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Impact absorption capacity of 3D-printed components fabricated by fused deposition modelling

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ABSTRACT

Despite additive manufacturing emerging as an effective alternative to conventional manufacturing methods, ought partially to the support of open source communities, little is known about the shock absorbing properties of the parts produced. An open source fused deposition modelling device was employed to fabricate 3D polymeric structures and their shock mitigating properties were evaluated. The effect of commercially available layer heights, infill patterns and density on the energy dissipation properties of the printed PLA (polylactic acid) cylinders was examined. A strong dependency of the apparent density on the impact absorption capacity, both in terms of sock mitigation and energy dissipation, of the components was determined whereas the effect of layer height was less pronounced and that of the filling pattern negligible. Results showed that porous specimens were prone to process parameter changes, an effect, gradually fading towards higher densities.

1. Introduction

The inception of additive manufacturing, as an alternative for prototyping purposes, dates back to the early 80s [1]. Over the past decade however, rapid prototyping (RP) techniques have been successfully introduced for a variety of purposes, ranging from concept evaluation and design optimization to the fabrication of highly customized and functionally gradient components. The comparative advantages of RP are predominantly time related, as RP facilitates the direct integration of complex features and application specific assemblies into the final product.

The appearance of several open source RP communities [2], has driven the adaptation of related techniques from industrial sectors (e.g. automotive and aerospace) and cost-sparing SMEs to customized medical products and consumer goods [3]. Recent studies have stipulated that 3D printing technologies could empower developing countries to develop their own local products such as toys and farming tools [4], leading to the rationale that additive manufacturing could become useful towards the sustainable design of consumer products [5].

This has revolutionized additive manufacturing, over the course of the past years, allowing it to rise from a period of infancy into a mainstream manufacturing process. RP has since gained tremendous importance as an alternative to conventional manufacturing processes.

Open source RP technologies evolve mainly around polymeric structures [6] as their low melting point provides enhanced design flexibility. Fused Deposition Modelling (FDM), adopted by open source communities as Fused Filament Fabrication (FFF) to avoid proprietary nomenclature, facilitates the adjustment of the component's apparent density through system integrated filling patterns, thus easing the production of porous structures. The unhindered integration of application specific features like tailored porosity, provides these specimens with competitive energy-absorbing characteristics. Ideally a shock-absorbing configuration would dissipate the kinetic energy of the impact, while transmitting a constant plateau force, within not-dangerous deceleration values, to the supporting structure [7].

As FDM becomes more prevalent, related process parameters have to be tuned for diverse applications, in order for the fabricated components to perform effectively. The initial hypothesis of this investigation is that by altering the production parameters of FDM produced PLA components, while maintaining their dimensional characteristics, may significantly enhance their impact absorption capacity, or at least mitigate an occurring shock to an acceptable degree.

For this purpose, cylindrical PLA specimens, of 20 mm in diameter and 30 mm height, were produced on an open-source FDM (FFF) printer (MendelMax 2). The influence of filling pattern, layer height and apparent density of the samples on their capacity to absorb energy during a high velocity impact was examined. The results were used to evaluate the effectiveness of these specimens as protective structures.

Research concerning the properties of RP produced components has gained tremendous interest over the last years. Several studies have focused on a wide range of topics from the influence of process parameters [8] to the effect of reinforcement materials [9] on the strength properties of the components produced, and even though the

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fundamental aspects of additive manufacturing have advanced significantly, the average consumer still remains uniformed as to the optimal/application specific process parameters of the device.

This paper addresses the needs of a vast open source community growing at a pace [10] that is estimated in tens of thousands of units per year. The available literature on strength characteristics of components fabricated with these open-source printers is nevertheless limited [11,12], thus forcing most users towards an empirical based optimization of their printing parameters.

2. Materials and methods

All specimens tested in this investigation were produced on a MendelMax 2 open source printer with a 3 mm extrusion nozzle (design and assembly files can be found online [13,14,15]). Only system integrated (default) variations of production parameters were employed in the comparative analysis that follows. As time is a key determining factor for productivity, printing velocity is often selected based on quality independent factors (i.e. production cost). Deposition speed was therefore not considered a variable in this study and a constant extrusion velocity was selected for all specimens, based on device parameters (e.g. effective printing range). The experimental results (stress strain curves of tensile test performed a 5 printing speeds) are presented below.

Based on these experiments, a 100 mm/s deposition speed was used for the production of the PLA samples (30 mm high at a 20 mm diameter), as this velocity provides acceptable productivity while ensuring proper strength values at an exceptionally high strain. Twenty seven specimen types were produced in total, varying in three different aspects (filling pattern, layer height and infill densities). Three system-based filling patterns were adopted: rectilinear, octagonal and concentric whereas the layer height ranged from 0.1 to 0.3 mm. Finally two infill densities of 25 and 50% were considered next to the bulk structure. The samples were produced at a 180 °C extrusion temperature as FDM is widely accepted as a procedure prone to temperature deviations [16]. A single 2.5 kg filament roll of white PLA was used to fabricate all samples, since PLA characteristics vary drastically, even changes in color have been reported to affect material's physical and mechanical properties [17]. All cylinders had two solid layers, one at the top and a second one at the bottom surface. A 0.4 mm thick shell covered the cylindrical surface, completely encapsulating the diverse internal structures.

Upon selecting the proper fabrication and testing parameters, three impact experiments were conducted on a drop tower system (CEAST 9350 by Instron) for each process variation (81 tests in total). The recorded test values for each specimen type were statistically evaluated using an analysis of variance (ANOVA) and paired t-test. No statistically significant variations were found among any triplet of specimens fabricated with the same parameters (layer height, infill density and pattern). All values presented in the results of this investigation, reflect the average of the three individual measurements conducted for the specific group of samples.

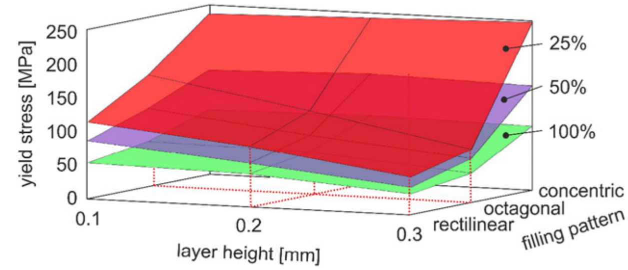


Fig. 2. Effect of infill density, layer height and filling pattern on the compressive yield strength of the printed cylinders.

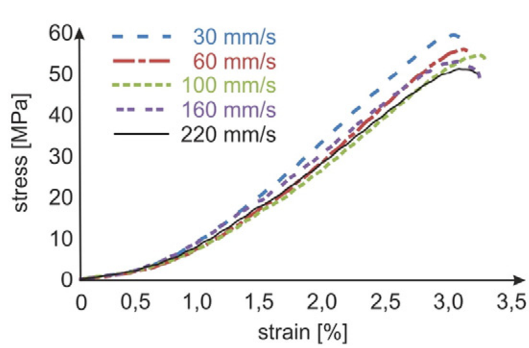
3. Results

In order to quantify the effect of printing speed on the mechanical properties of PLA specimens produced by FDM and isolate the influence of layer height infill density and pattern on their properties, an efficient printing velocity was determined based on tensile tests. Specimens conforming to ASTM:D638 (Type IV) were produced at 5 different extrusion speeds (ranging from 30 to 220 mm/s) and tested at a strain rate of 0.0087 s^{-1}. All other process parameters were unaltered at a 180 °C extrusion temperature a 50% infill density and a rectilinear filling pattern. Two solid layers of 0.2 mm each were deposited at the bottom and the top surface of the specimen, while the perimeter was delineated by two 0.4 mm passes. The mean value of three experiments per velocity is plotted in terms of a stress strain diagram as illustrated in Fig. 1, and are in good agreement with recent literature describing the dependency of tensile strength on a variety of other process related parameters [9].

To determine the force dissipating capacity of these specimens, the impact energy had to be calculated in relation to the impact velocity, based on static compressive tests, according to ISO 17340. In agreement to this standard, the impact energy must be sufficiently large to ensure the appropriate evaluation of the compressive characteristics at a specified test speed. Therefore the static energy absorption up to 50% of the compressive strain, has to be determined and the impact mass calculated in relation to impact velocity.

Static compression tests showed that concentric filling (with a 0.3 mm layer height and a 25% infill density) made the specimen to yield last among all the ones tested (see Fig. 2). It is noteworthy that concentric filling performed better in all cases as did the 25% infill density while the rectilinear patterns and bulk filling exhibited the worse compressive response. The effect of layer height was somewhat more complex as it seemed to be related to the filling pattern e.g. a 0.1 mm layer outperformed a 0.2 mm rectilinear one but this tendency was not observed for concentric filling paths.

An impact speed of 8.3 m/s was used for all specimens to avoid strain rate sensitivity phenomena. Based on this principle and the results summarized in Fig. 2, a 5.6 kg impact load was considered appropriate, resulting in an impact energy of 194.4 J.



Printing velocity [mm/s]	Tensile strength [MPa]
30	57,21
60	54.62
100	52.98
160	51.12
220	49.32

Fig. 1. Stress–strain curves and tensile strength values for various printing velocities of FDM fabricated PLA specimens.