Shear and Impact Toughness Testing of 3D Printed Polymer Specimens Obtained by Fused Deposition Modeling

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Abstract: - In this work, mechanical tests were performed on 3D printed polymer test specimens obtained using Fused Deposition Modeling technology. The test specimens are from different groups of materials - easy to print, resistant to wear and high temperature, and mechanically strong and elastic. All were printed with identical characteristics: layer height, printing direction, percentage of filling, and grid type. They differ in printing temperature, printing speed, and cooling during the printing process. A standard testing machine was used, equipped with a shear testing device, and a Charpy hammer was used for impact toughness testing. The shear strength and the energy required for impact failure were determined. Two of the tested materials were subjected to additional heating to strengthen them. The results for one of them- PC showed the highest shear strength of 23 MPa, while the highest impact strength was obtained for the PC that was not heated.

Key-Words: - Shear strength, Impact toughness, 3D printing, Fused Deposition Modeling, Polymers, Test specimens, Heating.

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1 Introduction

3D printing, also known as additive manufacturing, is one of the key technologies for future precision manufacturing to operate processes in various industries such as product development, mechanical engineering, biomedical innovation, construction, etc., [1]. The primary reasons for the increasing applications of 3D printing are the rapid prototyping of complex geometries, reduced weight of the manufactured part, reduced material consumption (due to the elimination of waste and the use of recyclable materials), high manufacturing accuracy, and a shorter production cycle, [2]. There are many rapid prototyping methods, but the most widely used method is Fused Deposition Modeling (FDM), [3]. This technology is the most competitive due to the low cost of 3D printers compared to other technologies. There is a large selection of filaments and the most usable are: polylactic acid (PLA), acrylonitrile butadiene styrene co-polymers (ABS), and polycarbonate (PC), [4], [5]. New materials are increasingly being created to achieve better material characteristics. They are enriched with impurities of steel, carbon, nanoparticles and fibers, and are called composite materials, [6]. 3D objects are produced by melting thermoplastic filaments at temperatures up to 280 degrees, passing through a nozzle and building up layer by layer until they are completed. The advantages of FDM printing over conventional production are that each produced object can have a different infill percentage and a different type of pattern, [7]. Changing even one of the printing parameters, such as temperature or fill percentage, also changes the mechanical properties. This is precisely what necessitates the continuous study of test bodies obtained by 3D printing with the FDM method.

Knowledge of the mechanical properties of materials is important for engineers when making decisions in the design of structural elements. Choosing the material, the shape, and the dimensions of the structural element are definitive decisions that ensure it can withstand the specified load. Also, researchers in scientific fields gain knowledge by

testing new materials, which they can compare with already established ones.

There are many methods for testing materials, through which their safety, reliability, and effectiveness can be determined. One of the most important is the mechanical properties of materials, such as shear and impact resistance tests. They are determined through standard tests. Through innovative technologies such as scanning electron microscopy (SEM-DIC), the quasi in-situ tensile tests and crystal plasticity (CP) simulation can be evaluated. The simulation results can effectively capture the overall micromechanical behavior, including the strain field, average grain strain, strain tendency along paths, and slip variants activation, [8], [9].

Shear is a mechanical test used to determine the shear strength (Rms) of the materials. For this purpose, a specimen made of the tested material is mounted in a shear fixture, which is subjected to tension or compression using a standard testing machine, [10], [11], [12], [13]. Shear testing applies to a variety of materials, including metals, polymers, ceramics, composites, and even soil and rock in geotechnical engineering, [10], [11], [14], [15], [16]. Knowledge of shear strength is significant for many industries, including automotive, aerospace, civil engineering, and product design, as it helps predict the behavior of a material under shear stresses. Bolts, rivets, pins, axles, and other structural elements are often subjected to this type of resistance.

Shear strength can be used to assess the strength properties of materials. The shear strength of metals is approximately 60% of the tensile strength. In [13], two methods are applied to test thin-walled steel pipes by compression and tensile, with the shear strength of metals generally being in the range of about 220-300 MPa. It would be useful to establish such a relationship for polymeric materials obtained by additive manufacturing.

Impact resistance is an important indicator in evaluating materials used in the production of protective equipment, such as helmets, safety glasses, etc. They must necessarily pass a mechanical impact toughness test before being available to consumers. Impact toughness is the energy required to break a test specimen of standard dimensions when an impact load is applied. It is determined by a standard procedure, most often using the Charpy method. This method uses a pendulum hammer, which breaks the test specimen with a notch in one blow. The breaking energy Ac is the difference between the energy of the hammer in its initial and final positions. Impact toughness can be used to assess the deformation properties of materials.

Thermoplastic composite materials are increasingly used in the aerospace industry. These materials are recyclable and can be used repeatedly by melting, forming, and the production process does not take much time, [17]. According to [18], [19], [20], they have superior impact resistance compared to their metal and thermoset composite counterparts. In [21], it was found that more than 80% of the damage to composite structures is due to impact. For this reason, in [17], a study was conducted on methods for their welding. The shear test method was used to evaluate the strength of different types of welds in polymeric materials - resistance, induction and ultrasonic welding. Therefore, impact toughness testing is important in the design of such structures.

This work aims to perform shear and impact toughness tests on test specimens produced by FDM printing, at the same infill percentage and with the same type of grid. Different types of materials were used - easy to print, resistant to high temperatures, wear-resistant, mechanically strong and flexible, [4]. The selected printing mode is suitable for rapid prototyping with a strong infill pattern, which is suitable for parts used in everyday life, household and industry.

2 Equipment Used

2.1 Shear Test

The shear tests were carried out with a hydraulic testing machine ZD20. Figure 1 shows the principle diagram for experimenting. A shear test fixture 3 is mounted in the grips 1 and 2 of the testing machine. Under the action of the force F exerted by the machine, the knives 4, 5, and 6 cut the cylindrical test body 7 into two sections. The test specimen is shown in Figure 2 with a diameter d=8 mm and a length 70 mm.

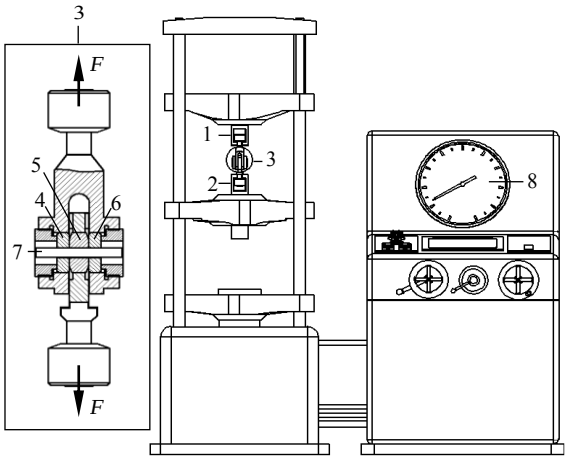

Fig. 1: Shear test setup

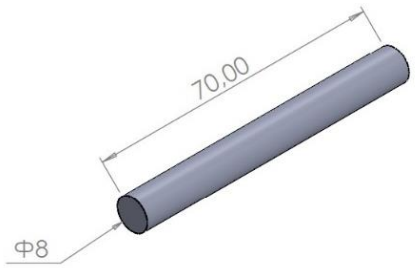

Fig. 2: Shear test specimen

The maximum breaking force F_{ms} is read on scale 8 of the machine. The shear strength R_{ms} is calculated by the formula (1):

$$R_{ms} = \frac{2F_{ms}}{\pi d^2} \quad (1)$$

where:
R_{ms} is shear strength;
F_{ms} is the shear force of the test specimen;
d is the diameter of the specimen.

Figure 3 (Appendix) shows snapshots taken during the shear tests. It includes images of the testing machine, the specimen mounted in the shear fixture, and the fractured specimens. Each specimen is divided into 3 parts.

2.2 Impact Toughness Testing

The impact toughness tests were carried out with a Charpy hammer, shown in Figure 4. Figure 5 shows the shape and dimensions of the test piece.

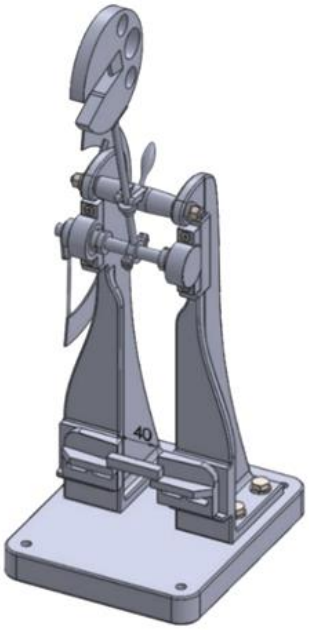

Fig. 4: Charpy hammer

It is rectangular in shape with dimensions of 10x55 mm and a 45° angle in the middle with a depth of 2 mm. The test piece is placed so that the pendulum hammer hits it where the notch on the test piece is. The pendulum hammer is placed in the upper position, released, and by free fall, hits and destroys the test piece. The destruction energy Ac is read from the Charpy hammer scale.

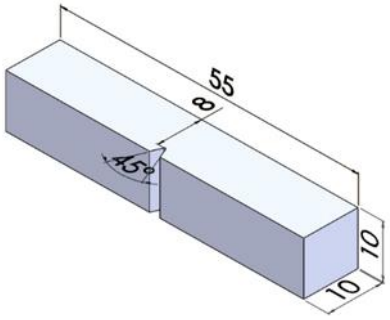

Fig. 5: Impact toughness test specimen

Figure 6 (Appendix) shows snapshots taken during the impact toughness tests. The images sequentially present 3D printed test specimens made of polymer material, positioning of the test specimen in the Charpy hammer, preparation of the pendulum hammer in the starting position, and destroyed test specimens.

3 Test Results

The test bodies were made using a 3D printer by FDM technology. Depending on the specifics of the printing materials, the test bodies were produced on two 3D printers. The materials easiest to print were extruded on a Tevo Tornado - PLA, PLA Wood and PETG, and the more specific ones on an Ultimaker S5- ASA, CPE HG 100, FilaFlex SEBS, and PC. The Cura software program was used to set the printing mode. The printing parameters, such as temperature, printing speed, and cooling, are described in detail in a previous work by the authors, [7]. The specimens were printed with a consistent nozzle diameter of 0.4 mm and a material batch. The remaining characteristics for the filling percentage and the type of filling pattern are the same for all test bodies, namely 30% filling, Geroid grid type, and 0.1 mm layer height. The test bodies were printed along the x-y axis with a longitudinal filament. This fill percentage was chosen due to the possibility of faster printing combined with a pattern that leads to greater strength. The tests were carried out at 23 degrees Celsius room temperature and 60% humidity. According to the recommendations of PC filament manufacturers, the obtained test bodies from this material should be heated to achieve their best strength characteristics. Some of the PC test specimens were heated for 2 hours at 90 °C in an electric resistance furnace and then tempered to room

temperature. Test specimens were tested before and after heating to verify the effect of annealing on the mechanical properties.

3.1 Shear Test Results

Thirty-nine specimens were tested in shear: 5 from PLA; 5 from PLA Wood; 6 from PETG; 5 from ASA; 6 from CPE HG 100; 5 from FilaFlex SEBS; 1 from PC and 6 from PC after heating. Table 1 (Appendix) shows the calculated shear strength results and average values for all tested materials.

The results obtained show good repeatability for each material. The lowest shear strength value is the FilaFlex SEBS material, with a result of 4 MPa. This is followed by ASA materials with a value of 14 MPa and CPE HG 100 with a value of 16 MPa. PETG, PLA Wood, and PLA materials have shear strengths of 18 MPa, 19 MPa, and 20 MPa, respectively. The highest shear strength is PC material with a result of 23 MPa. Heating of PC material leads to an increase in shear strength by 2 MPa (an increase of 8.7 %).

Figure 7 shows in ascending order a graphical representation of the obtained results for the shear strength of the investigated materials.

Fig. 7: Shear strength of the tested materials

3.2 Impact Toughness Test Results

Forty test specimens were tested for impact toughness: 6 from PLA; 6 from PLA Wood; 5 from PETG; 5 from ASA; 6 from CPE HG 100; 6 from FilaFlex SEBS; 1 from PC and 5 from PC after heating. The test specimens from FilaFlex SEBS did not break, which means that this material is a very tough plastic. It is necessary to use a larger Charpy hammer. Table 2 (Appendix) shows the results obtained for the remaining materials tested. The values marked in red were not taken into account when calculating the average values of A_c.

The obtained results show worse repeatability compared to the results of the shear tests. Of the materials tested, the most brittle is PETG with a result of 1.35 cm.kg., followed by PLA with a value of 1.9 cm.kg. The materials ASA and PLA Wood have relatively close values, with 2.36 and 2.54 cm.kg, respectively. The best deformation properties are received by the PC material before heating with a result of 5.2 cm.kg. After heating the PC material, its impact toughness decreases by 26%, but remains higher than the other materials with the exception of the CPE HG 100 material.

Figure 8 shows a graphical representation in ascending order of the results obtained for the impact toughness of the materials.

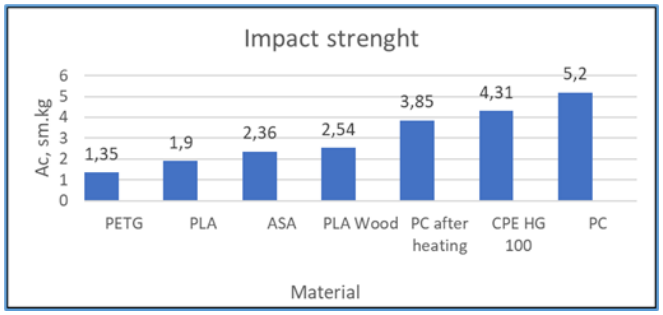

Fig. 8: Impact toughness of the tested materials

4 Conclusion

One of the most important mechanical tests of materials is the shear and impact toughness test, which are destructive methods. Thanks to their evaluation and knowledge of their properties, they can be used to evaluate the strength and deformation properties of the studied materials. These methods could be used in different areas of industry and for different materials.

The conducted studies show a difference in shear resistance and impact toughness for the same materials. For example, the most widely used material PLA has good shear resistance, while its impact toughness is almost the lowest of the studied materials. According to the authors, shear resistance is directly related to the hardness of the materials, which was studied in a previous work [22]. According to the hardness values, the lowest was for FilaFlex SEBS- 16.6 HDD on the Shore D scale, and the shear strength is also the lowest for this material. The Filaflex material is too elastic to break with the applied impact force. Accordingly, the highest hardness was measured for PC, and this material also has the highest fracture strength. The regularity for impact toughness resistance is not the same, but PC again has the best performance in this test. After heating, the PC material has the highest shear strength and reduced impact toughness due to the resulting brittleness.

The materials studied are from different groups with different characteristics, which is why there is a large variation in the results for shear strength and impact toughness.

5 Future Steps

Many publications indicate that the shear strength of metals is approximately 60 % of the shear strength. Due to the relationship between tensile strength and shear strength in materials, the authors will perform tensile strength testing under normal conditions to verify whether this relationship is also found in the studied polymer materials obtained by FDM extrusion of objects. Standardized testing machines are used in testing metals and polymers. For both types of materials, the most important characteristics are tensile strength, modulus of elasticity, and elongation. Knowing the relationship between tensile strength and impact resistance would be useful for faster data collection in the absence of one of the parameters.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare.

APPENDIX

Fig. 3: Shear testing

Fig. 6: Experimental setup for impact toughness testing

Table 1. Shear test

		Material							
	Test specimen	*PLA*	*PLA Wood*	*PETG*	*ASA*	*CPE HG 100*	*FilaFlex SEBS*	*PC*	*PC after heating*
R_{ms}, MPa	№ 1	21	21	19	14	16	4	23	26
	№ 2	22	21	15	13	17	3		27
	№ 3	20	19	19	14	15	4		25
	№ 4	20	17	20	14	15	4		26
	№ 5	20	19	15	15	15	4		25
	№ 6			19		16			24
	Average	20	19	18	14	16	4	23	25

Table 2. Impact toughness test results

		Material						
	Test specimen	***PLA***	***PLA Wood***	***PETG***	***ASA***	***CPE HG 100***	***PC***	***PC after heating***
A_c, cm.kg	№ 1	1.93	2.05	1.14	2.20	4.58	5.20	2.95
	№ 2	2.00	2.54	3.00	2.30	2.58		3.80
	№ 3	1.90	2.70	2.00	4.15	3.14		4.40
	№ 4	1.90	2.40	1.15	2.40	4.26		4.35
	№ 5	1.85	2.53	1.10	2.54	1.90		3.50
	№ 6	1.80	2.15			5.26		3.20
	Average	**1.90**	**2.54**	**1.35**	**2.36**	**4.31**	**5.20**	**3.85**