

Testing Sustainable 3D-Printed Battery Housings with DIC Technology [†]

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Abstract: Three-dimensional printing has rapidly gained traction in the automotive industry, offering significant benefits in terms of design flexibility, production speed, and cost efficiency. However, as the use of 3D printing grows, there is a rising focus on incorporating sustainable materials to minimize the environmental footprint of automotive components. This study centers on using eco-friendly, 3D-printable materials to produce electric vehicle battery covers. The primary goal is to assess these sustainable battery housings' mechanical properties, durability, and overall feasibility. Additionally, the research explores the potential of foaming polylactic acid filaments in measurement applications using Digital Image Correlation technology, which is widely employed in the automotive sector. The study also evaluates these housings' manufacturability and real-world applicability, offering insights into their role in the future of automotive production, where sustainability is becoming increasingly important. The research seeks to contribute to the broader movement toward greener manufacturing processes within the automotive industry by conducting these analyses.

Keywords: 3D printing; foam PLA; sustainability; battery housing; printing strategy; filaticum



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1. Introduction

Due to their low weight, energy absorption, low thermal conductivity, and good thermal and acoustic insulation properties, foamed polymers are widely used in applications such as building materials, furniture, transport, automotive, medical, sports, and so on [1]. Most of them are energy efficient [2]. Their performance is affected by their density and foam structure [3]. Various methods exist to create foam structures using 3D printing, such as built-up porous structures, syntactic foams, post-foaming of already formed solid structures, and the simultaneous foaming of filaments containing foaming agents by 3D printing [4–6].

Foaming polymers are typically based on a solid polymer and a gas phase. These materials are impregnated with a physical or chemical foaming agent responsible for creating the foam structure in the thermoplastic polymer. Chemical blowing agents are solids that decompose at high temperatures either exothermically or endothermically to form gasses such as CO₂ or N₂. CO₂ or N₂ is usually dissolved in the polymer in the gas or supercritical phase as physical blowing agents. During printing, the foaming agent produces a gas and then, at high temperatures, thermodynamic instability occurs due to pressure drop, leading to foaming. This pressure drop occurs at the nozzle, where the material is deposited, and the foam cells are formed and grow. As a result of cooling, the cells in the foam structure take their final shape. For materials capable of foaming, the density of the printed body can be controlled by the 3D printing settings, nozzle temperature and nozzle diameter, printing speed, feed rate, and layer thickness [4–7].

Foamed/porous polymers produced using CO₂ or N₂ can be used as substitutes for more brittle, stiffer, damage-prone syntactic foams [8].

The filaments foamed during 3D printing are usually based on PLA (polylactic acid), which has the advantage of being biodegradable. Unlike syntactic foams, the printed pieces are free of foreign materials and contaminants, positively impacting their recyclability [7–9].

Among the foaming agents, CO₂ is often used in green technologies for environmentally friendly methods because it is non-toxic, non-flammable, inert, and cheap. Creating the foamed polymer using PLA enriched with CO₂ allows the production process to be maintained [9,10].

Testing of PLA containing an endotherm foaming agent showed that by increasing the printing temperature from 215 °C to 250 °C and reducing the filament dosage from 95% to 35%, and with constant additional printing parameters, a 59% density reduction in the foamed material could be achieved. Microscopic images of the printed samples showed that the volume and size of the foam structure's cells increased with increasing temperature [8].

Experiments have shown that a printing temperature of 180 °C does not cause cell growth; at this temperature, no foam structure is formed, the heat effect is not yet sufficient, and in addition, as the speed increases, the material passes through the heating block faster, and the foam expansion rate will decrease. Between 200 and 250 °C, as the printing temperature is increased and the printing speed is increased continuously from 10 m/s to 100 m/s, the pressure drop occurs more and more rapidly, leading to an increasing rate of foam expansion, and the fiber diameter increases progressively [4,11].

The printing speed affects the morphology of the foam. Printing at 10 mm/s at a printing temperature of 250 °C results in the foam cells being more extensive but less homogeneous, decreasing in size towards the center of the fiber, which is much finer and more uniform at 100 m/s, and the fiber shell thickness is relatively thin. When the fiber stays in the heating block for too long, the bubbles collapse and become a shell layer. The thickness of the shell layer has a significant influence on the density of the foam structure [4,11,12].

The difference between Filaticum Foam filament and Filaticum PLA is that 3D-printed objects have a spongy structure, with a density of only 50–60% of conventional PLA objects. An examination of the printed test pieces shows that the layers are barely visible, forming a sandblasted effect due to the foam structure [13].

A special feature of the material is that, by varying different printing factors, it is possible to significantly influence the structure of the foam, such as filament dosage (40–120%), nozzle size (0.2–1 mm), temperature (190–250 °C), and printing speed (20–100 mm/s) [13].

The lowest-weight foam can be achieved by increasing the temperature and nozzle diameter, reducing the feed rate and lowering the print speed [13].

Experiments have confirmed that, with the same printing parameters, Filaticum Foam filament can be used to print pieces with a significantly lower density than conventional Filaticum PLA due to its structure and foaming. By using a constant nozzle diameter of 0.4 mm and a printing speed of 60 mm/s, and only varying the printing temperature, it is found that, at a higher printing temperature of 245 °C, a lower mass specimen can be obtained than at 215 °C, which occurs because, at higher temperatures, the material has more time to foam and solidifies more slowly [13].

The frequent impact of PLA on the environment is also satisfactory. There is much research on the recycling and sustainability of PLA. After repeated recycling, the mechanical properties of rPLA (recycled PLA) deteriorate further. Research shows that the tensile strength decreases significantly after each recycling cycle. The properties of rPLA can be improved by using additives or adding virgin PLA. Such mixtures can help maintain or improve the mechanical properties of the material. Using rPLA is environmentally beneficial as it reduces the demand for virgin PLA and the amount of waste. Potential applications for PLA biocomposites include automotive, construction, packaging, and medical devices. Subsequent research should aim to improve the properties of PLA biocomposites further and make them suitable for a broader range of industrial applications [14–18].

The literature also shows that 3D printing can produce prototypes of foam materials that can be used as battery housing materials. Using foamed PLA filaments for battery housings over conventional materials is advantageous because the air bubbles have an insulating effect, and the small micro-cells have a vibration-absorbing and shock-absorbing effect in the event of a collision. The main objective of the present study is to determine the technical parameters for printing battery housings of suitable quality from commercially available foam PLA materials.

The current paper is a continuation of the authors' previous articles [19–21].

2. Materials and Methods

This section introduces the applied materials, 3D printers, measurement methods and printing strategies.

2.1. Materials and Printers

In preparation for the experiments, the 3D printers (Flashforge, Hangzhou, China; Creality, Shenzhen, China) listed in Table 1 were used to print the test pieces. The test specimen used for the tests was a calibration cube known in the world of 3D printing that was $20 \times 20 \times 20$ mm in size.

Table 1. The 3D printers used.

Printer	Flashforge Creator Pro 2	Creality Ender 3 S1
Technology	Fused Filament Fabrication (FFF)	Fused deposition modeling (FDM)
Build Volume	XYZ: $200 \times 148 \times 150$ mm	XYZ: $220 \times 220 \times 270$ mm
Filament diameter	1.75 mm	1.75 mm
Feeder type	Double Direct Drive Extruder	“Sprite” Dual-gear Direct Extruder
Max. hot end temperature	240 °C	260 °C
Max. heated bed temperature	120 °C	100 °C
Print speed max.	100 mm/s	150 mm/s
Slice thickness	0.1–0.4 mm	0.05–0.4 mm
Print precision	± 0.2 mm	± 0.1 mm

Since the main objective of the experiments was to analyze the properties of Filaticum PLA Engineering Foam (Filaticum, Miskolc, Hungary) under different printing parameters, Table 2 summarizes the properties of the Foam filament. The research is focused on this material because it is a domestically produced product which is easily available and of controlled quality.

Table 2. Properties of PLA Foam filament.

Filaticum	Foam
Nozzle temperature	190–250 °C
Nozzle size	0.2–1.2 mm
Bed temperature	max. 70 °C
Cooling fan	recommended up to 100%
Layer height	0.4–0.8 mm
Print speed	optimal 20–80 mm/s, max. 100 mm/s
Flow rate	40–120%

The following software was applied to set the printing parameters: FlashPrint (Version 5.3.1) for the FlashForge printer and Ultimaker Cura (Version 5.8.1) and PrusaSlicer (Version 2.6.0) for the Creality Ender 3 S1.

2.2. Printing Setup and Measuring Methods

As confirmed by the literature, the main parameters that needed to be set were nozzle temperature and flow rate, which are the main parameters that influence the foaming outcome. The nozzle temperature was set at 200–220–240 °C, and the table temperature was set at 60 °C. The flow rate was set at 50–60–70–80–90–100%. Data from the literature showed that it is not recommended to go below 70%, but the present research considered it essential to check this. Increasing layer thickness and reducing velocity can increase the number and size of air bubbles. Investigating these two parameters is not the subject of this research.

Visual inspection was not sufficient to detect any differences, so the Kern ABP 100-5DM analytical balance (Kern & Sohn GmbH, Balingen, Germany) was used to perform the weight measurements. Table 3 summarizes the most important technical data.

Table 3. Properties of the digital weight scale.

Technical Data	Kern ABP 100-5DM
Max. weighing capacity [g]	52
Min. weight [g]	0.001
Readability [g]	0.00001
Verification scale interval [g]	0.001
Linearity [g]	±0.00005
Reproducibility [g]	0.00002

3. Results and Discussion

Table 4 summarizes the results of the weight measurements of the proofs printed with different printing strategies. It is worth noting that three samples were taken from each setup, and the table gives the average of these samples.

Table 4. Results of the weight measurement (the layer height/thickness was 0.2 mm).

ID	Nozzle [°C]	Bed Temperature [°C]	Flow Rate [%]	Weight [g]
P1.1	240	60	100	3.65083
P1.2	220	60	100	3.65097
P1.3	200	60	100	3.61644
P2.1	240	60	90	3.29265
P2.2	220	60	90	3.28735
P2.3	200	60	90	3.27181
P3.1	240	60	80	2.94245
P3.2	220	60	80	2.94134
P3.3	200	60	80	2.90200
P4.1	240	60	70	2.56432
P4.2	220	60	70	2.55836
P4.3	200	60	70	2.54779
P5.1	240	60	60	2.19202
P5.2	220	60	60	2.19054
P5.3	200	60	60	2.18127
P6.1	240	60	50	1.83459
P6.2	220	60	50	1.81506
P6.3	200	60	50	1.81840

The results confirm the literature data, as the temperature has no significant effect on weight and it is likely that only the porosity rate changes. For battery housings, weight reduction is the critical parameter (along with vibration reduction), which can only be achieved by reducing the flow rate accordingly. As the weight data in Table 4 show, the most significant effect was the flow rate setting.

Figure 1 shows that the two types of slicing software do not set similar flow rates. Cura does not set this value for the sub-configured printers despite the setting being changed, so this should be monitored in further research.

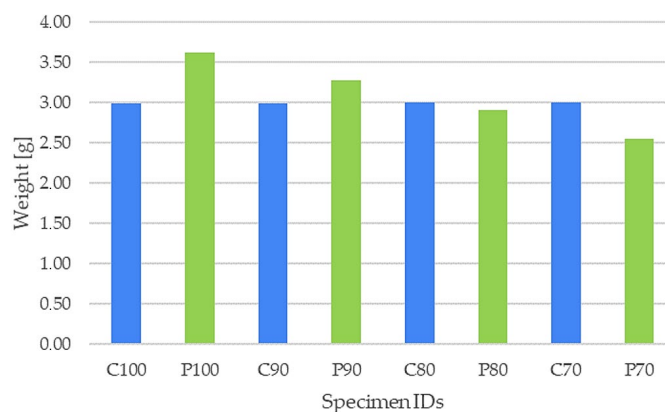


Figure 1. Weight difference due to the Cura (C) and the Prusa (P) slicer.

4. Conclusions

The study's results confirmed that the temperature effect is insignificant when applying PLA Foam filaments, with a 40 °C increase in nozzle temperature causing only a 1% change in the mass values. Interestingly, the lower temperature resulted in a lower sample weight, which may be due to a faster bubble cavity solidification. The effect of the flow ratio is striking; the weight of the pieces decreases significantly according to the % ratios. At the same nozzle temperature, there was a 40–45% weight reduction, while the outer size of the samples did not change significantly. The foaming material fills the available volume. It is important to note that the filling and visual appearance of the samples were satisfactory, and they did not fall apart. An additional advantage is that they showed good blooming at lower temperatures (200 °C), so printing can be carried out energy efficiently (with less power consumption) with simpler printers. Another significant result of the present study is that the choice of slicing software for the printer is critical because Cura cannot adequately reduce the flow rate compared to the Prusa slicer's software.

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