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Numerical and experimental study for FDM printed specimens from PLA under IZOD impact tests

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ABSTRACT

Additive manufacturing (AM) is a process that can achieve many parts with complex features in the production. The most important aspect of AM is that there is no material wastage, which reduces costs. The benefits of AM have been noticed and the process is now being used in many fields like in medicine, in automotive, in aircraft, etc. Additive manufacturing materials can be tested by stretching, Charpy or Izod impact, bending, shearing, etc. For plastics, the most widely used process for impact testing is Izod. Prusa MK3 printer was used for the manufacturing of the specimens from polylactic acid (PLA). The specimens were tested with the CEAST 9050 pendulum impact system, according to the ISO 180:2000 standard. The numerical modeling of the experimental measurements has been done with the ANSYS finite element software's explicit module, called LS-DYNA. A good correlation between the numerical model and experimental tests was observed.

1. Introduction

Current day engineers are able to build parts with complex geometries thanks to rapid prototyping. The method of layer-by-layer addition is used for a wide range of materials: plastics, metals, and ceramics [1]. Additive Manufacturing (AM) became a crucial process for manufacturing of the products, due to its numerous benefits [2]. Raw materials used in AM can be distinguished in: AM that are using solid, liquid or powder. AM technologies using a solid state raw material are the most attractive option, particularly FDM (fused deposition modeling). FDM is one of the simplest and most cost-effective manufacturing process. This technology allows the use of various raw materials [3]. Benefits of using fused deposition modeling are as follows: the ability to print parts assembled together, the parts can be used soon after printing and printing resolutions of approximately 100 μm [4].

Multiple studies where performed by Ibrahim and Hafsa on the specimens using PLA as a raw material for FDM. The effects of the internal pattern structure and orientation of the part during the AM fabrication on the part master pattern was investigated Ibrahim and Hafsa, [5]. The results have shown that using PLA as a raw material for FDM produced a superior accuracy and increased surface roughness when the part is fabricated with an internal pattern structure compared to a hollow structure. Bergonzi et all investigated the infill influence over FDM produced parts using PLA [6]. The optimum printing temperature has been found to be higher than the filament's manufacturer recommended maximum, being 235 °C instead of 230 °C. Therefore the mechanical properties are influenced by the infill topology. The influence of thickness on the IZOD test impact strength for polylactic acid specimens printed using FDM was investigated Popa et all [7]. Mercado-Colmenero et all demonstrated that it is possible to characterize the PLA FDM material as isotropic. The advantage defining the isotropic material is that the numerical simulation software can run easier and it does not require the modification of the constitutive equations in the material database was investigated Mercado-Colmenero [8]. On the other hand, Shi Dai et all investigated the morphology of PLA material using scanning electron microscopy, from which they obtained the orthotropic behavior of PLA material [15].

The purpose of this study was to correlate the results of the numerical analysis and experimental measurements on the PLA specimens obtained by FDM technology. First chapter of the paper presents the materials used, test method, and equipment. Therefore the setup for the numerical analysis model was realized. At

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the end of the paper the correlation between numerical simulation results and experimental measurements was discussed. Next the main conclusions were drawn.

2. Material and methods

Prusa MK3 printer was used for the manufacturing of the specimens. The diameter of the filament was 2.85 mm [9,10]. Using the 3D printing software, the parameters were set. The specimens' dimensions used were in accordance to ISO 180 [11]. For this paper six PLA specimens of each of the following thicknesses 6 mm, 8 mm and 10 mm were used. The infill density was stated at 100 %, with raster angle ± 45°for each specimen.

The tests were performed using Instron CEAST 9050 equipment with a hammer weight of 0.9225 [kg] and a velocity of 3.46 [m/s]. The impact hammer reaches a velocity of 3.46 m per second at impact [12 –14].

The tests were carried out in the edgewise direction. The impact energy absorbed by the specimen and IZOD impact strength were computed using the Eq. (1) and (2).

$$E_c = \int_0^{s_j} F(s) \cdot ds \tag{1}$$

$$a_{iN} = \frac{E_c}{h \cdot b_N} \cdot 10^3 \tag{2}$$

where:

s_j – is deflection, m.
F– is force, N.
a_{iN}– is Izod impact strength, KJ/m^2.
E_c – is the corrected energy, in Joules, absorbed by breaking the test specimen.
h – is the thickness, in millimeters, of the test specimen.
b_N– is the remaining width, in millimeters, of the test specimen.

3. Numerical investigation

The numerical analysis was performed using the commercial program LS-Dyna, a sub-system of ANSYS. LS-Dyna is used to perform dynamic simulations similar to the Izod test process. A high strain rate was applied to the specimen and breaking occurs in a very short time in the order of tenths of milliseconds. The model was built considering the entire model of the test specimen and for the hammer only the impactor has been represented. The sample was created by using solid elements and for the impactor, shell elements have been used. The numerical simulation of the IZOD test was based on a pendulum impact energy of 5.5 [J], pendulum weight of 0.9225 [kg] and an impact velocity of 3.4 [m/s].

The specimen was locked similar to the fixation of the test machine, held on the two sides, having the degrees of freedom blocked on the frontal side and on the back side Fig. 1.The impactor was defined as rigid body and all its degrees of freedom were blocked except for the direction of the strike.

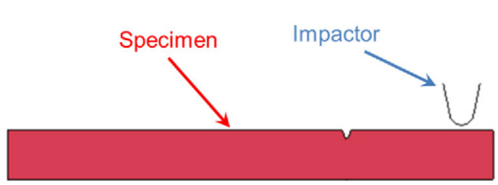

Fig. 1. Analyzed model.

For the mesh of the specimen hexahedral elements have been used, with a mesh refinement in the notch area, summing up to a total number of 37,377 elements and 87,416 nodes.

The contact used between the impactor and the sample has been set as *CONTACT_AUTOMATIC_SINGLE_SURFACE. In this case the software detects when the elements come in contact.

The material for the specimen was defined as *MAT_PLASTICITY_POLYMER_89 with properties from Fig. 2 and a stress–strain curve was used do define the limits of plasticity. For erosion of elements a *MAT_ADD_DAMAGE_DIEM parameter was used, which is applied to the material, based on a triaxiality curve.

The correlation between the physical tests and the numerical simulation had a good matching in terms of velocity and kinetic energy obtained after specimen breakage. The numerical model slightly overestimates the time of specimen breakage. A possible cause for this could be the limitation of the homogeneous isotropic numerical model. The 3D printed part is heterogeneous and anisotropic; the mechanical properties depend on location and direction. The outer layers of the test parts are more brittle than the middle layer of the parts, and in the numerical model, all elements are considered isotropic.

In Fig. 3 the Velocity - Time and Kinetic Energy - Time plots are shown. These curves were recorded from the finite element numerical analyses for each thickness of the specimens. The 6 mm is depicted in purple, the 8 mm is shown in blue and the 10 mm is represented in green. It can be seen that the velocity decreases is higher for the 10 mm specimens, similar to the experimental data. In Fig b) it can be seen that the energy increases with the thickness of the specimens.

4. Results and discussion

As results we shown the experimentally determined curves and the curve obtained in the numerical analysis, overlaid in the graph with the corresponding value of the specimen thickness.

For each specimen thickness and for each material the specific curve from the numerical analysis was superimposed and the Velocity - Time and Kinetic Energy - Time graphs were determined.

In the numerical analysis using the finite element method, the aim was to simulate the experiment in as many details as possible, but the material being orthotropic and inhomogeneous led to different results from the numerical ones. The elements used in the analysis are isotropic and homogeneous.

In Fig. 4 the plots of the 6 mm specimens recorded from the experimental tests (green plots) are shown, where the data recorded from the numerical analysis (magenta curve) were added. The curves from the experimental tests have a sharp decrease in velocity.

Fig. 5 shows the graphs of the 8 mm thick specimen. In this case, the curve recorded in the numerical analysis is similar on the linear-elastic domain to the experimental values.

Fig. 6 shows the curves of 10 mm thick specimens made of PLA following the experimental IZOD impact test. In this case, the numerical analysis curve is similar to the experimental curves.

The average energy difference between the thickness of 6 mm and 8 mm is 0.034 J, and between the thickness of 8 mm and 10 mm is 0.037 J. The increase is linear with the increase in thickness, Popa et all [7].

Fig. 7 shows the microscope analyses in the crack area, the voids between the layers can be seen. In the area closer to the printing bad, the material is more melted, and sintering is better than the area further away. In Fig. 7 a) on the right side of the specimen the gaps are better seen. On the edge of the notch, the wires are not melted and do not have good sintering.

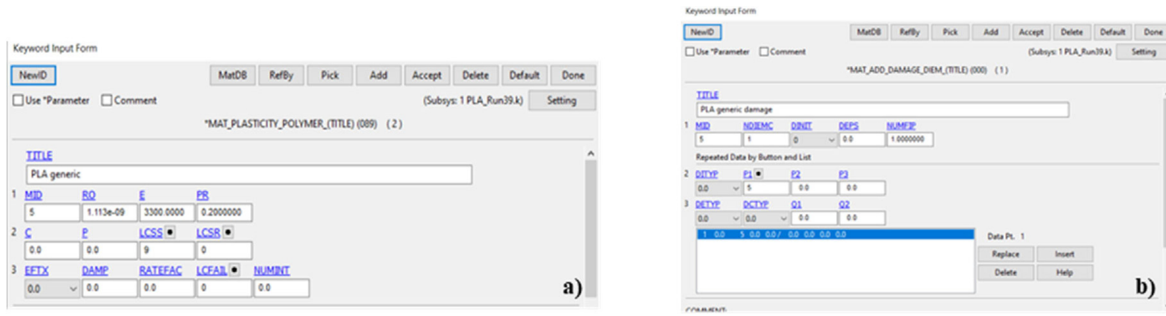

Fig. 2. A) material card used in the fea and b) erosion parameter used for the material card.

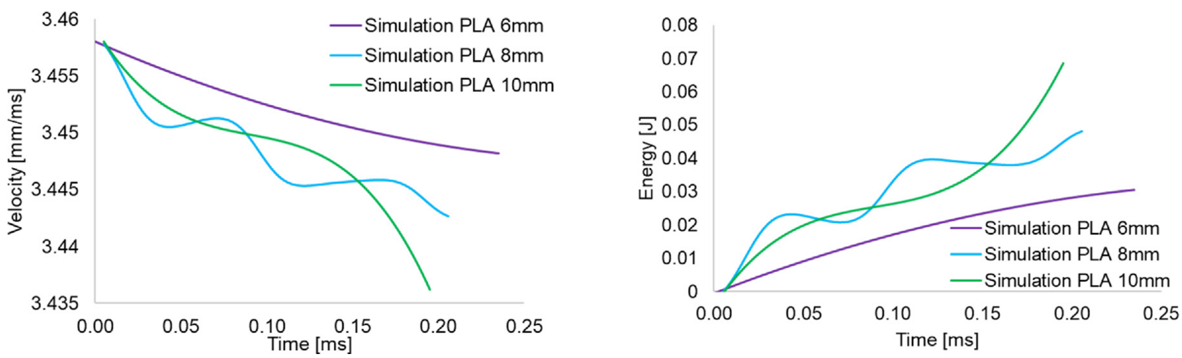

Fig. 3. Simulation results for PLA material a) Velocity - Time plot and b) Kinetic Energy - Time plot.

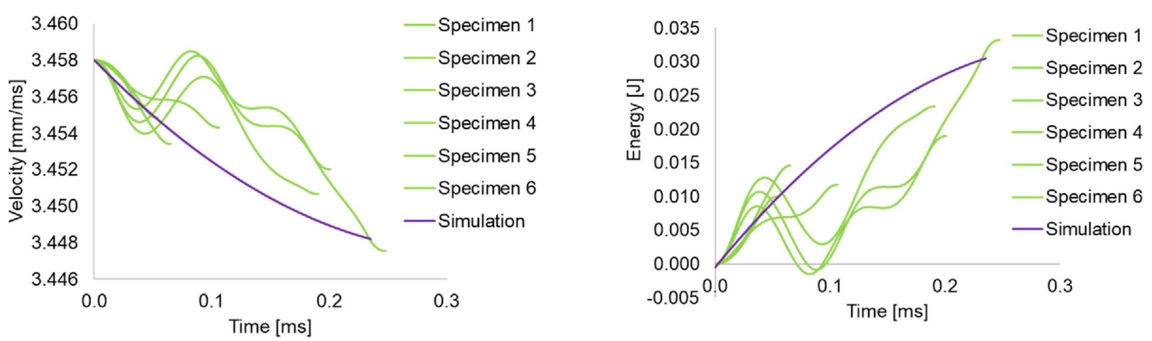

Fig. 4. A) velocity – time curves, and b) energy – time curves for the 6 mm thickness specimens.

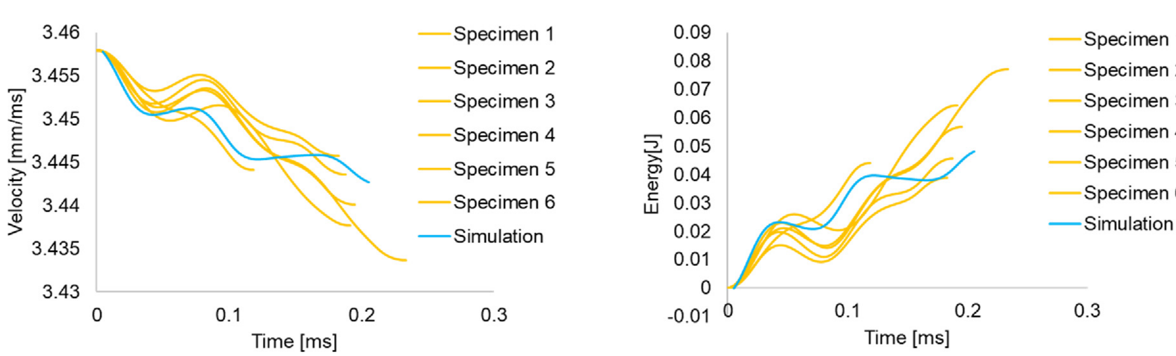

Fig. 5. A) velocity – time curves, and b) energy – time curves for the 8 mm thickness specimens.

For fused deposition modelling technology, the sintering increases with thickness, for 6 mm specimen thickness the sintering is worse than the 10 mm thickness. For a bigger thickness the material has more time to melt and to make a good sintering between wires.

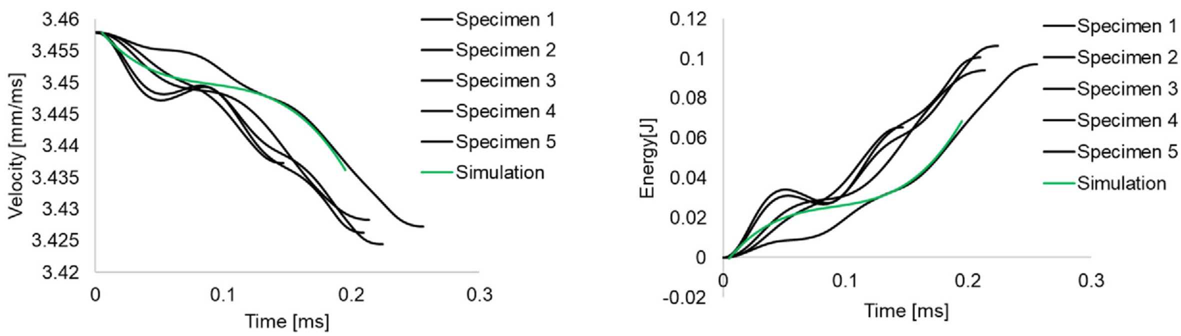

Fig. 6. A) velocity – time curves, and b) energy – time curves for the 10 mm thickness specimens.

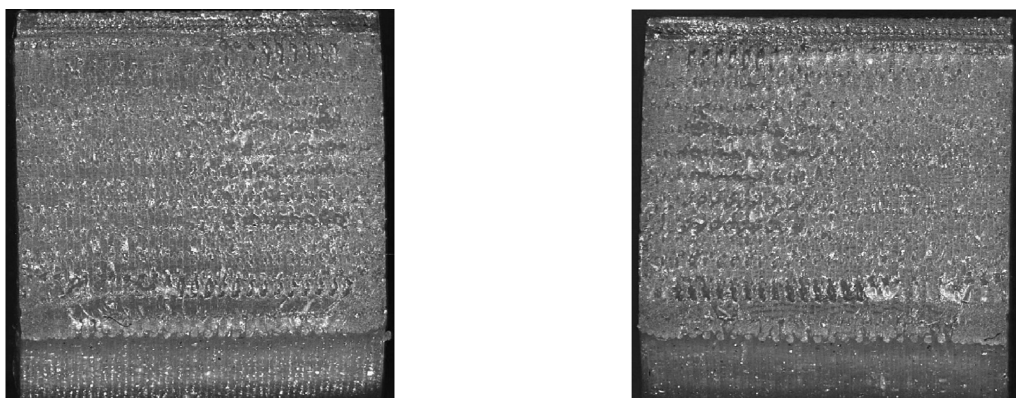

Fig. 7. Section after breaking PLA material a) section of the upper specimen and b) section of the lower specimen.

5. Conclusions

Following the numerical analyses and the experimental determinations of the impact parameters, it could be observed that materials made by additive manufacturing can be numerically modelled and calibrated with experimental ones, which brings a plus in terms of using numerical models in the automotive, aerospace and medical industries.

The numerically obtained results were compared with the experimental results and a similar behavior could be observed.

The kinetic energies obtained in the numerical analysis have similar values to the measured data. In the case of the PLA material the kinetic energies recorded in the numerical analysis have the values: 0.03 J in the case of 6 mm thick specimens, 0.047 J in the case of 8 mm thick specimens and 0.068 in the case of 10 mm thick specimens. The averages of the experimentally determined energies are: 0.0186 J for the 6 mm thickness, 0.0544 J for the 8 mm thickness specimens and 0.0858 J for the 10 mm thickness specimens. In the case of the PLA material, it can be said that it behaves similarly to the experimental one.

CRediT authorship contribution statement

Cosmin Florin Popa: Conceptualization, Resources, Software, Writing – original draft, Validation, Data curation, Formal analysis, Investigation. **Tamas Krausz:** Conceptualization, Writing – original draft, Data curation, Resources, Software, Investigation. **Sergiu-Valentin Galatanu:** Conceptualization, Project administration, Writing – review & editing, Methodology, Supervision, Data curation, Resources, Investigation, Validation, Formal analysis. **Emanoil Linul:** Conceptualization, Validation. **Liviu Marsavina:** Methodology, Supervision, Writing – review & editing, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Galatanu Sergiu-Valentin reports financial support was provided by European Commission.

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