparison of test results for samples with a similar infill percentage, yet different in terms of infill type, was to enable determining the impact of infill type on the strength of the printed element.

The percentage share of material mass in body filling is directly associated with the printing time – the greater the material percentage share, the longer the printing time.

Selected infill affects specific printing time, its form and material consumption. These are the software elements that enable users to control printing form and quality, e.g., through interfering with layer thickness, amount of material used for printing and printing time.

Fig. 3. Examples of infill types (10% infill) applied in a MakerBot printer left to right: hexagonal, diamond, Moroccan star, linear, catfill

A further factor analysed in the course of the tests that directly translated to strength was the positioning of the body in the printer chamber. The procedure involved verifying the positioning of the model to be printed on the final strength properties of a product – Fig. 4.

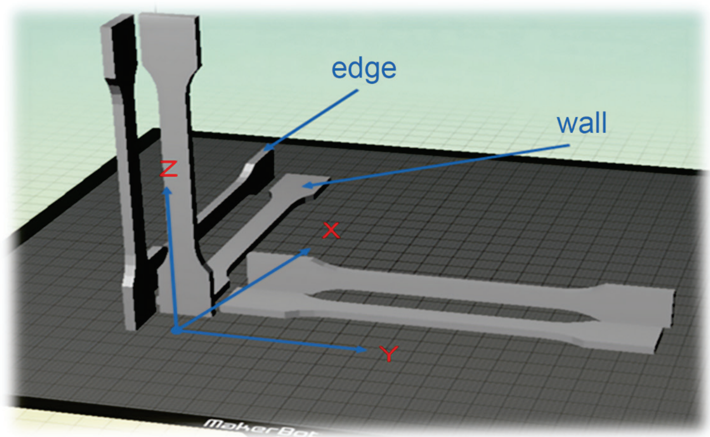


Fig. 4. Examples of sample model positioning under different printing variants

Test samples were printed in series of 5 to 7 units, under previously presented material and printing settings.

Tensile test samples were printed on a MakerBot Replicator Z18 printer. The input material was a 1.75 mm thick PLA filament supplied by the printer manufacturer, in 0.9 kg reels; specification MP05775 LOT7125. The prepared samples had a widened 7 mm raft (4 mm is the standard), to prevent potential printout degumming from the table.

The software provided with the printer enable simulating sample positioning on the platform and analysing the position of each layer applied when the material is fed by the extruder.

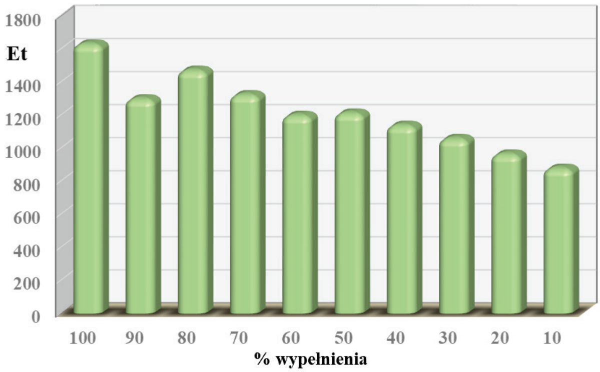
3. Tensile strength testing

The first test involved assessing tensile strength, and was conducted using a Zwick Roell Z100 machine. Initial force on the machine was set to 0.2 MPa, and the tensile modulus rate and test rate was 2 mm/min. Test results for the PLA material provided by MakerBot concerned sample diversification in terms of infill percentage.

It was found that a decrease in the percentage share of the material in the sample infill entailed a decrease in the Young's modulus value – Fig. 5.

The permissible material tensile strength behaves in a similar manner. An infill percentage share leads to its reduction ranging from 30 to more than 50 MPa – Fig. 6.

Whereas the strain corresponding to tensile strength falls in the range of 3.5 ÷ 4 %. This is highlighted by a virtually negligible impact of the infill percentage on strain – Fig. 7.



% Wypełnienia – *infill* %

Fig. 5. Impact of material percentage share on the Young's modulus

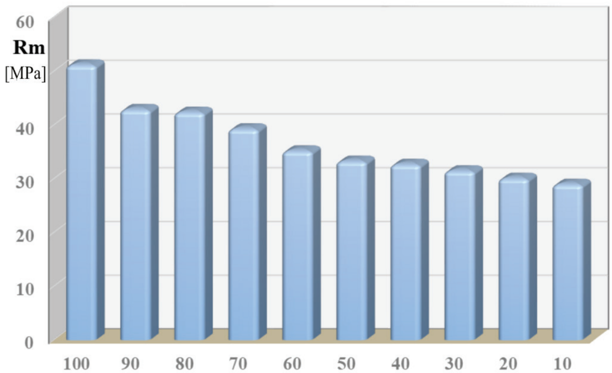


Fig. 6. Permissible tensile strength

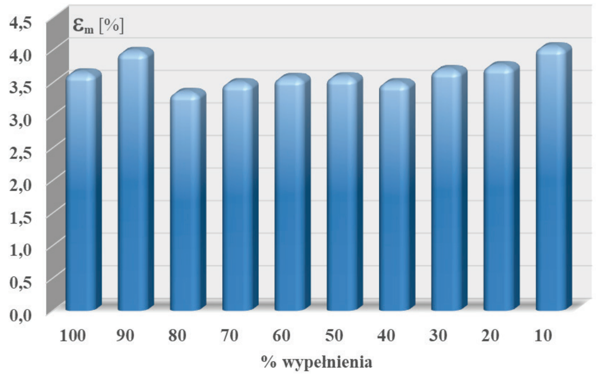


Fig. 7. Strain corresponding to tensile strength

X, Y, Z orientations were tested using PLA material samples with hexagonal infill and printing parameters as per printer software settings.

The samples were printed on a MakerBot Z18 printer, using the material provided by one manufacturer, with an infill percentage of 10, 30, 50, 70 and 100 in series of 5 samples per cycle. The conducted analysis applies to mean values of the Young's modulus, standard deviation and confidence interval.

The conducted tests investigating the impact of sample printing orientation on Young's modulus value indicate significant result diversification – Fig. 8.

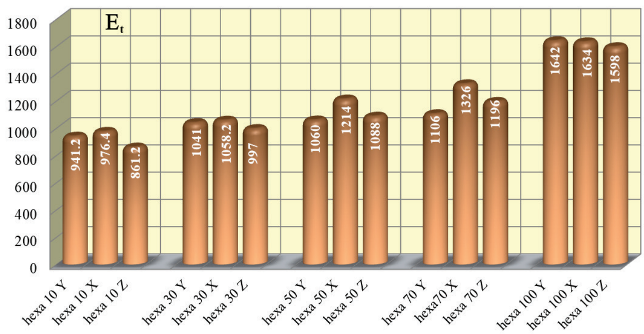


Fig. 8. Impact of sample printing orientation on the mean Young's modulus

The results also demonstrated the significant impact of print model positioning on the value of the Young's modulus. This experiment revealed that the greatest value of the analysed coefficient was exhibited by samples printed with an X orientation. Lower values were achieved by Y and Z oriented samples, with poorer values in the Z orientations. The differences between Z-oriented and X-oriented samples, for an identical infill percentage range varied from 100 to 150 MPa.

The test showed correlation between sample printing orientation and the permissible tensile strength – Fig. 9.

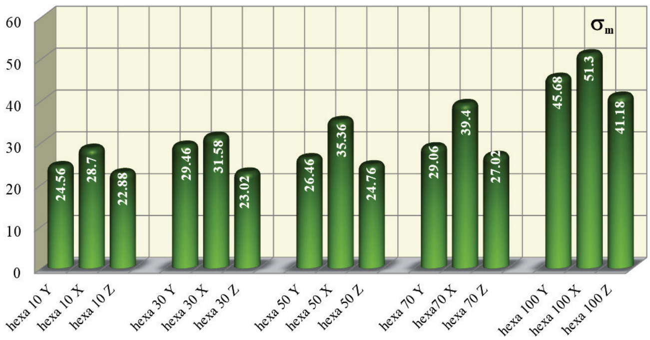


Fig. 9. Mean permissible tensile strength in the context of print plane orientation

The tested samples with an infill percentage from 10 to 100, and with X orientation, were characterized by a significantly higher permissible tensile strength range (differences from several to a dozen or so MPa) relative to Z and Y orientation samples. A comparison of the samples in the X and Z orientations indicated tensile strengths of Z-orientation samples lower by several MPa.

Figure 10 shows the standard deviation of individual samples with the following infill: 10, 30, 50, 70, 100. Young's modulus standard deviation varies from 14.10 (X-orientation sample with an infill of 10%) to 91.26 (Y-orientation sample with a 30% infill).

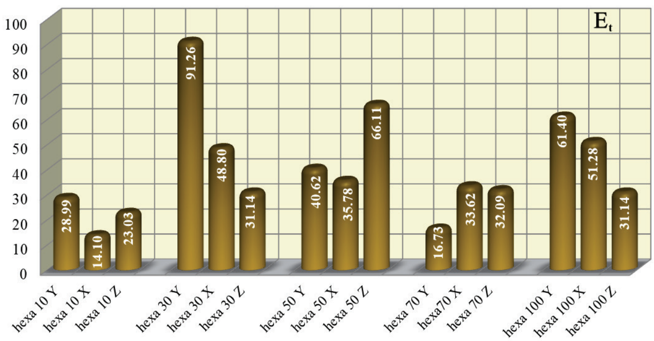


Fig. 10. Impact of print sample orientation on the Young's modulus standard deviation

The mean standard deviation of the Young's modulus for the entire range of samples amounted to 40.41. In turn, the mean Young's modulus standard deviation for individual orientations amounted to 47.80 for Y, 36.71 for X and 36.70 for Z.

Figure 11 shows a change in the standard deviation of permissible tensile strength in relation to samples with the following infill percentage: 10, 30, 50, 70, 100. Samples in Y, X, Z printing orientation.

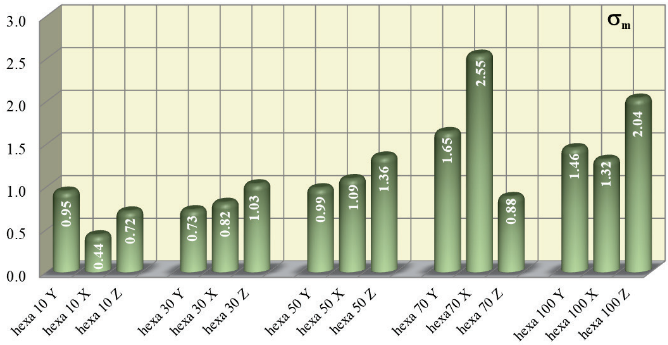


Fig. 11. Impact of print sample orientation on the permissible tensile strength standard deviation

The mean standard deviation of the permissible tensile strength for the entire sample range was 1.20, whereas the permissible tensile strength standard deviation for individual printing orientations within the studied range was 1.15 for Y, 1.24 for X and 1.21 for Z.

The studied sample group was characterized by a Young's modulus confidence interval ranging from 12.36 (X-oriented sample with a 10% infill) to 79.99 (Y-oriented sample with a 30% infill) – Fig. 12. Based on the results from the graph, the authors calculated the mean Young's modulus confidence interval for all samples, regardless of the printing orientation type. The obtained value was 35.27. The mean confidence interval in relation to printing orientation was also calculated. The obtained results were 31.73 for the Y orientation, 32.18 for X and 41.90 for Z.

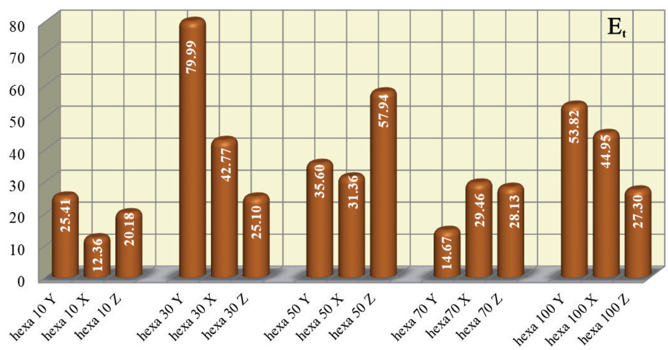


Fig. 12. Impact of sample printing orientation on the Young's modulus confidence interval

In terms of the permissible tensile strength of the studied samples, the confidence interval ranged from 0.38 (X-oriented samples with a 10% infill) to a max. of 2.24 (X-oriented samples with a 70% infill) – Fig. 13.

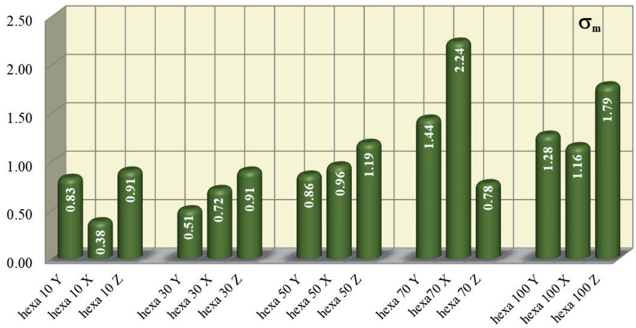


Fig. 13. Impact of sample printing orientation on the permissible tensile strength confidence interval

Based on the obtained graph results, the authors calculated a mean confidence interval for permissible tensile strength at 1.06 for the entire range of tested samples. Moreover, the authors calculated mean confidence interval for the permissible tensile strength, taking into account sample printing orientation, was from 0.98 (X orientation), through 1.09 (Y orientation), to 1.11 (Z orientation).

A series of tests were then undertaken aimed at studying the impact of infill type on print-out strength properties. The obtained results show the impact of infill type on the value of the Young's modulus. Hexagonal and linear infill types were selected for the study. The tested infill types are the most popular available for FDM. The obtained results indicated an impact on the value of the Young's modulus. For example. the mean modulus for samples with a hexagonal (100% infill) is approx. 1633 MPa, while the same quantity for samples with a linear infill (100%) is approx. 1594 MPa – Fig. 14.

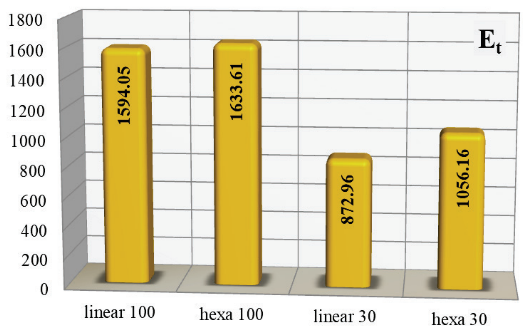


Fig. 14. Impact of sample infill type on Young's modulus

Both sample series were prepared using the same material and the same printer, as well as in the same pigment colour and employing a 100% infill. The obtained differences in the Young's modulus (approx. 40 MPa) are insignificant, but indicate the impact of the infill type on the strength properties of materials. This impact is evident for a lower infill percentage, e.g., for samples with a 30% infill, the difference between linear and hexagonal infill reaches 183 MPa in favour of the latter. A decrease in the material percentage share in sample infill entails the growing significance of infill type selection as a factor impacting the Young's modulus.

Other obtained results included permissible tensile strength values. Result analysis confirmed the differences in the values of this coefficient dependent on infill type selection – Fig. 15. Test results demonstrated a difference of approx. 4 MPa between linear and hexagonal infill in favour of the latter. A noteworthy fact is that this value differs in almost any sample material percentage share range.

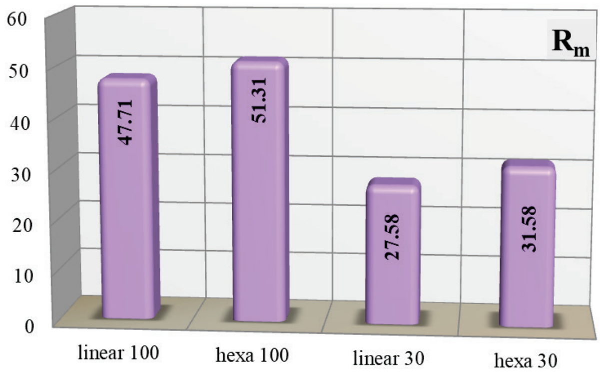


Fig. 15. Permissible tensile strength depending on sample infill type

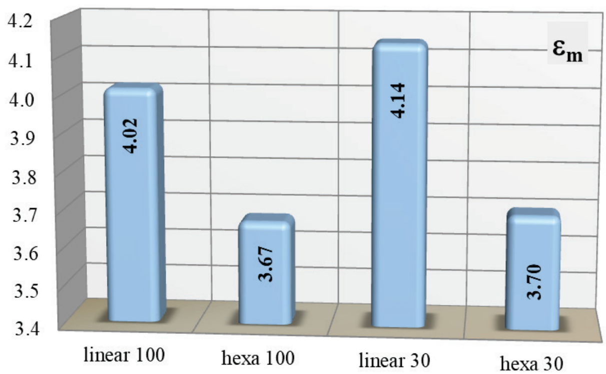


Fig. 16. Impact of sample infill type on strain corresponding to tensile strength

A significant impact on the percentage strain corresponding to strength was identified when analysing the result comparing both infill types. Herein, a significant difference between linear and hexagonal infill was identified in both studied series, with a 100% and 30% infill – Fig. 16. The difference in each case was approx. 0.3-0.4%, which confirms the impact of infill type selection on the strength properties of the tested material.

Therefore, It can, therefore, be said that the lower the model infill percentage, the higher the impact of infill type selection on the tested physical and strength properties. It should be emphasized that infill type selection greatly affects object mass, as well as the printing time and price.

4. Summary and conclusions

The conducted analysis indicated that the quality and physical properties of a printed element are impacted by, among others, model positioning – print-out orientation (X,Y,Z), material selection – manufacturer, printing equipment, printing technology – associated with material selection and its properties, as well as other factors. The analysis process involved printing hundreds of samples based on different materials and different printing technologies. The results clearly demonstrate the diversification of physical parameters due to factors that impact model printing in a printer. The selection of the printing technology and the material itself should be based on the print quality and parameters, and take into account the application and parameters of the aviation equipment.

The most important conclusions drawn during the strength tests include, among others:

- the need and possibility to gradually employ spatial printing in creating and repairing aviation equipment,
- the applied printing and rapid prototyping technology enables creating aviation equipment far from manufacturing plants, which significantly enhances the capabilities of restoring equipment readiness – under combat conditions in particular,
- knowledge of strength properties exhibited by materials used, and the application of such modern technologies as CAD, CAM and CAE significantly improve and streamline the performance of the engineering and aviation services responsible for aviation equipment operation.

Further effort related the issue should concentrate, among others, on appointing a team dealing with the creation of aviation equipment databases, and analysing the potential application of specific materials and printing technology in producing specific parts.

It is suggested to study the possibilities of a mobile kit for rapid prototyping and creation of aviation equipment.

The kit may be equipped with a 3D scanner and CAD, CAM and CAE software. Additional equipment of test configurations can also include strength and fatigue testing machines. The main equipment of such a kit should be 3D printers, depending on the type of needs and intention offering printing in technologies that ensure technical support for operated aviation equipment types.

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