TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 63, Issue IV, November, 2020

EVALUATION OF IMPACT PROPRIETIES OF 3D PRINTED MATERIALS

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Abstract: *The aim of this article is to analyze the influence of infill percentage and infill pattern on the impact toughness of parts printed using the fused deposition modeling method. The mechanical behavior of the 3D printed materials under dynamic load was tested by Charpy impact test on standard specimens to find out the impact resilience of the samples. Influence of the printing parameters on the resilience of the samples was studied using two sets of specimens. The first set of samples where printed with the same infill pattern related to the longitudinal axis of the sample and a various infill percentage: 20%, 40%, 60%, 80% and 100%. The second set of samples were manufactured with an infill rate of 100%, but using various infill patterns. Impact resilience if 3D printed samples are increasing together with the infill rate, a noticeable improvement occurs when the infill range is passing over the 40%. Impact tests indicate that beside the infill rate the infill pattern is seriously influencing the result, the best result can be obtained when the printing direction of the pattern is transversal in relation to the impact load.*

Key words: *impact proprieties, 3D printed materials, Charpy test, infill rate, infill pattern.*

1. INTRODUCTION

Additive manufacturing or 3D printing gained a widespread popularity in recent years due to the methods ability to manufacture components with high geometrical complexity in a time efficient manner. The most cost-effective process to manufacture plastic parts using 3D printing is the fused deposition modeling (FDM) method. This manufacturing method is especially useful for producing prototypes or parts for showcasing products, but functional components can be produced also. FDM method can be very effective for producing low volume parts with a high level of complexity.

In contrast to conventional subtractive manufacturing methods, fused deposition modeling is manufacturing technology that produces parts with complex geometries by constructing the parts layer by layer out of a deposition material, such as acrylonitrile butadiene styrene (ABS) plastic or polyetherimide. The partially melted deposition material is extruded though a heated nozzle within a temperature-controlled build environment and is deposited in the form of a prescribed two-dimensional (x-y) layer pattern onto a heated build platform. The material is extruded and laid in tracks as a molten state and the newly deposited material fuses with adjacent material that has already been deposited. After an entire layer is deposited, the extruder is moving along the z-axis by an increment equal to the filament height (layer thickness) and the next layer is deposited on top of it [1]. The mechanical properties of parts produced with FDM technology and intended to be used as a functional part, should satisfy the operational requirements and must be comparable with parts produced by traditional manufacturing techniques. Compared to the conventional manufacturing processes, properties of the FDM parts can depend on structural and process parameters rather than purely on material properties. The most important process parameters that influence the result are such as extruder and building platform temperature, printing speed, layer height, infill percentage and pattern. Due to this process effects, delamination of the component layers or materials anisotropy can occur. Additionally, printed components typically have lower elastic properties than injection molded components of the same thermoplastics, thus the designers cannot rely on values from static material databases, the material selection becoming a complex process.

It is also interesting to compare these results with the ones that are available in the literature for the same material (ABS) but different printers. Results from Tymrak 2014 [2] show that the mean tensile stress for 100 % infill is 28,5 MPa, which is significantly smaller than the (34,57 MPa) result obtained in tests by Alvarez 2016 [3]. From this it can be concluded that the printer type or printer manufacturer, as well as the plastic roll manufacturer, are parameters than can significantly influence the mechanical properties of the printed parts. Another parameter proven to be important by Rankuohi 2016 [4] is the layer thickness. Tensile test results along with static analyses of the data clearly suggest that samples with a smaller layer thickness (ex: 0.2 mm) are stronger than specimens with higher layer thickness (ex: 0.4 mm). To determine if 3D printed materials can be used for functional components, the mechanical properties need to be determined [5-7] and is also important to predict not only the strength, stiffness but also impact resistance and how they relate to process parameters [3]. In the literature we can find examples of comparation between samples manufactured with FDM method compared to parts obtained from the same material but produced with injection molding technology. Górski 2014 [8] analyses the influence of various printing orientations on impact strength of ABS material produced with FDM technology. The results have proven that the impact strength of the FDM samples are far less than the strength of injection molded samples. In case of 0-degree printing orientation (along the longitudinal axis of the specimen) is only 47% of the impact strength of the monolithic sample produced by injection molding. A consistent difference in behavior was observed in case of impact test results compared to tensile strength. The upper limit of strength of the FDM samples relative to base ABS material, in case of impact strength is almost twice lower than in case of tensile strength (80%- versus 47%).

Material discontinuities being an effect of layered material deposition and method of layer filling have a significant influence on the overall strength of the product. If it is possible, FDM method process should be carried out in a way to minimize the discontinuities and cavities in place of the product which are the most vulnerable. To enhance the mechanical behavior of FDM printed parts a solution could be to use fiber reinforced thermoplastic materials. A major topic concerning the usability of 3D printed composites is the effect of impact damage on structural integrity. Caminero 2018 [9] investigated the effect of build orientation, layer thickness and fiber content on the impact performance of 3D printed continuous carbon, glass, and Kevlar® fiber reinforced nylon composites, manufactured by FDM technique. The results show that impact strength increases as fiber volume content increases in most cases. Glass fiber reinforced samples exhibits the highest impact strength and carbon fiber reinforced samples the lowest one and similar to nylon performance. The data obtained demonstrate that impact strength exhibited by 3D printed composites are significantly higher than the usual 3D printed thermoplastics and, in some cases, even better than common pre-preg materials.

2. MATERIALS AND METHODS

2.1. MATERIALS AND PRINTING PARAMETERS

The aim of this article is to analyze the influence of infill percentage and infill pattern on the impact toughness of parts printed using the fused deposition modeling method and a WANHAO Duplicator i3 printer. Test specimens were manufactured (55 pieces) using acrylonitrile butadiene styrene ABS material (Plasty Mladeč, Czech Republic). Its mechanical properties, according to the producer, are: tensile modulus E_f=2140 MPa, tensile stress σ_f = 43 MPa and tensile strain ε_f= 2,7%. The printing parameters used to manufacture the test specimens are presented in Table 1.

Tab. 1. FDM parameters

Parameter	Value
Layer height (mm)	0,2
Infill percentage (%)	20-100
Infill orientation (°)	0
Number of infill layers	12
Shell thickness (mm)	0,4
Number of floor layers	4
Number of ceiling layers	4
Number of solid layers	8
Printing speed (mm/s)	30
Nozzle temperature (°C)	250±5
Platform temperature (°C)	100±2
Extruder diameter (mm)	0,75

The geometry of the samples were constructed in SolidWorks 2016 using standard dimensions in compliance to EN ISO Standard 179-1: 2000, (which was accepted by the Romanian Technical Committee CT 108 for Thermoplastics), type C, using a V form notch at angle of 45 ° ± 1 °. The dimensions of the test samples are: L=80mm, T=10mm, H=4mm. The CAD data was processed with Simplify3D 3.1.0. tool to generate the machine-readable g-code for the printer.

The first set of samples where printed with the same infill pattern, 0° according to the longitudinal axis of the sample, with a various infill percentage: 20%, 40%, 60%, 80% and 100%. The second set of samples were manufactured with an infill rate of 100%, but using various infill patterns available in Simplify3D software as presented in Figure 1.

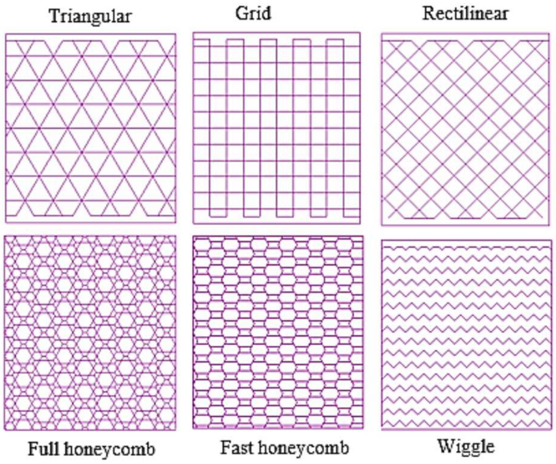

Fig. 1. Representation of infill patterns of the samples

The printed samples were analyzed trough microscope and the image imported to Digimizer Image Analysis tool to make sure the notch of the samples respects the quality requirements. The results shown a notch angle of 45.688° and a radius of 0.156 mm. as presented in Figure 2.

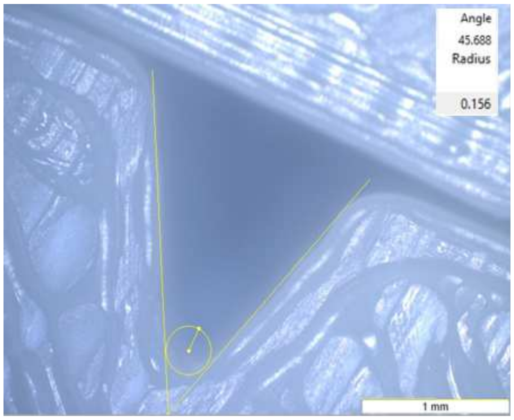

Fig. 2. Microscopic image of the test samples in Digimizer Image Analysis tool.

2.2. EXPERIMENTAL SETUP

Each set consisted of five specimens for a given group of process parameters. Since the mechanical properties of many thermoplastics can vary depending on ambient temperatures, tests were carried out in compliance to the standards for room temperature. Charpy tests were performed to study the energy absorption of the different sample configurations.

The Charpy test is the most used method to evaluate the impact toughness (or relative toughness) of materials. It can be used on various types of materials such as: polymers, ceramics and composites. Impact tests are designed to measure the resistance to failure of a material to a suddenly applied force. The test measures the impact energy, or the energy absorbed prior to fracture.

In this study an Instron CEAST 9050 Charpy test rig with a maximum 7.5 J was used to determine the impact damage strength of the 3D printed samples.

The experimental setup consists of anvils were the specimens are positioned, a pendulum with a defined mass attached to a rotating arm pinned at the machines frame. The pendulum is raised to a defined height and released to fall. The released pendulum falls following a circular trajectory and hits the specimen at the middle, thus transferring kinetic energy to it and rising to a measured height. The difference between the initial and final height of the pendulum is directly proportional to the amount of energy lost due to fracturing the specimen. The amount of energy [9] used for fracturing the specimen is determined by:

$$E_T = mg(h_0 - h_f) \pm 0.2J \qquad (1)$$

where E_T is the total energy, m is the mass, g is gravitational acceleration, h_o is the original height and h_f is the final height. The absorbed energy per unit cross-sectional area (kJ/m2) or impact strength E_C is defined as:

$$E_C = \frac{E_T}{wt} \qquad (2)$$

where w and t are the width and the thickness of the specimen, respectively. Energy losses due to bearing friction and air resistance were disregarded due to their small contribution to the energy balance. Usually the testing rig directly displays the consumed or absorbed energy. When reporting the results of a Charpy test, the absorbed energy (in J) is always reported, while the percentage crystallinity and lateral expansion are optional on the test report. In some cases, the mechanical characteristics of the materials are defined by fracture toughness or notch toughness (J/cm^2), generally indicated by KCV vor V notch samples or KCU for U notch samples. It should be emphasized that Charpy tests are *qualitative*, the results can only be compared with each other or with a requirement in a specification - they *cannot* be used to calculate the fracture toughness of a weld or parent metal.

3. RESULTS AND DISCUSSIONS

3.1 INFLUENCE OF THE INFILL RATE

Influence of the infill rate on the resilience of the samples was studied on specimens printed with rectilinear 0^o orientation of the pattern with respect to the longitudinal axis. After testing each sample, the following properties were measured and registered: energy deviation, resilience deviation, deviation angle, resilience, energy, angle variation, resilience average, impact speed. The most important factors for our study are average and standard deviation, and the nature of the fracture if the sample is completely broken or only partially. The results are presented in the Table 2. were the values (kJ/m^2) of the mean resilience of the samples printed with different infill rate are revealed.

Tab. 2. Mean values of resilience for samples printed with same infill pattern but different infill rate.

Sample	CH-0-20%	CH-0-40%	CH-0-60%	CH-0-80%	CH-0-100%
Resilience [kJ/m^2]	7,4185	9,71	13,015	15,347	16,708

As was expected, the direct correlation between resilience and infill rate was confirmed. The result has shown that the resilience of the 3D printed parts is increasing, and the capacity to absorb more energy, together with the increasing of the infill percentage of the test samples. Test sample with the lowest infill ratio CH-0-20% (7,4185 kJ/m^2) has the lowest resilience and the sample with the highest infill ratio shows the highest resilience CH-0-100% (16,708 kJ/m^2). The result clearly demonstrate that the infill rate is clearly influencing the resilience of the 3D printed specimens, the difference being 116.2% between the lowest and highest performing sample.

3.2 THE INFILL PATTERN INFLUENCE

The influence of the infill pattern was studied on the second set of samples. The test samples were printed using the same material, same printer settings only the infill pattern was changed. Six different infill patterns were used such as: Grid 0^o-90^o, Grid -45^o+45^o, Fast Honeycomb, Full Honeycomb, Wiggle and Triangular 60^o. The results of the impact tests were the values of the mean resilience of the samples printed with the same infill rate, but different infill pattern is presented in Table 3. After reviewing the data obtained by Charpy impact test performed on the3D printed samples, it is clearly shown that the infill pattern seriously influencing the mechanical behavior of the samples. The lowest resilience was shown by the samples printed with a Grid infill (were the filament layers are built up according a 0^o-90^o direction grid) representing 5,687 $\mathrm{kJ/m^2}$. The infill pattern that proved to demonstrate the highest resilience is the one printed with the Wiggle pattern 12,36 $\mathrm{kJ/m^2}$. Comparing the results of the lowest ang highest performing sample, the result can be expressed as a 119.6% difference.

Tab. 3. Mean values of resilience for samples printed with same infill rate but different infill pattern.

Sample	G 0-90	G 45±45	Tria.	Fast HC	Full HC	WG
Resilience [$\mathrm{kJ/m^2}$]	5,687	6,919	6,936	8,22	9.76	12,36

To have a better overview of the impact resilience performance of the test specimens, the results of the impact test are arranged in an ascending order, shown in the Table 4.

Tab. 4. Mean values of resilience of the samples organized in ascending order.

Nr.	**Sample**	**Mean resilience** $\mathrm{kJ/m^2}$
1	CH-0-100%	16,71
2	CH-0-80%	15,35
3	CH-0-60%	13,02
4	CH-WIGGLE-100%	12,36
5	CH-FULLHONCB-100%	9,76
6	CH-0-40%	9,71
7	CH-FASTHONCB -100%	8,22
8	CH-0-20%	7,42
9	CH-TRIA-100%	6.94
10	CH-45+45-100%	6,92
11	CH-0-90-100%	5,69

4. CONCLUSIONS

In this paper the influence of infill rate and infill pattern on impact resilience was studied on 3D printed samples fabricated with fused deposition modeling technique. Two set of samples were analyzed. The first set consisting of specimens printed with the same infill pattern, (0^o- according to the longitudinal axis of the sample) with infill rate ranging from 20%, 40%, 60%, 80% up to 100%. The second set of samples were fabricated with the same infill rate, all of them with 100%, but the infill pattern was different for each of them. The used infill patterns were available in Simplify 3D software, namely: Full Honeycomb, Fast Honeycomb, Triangular, Wiggle, Grid with 0°-90°, and 45°-45° orientations.

The mechanical behavior of the 3D printed materials under dynamic load was tested by Charpy impact test on standard specimens to find out the impact resilience of the samples.

In case of the samples printed with the same infill pattern but with a different infill rate, the connection between the infill rate and the impact resilience is noticeable. Can be concluded that the impact resilience if 3D printed samples are increasing together with the infill rate. This behavior was expected, because generally more material in the sample leads to a higher impact resilience. The problem investigated in this paper is to see if there is an infill ratio range that has the most significant effect on the impact resilience. There is a noticeable improvement in impact resilience when the infill range is passing over the 40% to 60% (3,3 $\mathrm{kJ/m^2}$), much greater than in case of passing from 20% to 40% (2,3 $\mathrm{kJ/m^2}$). Generally, the best performer in term of impact resilience among our test was the sample printed with 100% infill rate and infill pattern Wiggle. With the same 100% infill rate the sample printed with the Grid pattern 0°-90° shows 2.9 times less impact resilience. It is found that the impact resilience is changing relatively less moving from one sample to other in the same category. Impact tests indicate that beside the infill rate the infill patter is seriously influencing the result. The best result can be predicted, based on our experience, with the given infill patterns, are those where the printing direction is transversal in relation to the dynamic load. The effect of the infill rate was important to be established in order to appreciate the optimum material consumption in order to manufacture parts and functional components without the compromise of the dynamic load bearing capacity.

The mechanical properties of ABS specimens fabricated by fused deposition modelling display are significantly influenced not only by the infill rates as expected, but also about the printed pattern of different layers and their orientation. The right combination between the optimum infill rate and infill pattern should result in a part printed time efficiently using the least amount of material necessary. Results are useful to choose future analytical or computational models of FDM strength or stiffness as a function of printing patterns, void density and raster orientation. Different void density, pattern, orientations and their combination can be employed in producing parts that fulfill a required stiffness or strength. A local variation of this parameters can lead to an optimized structure that do not presume geometrical changes, just adjustments of the printing parameters.

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EVALUAREA PROPRIETĂȚILOR LA IMPACT ALE MATERIALELOR OBȚINUTE PRIN IMPRIMARE 3D

Articolul prezintă influența gradului de umplere și a modelului de imprimare asupra proprietăților la impact (Charpy) ale pieselor imprimate 3D. Influența parametrilor de imprimare asupra rezilienței a fost studiată folosind două seturi de epruvete. Primul set reprezintă epruvete imprimate cu același model de imprimare dar cu un procent de umplere diferit: 20%, 40%, 60%, 80% și 100%. Al doilea set de probe au fost fabricate cu o rată de umplere de 100%, dar folosind diferite modele de imprimare. Rezistența la impact crește cu rata de umplere, o îmbunătățire vizibilă apare atunci când această trece de 40%. Testele de impact indică faptul că, pe lângă viteza de umplere, modelul de umplere influențează rezultatul, valori crescute fiind obținute atunci când direcția de imprimare a modelului este transversală în raport cu sarcina de impact.

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