Studies on the influence of design parameters on the behaviour at shock of 3D-printed components fabricated by fused deposition modelling

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Abstract. In the last years, more and more products are made through fused deposition modelling (FDM). Although it has the disadvantage that it is a slow process, it is very well suited for the parts with complex shapes, which are difficult to obtain by classical machining. A huge advantage of this process is that the internal structure of the piece can be personalized according to the operation requirements. In the FDM process, the parts are builds up layer by layer. 3D printed objects will often have anisotropic mechanical properties. This means a printed part will be weaker in the direction of the Z axis. This paper presents studies on the influence of design parameters on the behaviour at shock of 3D-printed components fabricated by FDM. For this purpose, test specimens for shock breakout were made. The specimens were made with various internal structures and different orientations. The material for the parts is ULTRAT.

1. Introduction

Over the years, in the construction of various structures, man used objects made of dense solids: steel, concrete, glass. Instead, nature uses porous bodies such as wood, bone, coral, and so on.

"There must be a reason for it," said Michael ASHBY, professor at Cambridge University, a renowned material researcher [1]. His statement is based on the fact that although they exhibit porosities and are lighter than dense materials, they are more resilient and behave better against shocks because the porous structure allows shock absorption.

Why are not these materials very much used? Because technologies have not allowed. Thus, product designers have been very limited by the old technologies, especially the cutting technologies, where the finished product is achieved by removing "little by little" material [3].

The new Additive Manufacturing technology, based on material deposition, results in the finished product being made by selective deposition of material, "little by little" exactly where needed, until what the designer has done.

Through this technology, it is possible to make "technological" parts, already assembled structures, parts with topological optimized structure, multilateral, non-homogeneous and anisotropic parts, etc [4].

Fused Deposition Modelling (FDM) is an innovative technology which uses various thermoplastics to produce complex geometrical parts from a 3D model. It is known that their life span and mechanical properties are not as good as, those of the prototypes processed by traditional technologies such as thermoforming and injection molding. One solution is to develop functional materials with better properties [1, 2].
By Fused Deposition Modelling technology, we can realize the devices able to absorb energy, able to reproduce biostructures, and to replace some specialized parts [5, 6, 7].

Impact performance, one of the most important properties of a material, is difficult to measure. The Charpy test is used to determine the impact strength of material. It measures the amount of energy absorbed prior to fracture. The present paper analyses the impact energy for samples made of 3D printed plastic material, called ULTRAT.

The method described in ASTM Standard D 6110 was used to analyse the impact behavior on samples made by ULTRAT 3D printed by plastic material. When the pendulum strikes the samples, they absorb the energy until they yield. Then, the sample began to suffer plastic deformations. When they cannot absorb any more energy, fracture occurs [8, 9, 10].

2. Materials samples and testing equipment
Z-ULTRAT is a thermoplastic material characterized by good impact resistance, which gives a uniform texture to the surface of manufactured parts. This material allows us to print parts with high durability, also finished parts, which can keep their original shape after a long usage. With Z-ULTRAT, objects can be produced that have properties comparable to those manufactured by conventional technologies (injection moulding), including functional prototypes, test casings, and mechanical parts. For the experiments, we used a filament with a diameter of 1.75 mm, which is suitable for all kinds of high quality applications: functional prototypes, supports, final parts etc. Z-ULTRAT is a thermoplastic material that contains ABS (acrylonitrile-butadiene-styrene), PC (polycarbonate), additives and dyes.

Tests were done on polymeric material made from ULTRAT and the samples measure 126±0,4x12,7±0,15x7,2 (mm), in accordance to ASTM D 6110 or SR EN ISO 179 Charpy plastics test. The specimens were manufactured using the Zortrax M200 3D printer with rectangular structures with multiple circular cells of different sizes.

A simple pendulum impact machine according to ASTM D 6110 or SR EN ISO 179 Charpy plastics testing was used to perform the tests.

An accelerometer model 353B33, series 77495 with a sensitivity of 104.5 mV / g, range 1 - 4000 Hz, Bias level: 8.6 V was mounted on the pendulum to acquire experimental data.

It was used the Photron FASTCAM Mini UX 50 high-speed camera which provides outstanding imaging performance. It provides 1.3-megapixel (1280 x 1024 pixels) image resolution with frame rates up to 2,000fps and it’s available with recording memory options up to 32GB providing extended recording times and triggering flexibility. The device was triggered by an infrared barrier to be able to record the tests in real time. The lighting system consists of two 600 W halogen lamps to eliminate intermittently. Data acquisition was made in MATLAB with National Instruments data acquisition system.

3. Experimental study
The tests involved simultaneous performance of an experiment on a real object by means of Charpy test and a numerical analysis in ABAQUS/CAE environment with the use of the Finite Elements Method.

Geometry used in simulation, figure 1 is a simplified geometry corresponding to the used samples. The simulation was performed using 5 specimens: compact specimen, 2a, one specimen with holes of 1 mm diameter, figure 2b, one specimen with holes of 1,5 mm diameter, figure 2c, one specimen with holes of 2 mm diameter, figure 2d and one specimen with holes of 2,5 mm diameter, figure 2e.
The meshing of the specimen was made with linear hexahedral elements of type C3D8R, rectangular four-node shaped elements, figure 3, in the area of the notch using a larger number of elements. The area of the notch is more discretized to have a good accuracy of the deformation representation in this area. Otherwise, the specimen is roughly mesh to reduce computing time.

The specimen is simply supported along two straight lines. In Abaqus/Explicit mechanical contact between surfaces has been defined by introducing a relationship between contact pressure between "master" and "slave" surfaces. The "master" surface is represented by the hammer head, considered non deformable and the surface "slave" is represented by the surfaces of the specimen.

![Figure 3. Mesh of specimen](image3)

In this work, material plasticity is governed by Johnson-Cook model:

$$\bar{\sigma} = [A + B \cdot (\bar{\varepsilon}^{\text{pl}})^n] \left[1 + C \cdot \ln \left(\frac{\dot{\varepsilon}^{\text{pl}}}{\dot{\varepsilon}_0}\right)\right] \left[1 - \left(\frac{T - T_{\text{ref}}}{T_{\text{melt}} - T_{\text{ref}}}\right)^m\right]$$

(1)

with: $\bar{\varepsilon}^{\text{pl}}$ - the effective plastic strain; $\dot{\varepsilon}^{\text{pl}}$ - is the effective plastic strain rate; $\dot{\varepsilon}_0$ - is the normalizing strain rate; n, and m are material constants; C represents strain rate sensitivity; $T_{\text{ref}}$ is the temperature at which we determine the parameters A, B, n; $T_{\text{solid}}$ is the material’s solidification temperature.

Thermal and mechanical parameters of Z-ULTRAT [11] material that were used in this analysis are shown in table 1.

The elastic behavior of the material is defined by the longitudinal elastic modulus, $E = 857$ MPa and the Poisson coefficient, $\nu = 0.4$. 
Table 1. Constants for Johnson-Cook material model

| Material | Tmelt (°C) | A (MPa) | B (MPa) | C   | n  | m   |
|----------|----------|---------|---------|-----|----|-----|
| ULTRAT   | 279      | 39      | 48      | 0.0053 | 1.5 | 0.879 |

The total energy is calculated in [J] with the equation:

\[ W = E \cdot g \]

where: \( E \) - the total energy recorded after the tests carried out and converted to [kg·m]; \( W \) - total energy in [J]; \( g \) - gravitational acceleration \([\text{m/s}^2]\).

Calculate the area of the cross-section in which the width \( l \) is ASTM dimension A:

\[ S = l \cdot h \]

where: \( S \) - area of the cross section in [cm²]; \( l \) - the width of the cross-section in [cm]; \( h \) - the height (thickness) of the specimen [cm].

\( K_{cv} \) - mechanical shock resistance or resilience in [J/cm²] is determined by the formula (4):

\[ K_{cv} = \frac{W}{S} \]

Table 2 presents the experimental data obtained from the tests performed, the values obtained from the calculations in Excel and the cross-sectional dimensions measured by means of a digital caliper.

Table 2. Experimental data

| No. | Sample | m [kg] | H [m] | \( v \) [m/s] | g [m/s²] | l [cm] | h [cm] | S [cm²] | E [kgm] | W [J] | \( K_{cv} \) [J/cm²] |
|-----|--------|--------|-------|--------------|----------|--------|--------|---------|---------|-------|---------------------|
| 1   | compact| 0.17   | 1.6677| 2.316        |
| 2   | 1 p    | 0.12   | 1.1772| 1.635        |
| 3   | 1,5 p  | 0.115  | 1.1282| 1.567        |
| 4   | 2 p    | 0.095  | 0.9320| 1.294        |
| 5   | 2,5 p  | 0.12   | 1.1772| 1.635        |
| 1   | compact| 0.08   | 0.7848| 1.090        |
| 2   | 1      | 0.06   | 0.5886| 0.818        |
| 3   | 1,5    | 0.774  | 0.775 | 3.9         | 9.81     | 1      | 0.72   | 0.72    | 0.055   | 0.5396 | 0.749      |
| 4   | 2      | 0.0425 | 0.4169| 0.579        |
| 5   | 2,5    | 0.085  | 0.8339| 1.158        |
| 1a  | compact| 0.085  | 0.8339| 1.158        |
| 2a  | 1      | 0.0475 | 0.4660| 0.647        |
| 3a  | 1,5    | 0.055  | 0.5396| 0.749        |
| 4a  | 2      | 0.045  | 0.4415| 0.613        |
| 5a  | 2,5    | 0.0825 | 0.8093| 1.124        |

For the impact test, the sample is laid horizontally across two end supports. Then, the pendulum is released from the height of 775 mm to break the sample in the middle and the speed with which the pendulum strikes the specimen is 3.9 m/s.

The sample is notched, and the notch is placed opposite the pendulum impact point. The pendulum is equipped with the accelerometer to acquire experimental data. SEM images of fractured surfaces are examined to assess failure mechanics of the different configurations.
The figure 4 presents the picture taken with the ULTRAT samples with thickness 7.2 [mm] used to determine the resistance to impact, at the time of the Charpy tests. The impact mass used was \( m = 0.77 \) [kg].

![Figure 4](image4.jpg)

**Figure 4.** The suggestive frames of Charpy test on the samples

### 4. Findings

Following dynamic mechanical testing by Charpy impact test the broken surfaces of the samples were examined by macroscopy and optical microscopy. Macroscopic evaluation of destroyed samples allows to characterize the destruction mechanism of FDM products. We identified the deformation of the cross sections. The samples present individual traces of plastic deformation of the material from the hammer crosswise. It can be observed that the magnitude of deformation is dependent upon the layer thickness.

![Figure 5](image5.jpg)

**Figure 5.** Macroscopy of broken surfaces after impact for samples with holes 1.5 and 2.5 mm

To complete the characterization, we achieved the micrographs with an Olympus BX 51M microscope are presented below.

![Figure 6](image6.jpg)

**Figure 6.** Micrographs of samples with holes 1.5 and 2.5 mm in the region of the hole

The structure of the materials during the printing process is organized by individual columns of melted ULTRAT, placed upon one another in a well-designed geometric pattern. It can be noticed that in areas characterized by a strong reinforcement the rupture avoids the cylinders from the product geometry. These areas are areas with maximum density of material.
The figure 7 show the result of impact simulation in Abaqus.

Figure 7. ABAQUS impact simulation for samples with holes 1.5 and 2.5 mm

In the figure 8, the two recorder accelerations show us a better resistance of impact for the sample with the holes with 2.5 diameters.

Figure 8. Variation of the acceleration recorded during impact for samples 1.5 and 2.5 mm
5. Conclusions
The behavior of impact for the parts obtained by FDM is important for the designers. This work aimed at analyzing the influence of design parameters on the behavior of the products obtained by FDM from the ULTRAT material. It has been noticed that better shock behaviors have been obtained in the case of larger hollow parts due to the fact that the porous materials behave better than the dense ones.

The investigation of more process parameters on to the behavior at shock is proposed as future work.

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