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Research article

L1 **Exploring the potential of *in-situ* foam 3D printing: Effects**
L2 **of printing parameters and the development of functionally**
L3 **graded foams**

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L8 **Abstract.** In this study, we investigated the influence of processing parameters on the cellular structure and density of spec-
L9 imens fabricated using in-situ foam 3D printing. First, we conducted a comprehensive analysis to examine how the combined
L10 effects of printing temperature and speed influence the four key stages of the foaming process: gas dissolution, cell nucleation,
L11 cell growth, and stabilization. By evaluating the structural characteristics of the printed foams, we identified the dominant
L12 mechanisms governing each stage. Next, we explored the effect of nozzle diameter, an aspect previously unexamined in the
L13 literature. We found that smaller nozzle diameters promote higher cell density due to enhanced pressure drop and shear-in-
L14 duced nucleation, resulting in a 36.8% reduction in density and a 60.3% increase in cell density when using a 0.4 mm nozzle
L15 instead of 0.8 mm (at 240 °C, 60 mm/sec). Finally, we fabricated functionally graded four-layer structures by adjusting the
L16 printing temperature for each layer to control porosity distribution. To evaluate the mechanical performance of these graded
L17 structures, we performed three-point bending and drop-weight impact tests, allowing us to assess how layer order influences
L18 mechanical properties. Our results showed that proper layer sequencing can increase flexural strength by up to 69.4% and
L19 improve perforation energy by more than 94.8% compared to homogeneous structures.

L20 **Keywords:** 3D printing, foam, additive manufacturing, fused filament fabrication, functionally graded design

L21 **1. Introduction**

L22 3D printing is becoming an increasingly widespread
L23 manufacturing technology and is growing rapidly
L24 due to its many advantages over traditional manu-
L25 facturing processes [1]. The technology allows for
L26 the rapid production of complex geometries and cus-
L27 tomized parts, reduces manufacturing waste, and
L28 shortens prototyping and final product production
L29 times [2]. These benefits contribute to the wide-
L30 spread use of 3D printing for prototyping and final
L31 products in many industries, including automotive,
L32 aerospace, and medical [1, 2]. Based on a report is-
L33 sued by Strategic Market Research (Report ID:
L34 80536350), the global 3D printing industry was worth

\$16.94 billion in 2022 and is predicted to grow to
\$77.83 billion by 2030.
FDM/FFF (Fused Deposition Modeling/Fused Fila-
ment Fabrication) technology is one of the most
widely used 3D printing processes, mainly due to its
simplicity, cost-effectiveness, and wide availability
of materials [3, 4]. FDM printers are among the fil-
ament-forming additive manufacturing processes,
where a melted polymer is extruded through a heated
nozzle to create the desired geometry layer by layer
[5, 6]. This method has become popular not only in
the industrial sector, but also among home hobby
printers, and the number of printers sold is increasing
every year [7]. According to the industry forecast of

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- L1 Grand View Research (Report ID: GVR-4-68040-
L2 270-8), the market for FDM printers is expected to
L3 grow at a compound annual growth rate of 21.8%
L4 between 2024 and 2030, reaching a market value of
L5 \$3 billion by the end of the decade.
L6 However, the more widespread use of this technolo-
L7 gy for technical purposes is limited by the anisotropy
L8 of the printed specimens and the weak adhesion be-
L9 tween the deposited layers, which results in weaker
L10 mechanical properties [8]. This problem can be
L11 solved by the use of *in-situ* foamable filaments con-
L12 taining chemical (CBA) or physical (PBA) blowing
L13 agents or thermally expandable microspheres (TEM).
L14 During printing, the elevated temperature causes the
L15 foaming agents to decompose, releasing gas. As the
L16 material exits the nozzle, the sudden pressure drop
L17 triggers expansion, which can help eliminate inter-
L18 layer gaps and weak adhesion. This improvement in
L19 layer bonding can lead to enhanced mechanical per-
L20 formance of the printed parts [9]. Additionally, the
L21 use of these filaments enables the controlled adjust-
L22 ment of printing parameters during manufacturing,
L23 allowing for the creation of functionally graded
L24 sandwich structures with tailored porosity [9–13].
L25 Such graded structures can also be produced using
L26 specialized techniques, such as static mixer nozzles
L27 with dual flow paths, where foaming and non-foam-
L28 ing filaments are combined to achieve programma-
L29 ble density profiles [14]. These density-graded struc-
L30 tures, featuring variations in cellular properties across
L31 the thickness, exhibit superior mechanical perform-
L32 ance compared to homogeneous structures of the
L33 same weight [15, 16]. Despite the increasing research
L34 interest in process-controlled foaming, the effect of
L35 nozzle diameter – an essential parameter influencing
L36 pressure drop, shear rate, and residence time – has
L37 remained largely unexplored in this context.
L38 In recent years, increasing efforts have been made to
L39 better understand the mechanisms of *in-situ* foam
L40 formation during 3D printing, particularly with the
L41 aim of optimizing cellular structure and mechanical
L42 performance. A research group at the University of
L43 Massachusetts Lowell has published multiple studies
L44 on the development of polylactide acid (PLA) fila-
L45 ments containing TEM particles. By incorporating
L46 triethyl citrate as a plasticizer, they successfully re-
L47 duced the processing temperature, thereby prevent-
L48 ing undesired pre-foaming during filament produc-
L49 tion [9, 17]. Their investigations also explored the
L50 impact of the PLA matrix material's melt flow index
on foaming behavior, as well as the effects of vary-
ing flow rates and printing temperature [17]. They
concluded that residence time and temperature play
a critical role in the expansion of microspheres, sig-
nificantly influencing the homogeneity of the result-
ing cell structure [18]. Utilizing these insights, they
created multilayered structures in which porosity
was controlled through printing parameter adjust-
ments [19]. Similarly, Nieduzak *et al.* [20] developed
foaming filaments using TEM particles in an
rHDPE/PP blend and found that the use of *in-situ*
foam 3D printing helped reduce the warping of print-
ed specimens. However, in these studies, the foam-
ing process was simplified by the presence of TEM
particles, which facilitated cell nucleation and con-
trolled expansion. While this approach is effective,
TEM shells are non-biodegradable, and the material
itself is relatively expensive, limiting its applicability
in certain fields.
Other foaming strategies, such as CO₂-based physi-
cal foaming, rely on a more complex interaction of
gas dissolution, nucleation, and growth. In this field,
Peng *et al.* [21] demonstrated that *in-situ* foaming of
PLA/chitin nanocrystal scaffolds during 3D printing
allows for tunable porosity and improved interlayer
adhesion by adjusting nanofiller content and printing
speed, while Zhang *et al.* [22] investigated the effect
of printing temperature and speed on the resulting
porosity by using supercritical CO₂-saturated ther-
moplastic polyurethane filaments. However, as
demonstrated by Li *et al.* [11] on CO₂-saturated
polyetherimide and PLA filaments, gas saturation in
the filament prior to printing requires significant
time (24–48 h), and maintaining the dissolved gas in
the system until printing is challenging, which sug-
gests that CBAs could offer a more practical alter-
native [10].
Damanpack *et al.* [23] investigated the effects of
printing temperature and flow rate on porosity and
mechanical properties using a commercially avail-
able PLA filament with an endothermic CBA. They
examined how changes in temperature influenced
density and mechanical performance, while they ad-
justed the flow rate accordingly to ensure consistent
interlayer adhesion across all conditions. The effect
of printing parameters such as temperature and speed
was also analyzed by Ozdemir and Doubrovski [24],
who investigated how these parameters influence the
expansion behavior of a commercially available *in-*
situ foamable filament (LW-PLA by Colorfabb).

L1 However, their primary focus was on changes in optical properties (e.g., color and translucency), while
L2 neither the resulting cellular structure nor the mechanical properties of the printed foams were evaluated.
L3 To improve CBA foaming efficiency, Choi *et al.* [25] enhanced the melt strength of PLA by using
L4 an epoxy-based chain extender, which improved foamability by promoting more stable cell nucleation
L5 and growth, resulting in a homogeneous cell structure. As their aim was material development, they
L6 kept the printing parameters fixed throughout the experiments.
L7 Although these previous studies have revealed valuable results on the process of *in-situ* foam 3D printing,
L8 several important underlying mechanisms remain unexplored. Most of the research investigates
L9 the effect of a specific processing parameter separately, despite the fact that these parameters have a
L10 combined influence on the different stages of the foaming process (gas dissolution, cell nucleation,
L11 cell growth, and stabilization). In addition, it is important to highlight that the current studies all used
L12 one type of nozzle, so the effect of nozzle geometry has not been explored. Since nozzle diameter affects
L13 shear rate, pressure, and residence time during printing, it is likely to influence cell nucleation and growth.
L14 A deeper understanding of this relationship may contribute to better control of the porosity distribution
L15 and mechanical performance of functionally graded foams.
L16 In this study, our main goal was to understand more deeply how printing parameters, such as temperature

and speed, influence the foaming behavior of PLA filaments containing a chemical blowing agent. While the effects of temperature and speed have already been examined in previous works, the impact of nozzle diameter has remained unexplored, despite its relevance to shear rate, residence time, and pressure drop. By including nozzle diameter as a variable, our work addresses this knowledge gap and contributes to a deeper understanding of its role in cell nucleation and foam morphology. To further explore the potential of process-controlled foaming, we conducted a case study in which four-layer graded structures were fabricated by adjusting printing parameters. The influence of layer order on mechanical performance was also evaluated.

2. Experimental

The aim of our research was to investigate the expansion of *in-situ* foaming filaments during 3D printing and the resulting cell structure. In the first stage, the effects of printing temperature and speed were analyzed using different parameter combinations. In the second phase, the influence of the nozzle diameter on the foaming mechanism at different printing temperatures was investigated. Finally, we created four-layer, functionally graded foam structures by applying different printing temperatures for each layer. We evaluated the effect of layer-order modification on the mechanical properties by performing 3-point bending and falling weight impact tests. The schematic representation of the experimental process is shown in Figure 1.

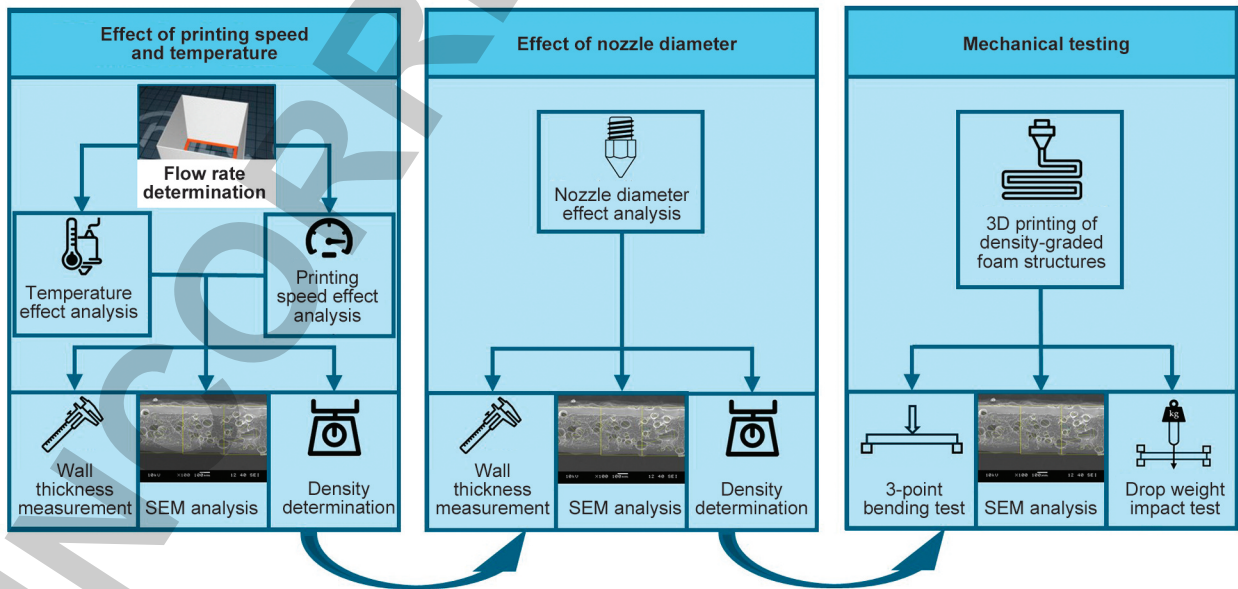


Figure 1. Schematic representation of the experimental process.

L1	2.1. PLA filament	2.2.2. Effect of nozzle diameter	R1
L2	In order to evaluate the effect of printing parameters,	In the second phase of the research, we investigated	R2
L3	a commercially available material, namely LW-PLA	the influence of nozzle diameter while keeping the	R3
L4	by Colorfabb (Belfeld, Netherlands), was used as an	printing speed fixed at 60 mm/s. To analyze its ef-	R4
L5	<i>in-situ</i> foamable filament for the tests. The material	fect on foaming behavior, hollow cubes with dimen-	R5
L6	has a glass transition temperature range of 55–60 °C,	sions of 25×25×25 mm and a single-layer wall	R6
L7	a melting temperature of 150–160 °C, and a melt flow	thickness were printed using three different MK8	R7
L8	index of 6 g/10 min (210 °C/2.16 kg). The activation	steel nozzles with diameters of 0.4, 0.6, and 0.8 mm.	R8
L9	temperature of the foaming agent is ±230 °C accord-	The 0.4 mm nozzle, already used in the first phase	R9
L10	ing to the manufacturer's datasheet, and the recom-	of the study, served as a reference for comparison.	R10
L11	ended print settings are 195–260 °C nozzle tem-	For the larger nozzle diameters, the layer height and	R11
L12	perature, 40–100 mm/s print speed and 50–60 °C bed	extrusion width were adjusted to maintain consis-	R12
L13	temperature. The material is expanding during the	tent proportions. For the 0.6 mm nozzle, the layer	R13
L14	3D-printing process due to the presence of the en-	height was set to 0.3 mm, with an extrusion width	R14
L15	dothermic blowing agent in the system [23].	of 0.6 mm, while for the 0.8 mm nozzle, the layer	R15
L16	2.2. 3D printing	height was 0.4 mm, and the extrusion width was	R16
L17	All specimens were fabricated using a Craftbot Plus	0.8 mm.	R17
L18	(CraftUnique Ltd., Budapest, Hungary) FDM print-	To examine the relationship between nozzle size and	R18
L19	er. The slicing software used was CraftWare, the pro-	foaming behavior, printing was conducted at tem-	R19
L20	proprietary slicer developed by CraftUnique for Craft-	peratures ranging from 220 to 250 °C in 10 °C incre-	R20
L21	bot printers, ensuring optimized compatibility with	ments. Since the nozzle diameter directly influences	R21
L22	the machine. We conducted three experimental phas-	shear rate, pressure, and residence time during print-	R22
L23	es to systematically investigate the effects of printing	ing, it is expected to have a significant impact on cell	R23
L24	parameters on the <i>in-situ</i> foaming process.	nucleation and growth dynamics. By systematically	R24
L25	2.2.1. Effect of printing temperature and speed	varying the nozzle size while keeping other param-	R25
L26	In the first phase, we focused on analyzing the in-	eters constant, we aimed to explore how these factors	R26
L27	fluence of printing temperature and speed on foam-	affect the cellular characteristics of the printed struc-	R27
L28	ing behavior. For that purpose, hollow cubes	tures.	R28
L29	(25×25×25 mm) with a nominal wall thickness of	2.2.3. Residence time and shear rate calculation	R29
L30	0.4 mm were printed. A 2 mm outer brim was added	<i>Estimation of wall shear rate</i>	R30
L31	to improve bed adhesion. Printing was performed	To evaluate the shear conditions experienced by the	R31
L32	using a 0.4 mm MK8 steel nozzle, with a layer height	material during printing, a theoretical approach was	R32
L33	of 0.2 mm and an extrusion width of 0.4 mm. The	employed to estimate the wall shear rate based on	R33
L34	cooling fan was set to 100%, and the bed tempera-	nozzle geometry and printing speed. The purpose of	R34
L35	ture remained constant at 60 °C. The extrusion mul-	the analysis was to understand how variations in	R35
L36	tiplier was set to 1 (100% flow rate) for all speci-	nozzle diameter influence the shear rate and, conse-	R36
L37	mens to ensure a consistent material input and nom-	quently, the apparent viscosity of the material. The	R37
L38	inal layer geometry in the absence of foaming, al-	wall shear rate $\dot{\gamma}_w$ [1/s] was estimated using the fol-	R38
L39	lowing a clear comparison of the effects of speed and	lowing expression, which assumes axisymmetric	R39
L40	temperature. The effect of printing temperature was	flow (Equation (1)) [26]:	R40
L41	examined over a range of 190–250 °C, while printing	$\dot{\gamma}_w = \frac{4Q}{\pi R^3} \quad (1)$	R41
L42	speed was varied between 20 and 60 mm/s. Both pa-	where Q [mm ³ /s] is the volumetric flow rate, and R	R42
L43	rameters were adjusted in increments of 10 °C and	[mm] is the internal radius of the nozzle. The volu-	R43
L44	10 mm/s, respectively. From the printed specimens	metric flow rate Q can be substituted by the product	R44
L45	we performed density measurement, SEM analyses	of the cross-sectional area of the nozzle and the av-	R45
L46	and determined the rate of expansion using the meth-	erage flow velocity (Equation (2)):	R46
L47	ods described in Section 2.3–2.4.		

$$L1 \quad Q = A \cdot v_{\text{print}} = \frac{D^2 \pi}{4} \cdot v_{\text{print}} \quad (2)$$

L2 where v_{print} [mm/s] denotes the printing speed, and
 L3 D [mm] is the internal diameter of the nozzle. Rec-
 L4 ognizing that $R = D/2$ we obtain Equation (3):

$$L5 \quad \dot{\gamma}_w = \frac{4 \left(\frac{D^2 \pi}{4} \cdot v_{\text{print}} \right)}{\pi \left(\frac{D}{2} \right)^3} \quad (3)$$

L6 This expression provides an estimate of the apparent
 L7 wall shear rate under steady-state flow conditions.
 L8 The calculation was repeated for a range of nozzle
 L9 diameters to quantify the sensitivity of shear rate to
 L10 geometric changes. This approach allows for a com-
 L11 parative analysis of the effect of nozzle design on
 L12 shear-driven flow behavior, which is especially rel-
 L13 evant in applications such as extrusion or material
 L14 deposition.

L15 *Residence time estimation*

L16 The melting of the filament is a fundamental process
 L17 in FDM-based 3D printing technology. This occurs
 L18 inside the nozzle, where different printing speeds
 L19 and nozzle diameters result in different residence
 L20 times. As a result, the foaming agent present in the
 L21 filament is subjected to varying durations of thermal
 L22 exposure, which influences its activation and the de-
 L23 gree of foaming.

L24 To calculate the residence time, we considered the
 L25 internal geometry of the nozzle to estimate how
 L26 quickly the material flows through it at given print-
 L27 ing speeds. We formulated the following expression

to estimate the residence time of the material inside
 the nozzle, taking into account the relevant geomet-
 ric and process parameters (Equation (4)):

$$t_r = \frac{h_{\text{nozzle}}}{\frac{v_{\text{print}} \cdot h_{\text{layer}} \cdot D_{\text{nozzle}}}{A_{\text{filament}}}} \quad (4)$$

where h_{nozzle} [mm] represents the height of the
 molten filament inside the (vertical) nozzle, v_{print}
 [mm/s] denotes the printing speed, h_{layer} [mm] is the
 layer height, D_{nozzle} is the nozzle diameter [mm] and
 A_{filament} [mm²] corresponds to the cross-sectional
 area of the filament, given in square millimeters.

2.2.4. Fabrication of density-graded multilayer foam structures

As the final part of this research, we conducted a
 case study to demonstrate the potential of *in-situ*
 foam printing for producing density-graded multi-
 layer foam structures. To achieve this, we fabricated
 four-layer structures with layer-by-layer variations
 in printing temperature, creating a controlled porosity
 gradient along the thickness. The specific tem-
 perature profiles used for these configurations are
 presented in Figure 2.

To establish a reference, one set of specimens was
 printed at a uniform nozzle temperature of 230 °C,
 resulting in a homogeneous structure. The second
 configuration followed a sandwich-like approach,
 with the first and final 1 mm layers printed at 210 °C,
 while the interior 2 mm section was printed at
 250 °C, creating a rigid shell with a porous core. The
 third configuration introduced a gradual temperature

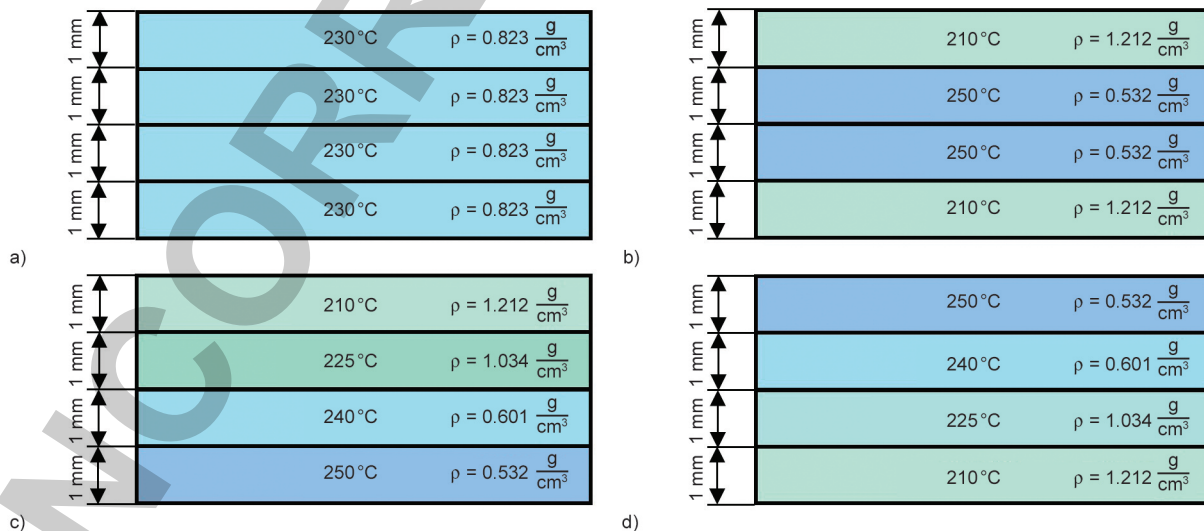


Figure 2. The temperature profiles and used for the printing of the multilayer structures and resulted density values. a)...., b)...., c)...., d)....

L1 variation, with sequential layers printed at 250, 240,
 L2 225, and 210 °C from bottom to top. The fourth con-
 L3 figuration mirrored this setup in reverse, with the
 L4 highest temperature layer at the top and the lowest
 L5 at the bottom. The nozzle diameter for all cases was
 L6 0.4 mm, while the printing speed was kept constant
 L7 at 60 mm/s throughout. The bed temperature was
 L8 maintained at 60 °C, and the layer height was set to
 L9 0.2 mm. The size of the test specimens was
 L10 80×10×4 mm (ISO/R 178) for the bending, while
 L11 80×80×4 mm for the falling weight impact tests.
 L12 To ensure consistency in sample dimensions despite
 L13 the variable expansion caused by foaming at different
 L14 temperatures, the extrusion multiplier was used for
 L15 each layer to adjust flow rate (Equation (5)) [27, 28]:

$$L16 \quad \text{Extrusion multiplier} = \frac{w_0}{w_i} \quad [-] \quad (5)$$

L17 where w_0 [mm] is the average wall thickness of the
 L18 unfoamed specimen (printed at 190 °C), while w_i
 L19 [mm] is average wall thickness of the foamed spec-
 L20 imen (printed at a given temperature), which were
 L21 determined by measuring the thickness of each of
 L22 the four sides of the printed hollow cubes with a Mi-
 L23 tutoyo CD-15APXR type vernier caliper. This ad-
 L24 justment ensured that the overall sample volume re-
 L25 mained consistent across all layer configurations.

L26 Since the slicing software did not support direct
 L27 modification of process parameters within a single
 L28 G-code file, manual G-code editing was required to
 L29 apply layer-specific temperature and extrusion mul-
 L30 tiplier settings. The nozzle temperature was modified
 L31 using the M109 SXXX command, where XXX de-
 L32 notes the target temperature (*e.g.*, M109 S210 for
 L33 210 °C). The M109 command instructs the printer to
 L34 wait until the desired temperature is reached before
 L35 executing any subsequent commands, ensuring that
 L36 each layer is printed at the correct temperature. To
 L37 prevent material leakage while waiting for the tem-
 L38 perature adjustment, the printhead was moved to the
 L39 home position along the X-Y axis using G28 X Y be-
 L40 fore resuming printing. To implement layer-specific
 L41 flow rate adjustments, we calculated the required ex-
 L42 trusion multiplier for each layer using Equation (5).
 L43 This value was then used to scale the corresponding
 L44 E -values in the G-code, which define the length of
 L45 filament extruded. By multiplying the original E -
 L46 values with the temperature-specific multiplier, we cor-
 L47 rected the material feed rate directly in the G-code.
 L48 This ensured that, despite the foaming-induced

expansion, the overall dimensions and mass of each
 printed specimen remained consistent. The modified
 G-code sections were then merged to create a single
 file for printing the multilayer structure.

The fabricated multilayer structures were then sub-
 jected to three-point bending and falling weight im-
 pact tests, as described in Sections 2.5 and 2.6, to
 evaluate the effect of layer-order modification on
 mechanical properties. By implementing controlled
 variations in printing temperature, these experiments
 aimed to assess how porosity gradients influence
 mechanical performance, providing insight into the
 structural optimization of functionally graded foams.
 To ensure comparability between different layer
 order configurations, the printing temperatures were
 selected to achieve similar overall density across all
 specimens. As a result, the variation in specimen
 mass remained within 10% in all cases. The density
 values for each layer are denoted in Figure 2.

2.3. Density and expansion measurement

To quantify the degree of foaming, the expansion
 ratio was evaluated by measuring the wall thickness
 of the printed cubes. Additionally, the density of the
 printed specimens was determined (Equation (6)) at
 room temperature through hydrostatic measurement,
 using distilled water as the measuring liquid [29]:

$$\rho_{\text{foam}} = \frac{m_a}{m_a - m_l} \cdot \rho_{\text{dw}} \quad (6)$$

where ρ_{foam} [g/cm³] is the density of printed foam
 structure, m_a [g] is the mass derived from the weight
 of the specimen in air, m_l [g] is the mass derived
 from the weight of the specimen measured in water,
 ρ_{dw} [g/cm³] is the density of the measuring medium
 (distilled water).

2.4. Scanning electron microscopy (SEM)

The cell structure of the samples produced with dif-
 ferent printing settings (temperature, speed, nozzle
 diameter) was examined using a JEOL JSM 6380LA
 scanning electron microscope (Jeol Ltd., Tokyo,
 Japan). Prior to testing, all samples were immersed
 in liquid nitrogen to generate cryogenic fracture sur-
 faces, after which they were coated with a gold-pal-
 ladium alloy to ensure adequate conductivity. The
 SEM samples were prepared by cutting out the side
 walls of the printed hollow cubes. Images were taken
 at 100× and 200× magnification to assess the cell
 morphology. Additionally, to examine the effect of

layer configuration, SEM images were also taken at 20× magnification from density-graded specimens produced for the mechanical testing. Based on the electron microscopic images and the density of the samples, the degree of expansion (Equation (7)) were determined, which were then used to calculate cell density (Equation (8)) and average cell wall thickness (Equation (9)) [30, 31]:

$$\phi = \frac{\rho_{\text{solid}}}{\rho_{\text{foam}}} \quad (7)$$

$$N_C = \left(\frac{n}{A}\right)^{\frac{3}{2}} \quad (8)$$

$$\delta = \left(3\sqrt{\frac{\phi}{\phi-1}} - 1\right) \cdot l \quad (9)$$

where ϕ [–] is the degree of expansion, ρ_{foam} [kg/m³] is the foam density, ρ_{solid} [kg/m³] is the density of the unfoamed material, N_C [pcs/cm³] is the cell density, n [pcs] is the number of cells visible in the SEM image, A [cm²] is the investigated area on the sample, δ [μm] is the cell wall thickness, and l [μm] is the average cell size. The average cell size was determined by using the ImageJ (National Institutes of Health, Bethesda, USA) image processing software. The cell wall thickness (see Equation (5)) was estimated based on Rangappa and Yeh [32] by assuming a homogeneous closed-cell structure, where the cells are approximated as regular cubes. The calculation was based on the average cell size obtained from SEM images and the degree of expansion, which was determined from the density of the foamed and unfoamed material. This simplified geometric model enables comparative analysis of structures produced under similar processing conditions [31].

2.5. 3-point bending test

The printed density-graded 4-layer specimens were subjected to a three-point bending test in accordance with ISO 187, using a Zwick Z250 universal testing machine (Zwick GmbH, Ulm, Germany) equipped with a 1.0 kN capacity load cell. During the tests, a standard support span of 64 mm was applied with a specimen size of 80×10×4 mm. The loading speed was 5 mm/min. The preload was set to 1 N, with a preload speed of 20 mm/min. The laboratory conditions during testing were maintained at 43.7% relative humidity and a temperature of 23.6 °C.

Throughout the experiment, a force-deflection curve was recorded, from which the flexural strength was subsequently calculated using the following equation (Equation (10)) [33]:

$$\sigma_{fs} = \frac{3FL}{2bh^2} \quad (10)$$

where σ_{fs} [MPa] is the flexural strength, F [N] is the recorded force, L [mm] is the support span, b [mm] is the specimen width, and h [mm] is the specimen height. In the evaluation, we compared the flexural strength corresponding to a deflection equal to 10% of the support span (*i.e.*, the limit bending stress) for each layer configuration.

Subsequently, the flexural modulus of elasticity for each foam structure was determined using the following equation (Equation (11)) [33]:

$$E_f = \frac{1}{4} \cdot \frac{L^3}{bh^3} \cdot \frac{\Delta F}{\Delta f} \quad (11)$$

where E_f [MPa] is the flexural modulus of elasticity, L [mm] is the support span, b [mm] is the specimen width, h [mm] is the specimen height, and $\Delta F/\Delta f$ [N/mm] is the slope of the force-deflection curve between 0.05 and 0.25% relative elongation. All properties were determined by testing five specimens for each configuration.

2.6. Impact testing

In order to evaluate the effect of layer order modification on the dynamic mechanical properties of the density-graded multilayer structures, we performed drop weight impact tests by using a Ceast Fractovis 9350 (Instron, Torino, Italy) impact tester. Specimens with a dimension of 80×80×4 mm were secured with a clamping ring and impacted by a hemispherical striker with a 20 mm diameter. The impact velocity was set to 3.14 m/s, with an impactor weight of 3.036 kg, resulting in an impact energy of 15 J. During the perforation of the samples, the force-time data was recorded by using a piezoelectric sensor with a 4.5 kN capacity. From these measurements, the maximum force, perforation energy (Equation (12)) and ductility (Equation (13)) index were determined using the following equations [34]:

$$E_{\text{perf}} = \frac{E_{\text{total}}}{v_{\text{sample}}} \quad (12)$$

$$DI = \frac{E_{\text{total}} - E_{F_{\text{max}}}}{E_{\text{total}}} \cdot 100 \quad (13)$$

where E_{perf} [J/mm] is the perforation energy, E_{total} [J] is the total energy absorbed by the specimen during the impact, v_{sample} [mm] is specimen thickness, DI [%] is the ductility index, while $E_{F_{\text{max}}}$ [J] is the energy absorbed up to the moment when the maximum force was recorded. All properties were determined by testing ten specimens for each configuration.

3. Results and discussion

3.1. Effect of printing temperature and speed on foam expansion and cell structure

To achieve the desired controlled foam structure and cell structure, the first step was to investigate the effect of printing parameters on the degree of foaming. The foaming process can be basically divided into four steps: first, the dissolution of the evolving gas in the polymer matrix, followed by cell nucleation due to the pressure drop at the exit of the nozzle, then cell growth, and finally cell stabilization by cooling. Printing temperature and speed play a critical role in these steps. Increasing the printing temperature promotes the dissolution of the gas in the polymer matrix, but can negatively affect the cell stabilization stage, as the reduced melt strength and the higher diffusivity of the gas can lead to cell collapse and cell coalescence. Conversely, increasing the printing speed reduces the residence time of the material in the nozzle, which can negatively affect the dissolution of the gas. At the same time, higher shear and faster exit from the nozzle result in higher pressure drop, which may promote cell nucleation and cell growth. In the first phase of the research, we aimed to investigate the combined effect of printing speed

and temperature to determine which parameters dominate in the different foaming stages and how their variations influence the final cell structural characteristics.

To better understand the underlying mechanisms, we used a theoretical approach to estimate the wall shear rate and residence time under each printing condition. These results are presented in Figure 3 and are referenced in Sections 3.1 and 3.2.

The effect of nozzle temperature and printing speed was analyzed by thickness measurement and density testing. The results, summarized in Figure 4, show the trends observed across a 7×5 parameter matrix. The results clearly indicate that at 210 °C and below, no foaming occurred regardless of the printing speed. This is likely due to the blowing agent not decomposing at these temperatures, preventing gas release, which is essential for foam formation. As the temperature increased, a significant decrease in density and an increase in wall thickness were observed. This can primarily be attributed to the greater heat transfer to the polymer, which accelerates the decomposition of the blowing agent. Consequently, a larger amount of gas was released and dissolved in the polymer matrix at higher temperatures. However, when analyzing lower printing speeds (e.g., 20 mm/s), it becomes evident that increasing the temperature beyond a certain optimum negatively affects foaming. This can be attributed to the reduced melt strength at elevated temperatures, making cell stabilization more challenging and leading to increased cell collapse and coalescence.

When evaluating the effect of printing speed on density, different trends can be observed depending on the printing temperature. At lower temperatures (at and below 210 °C), where foaming did not initiate, speed had no measurable effect on density values.

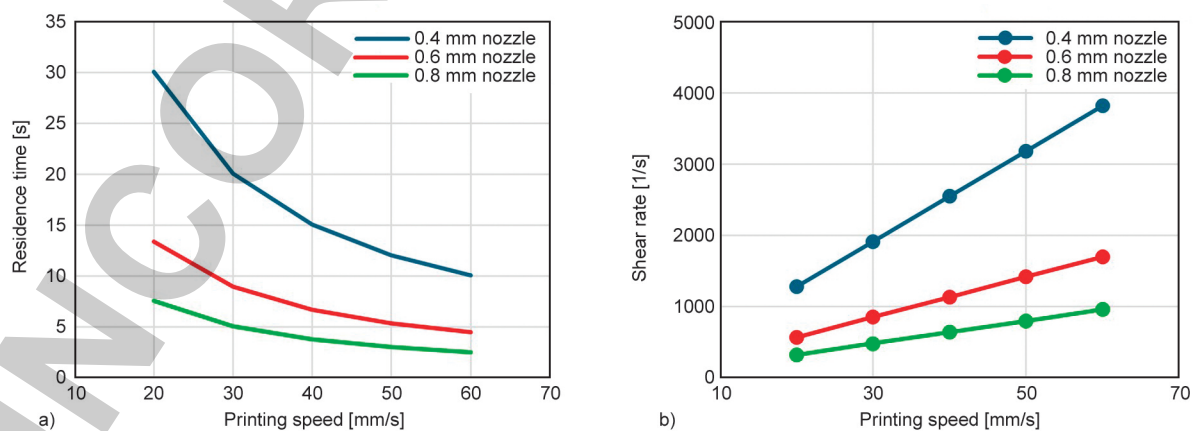


Figure 3. Estimated residence time (a) and wall shear rate (b) as a function of nozzle diameter and printing speed.

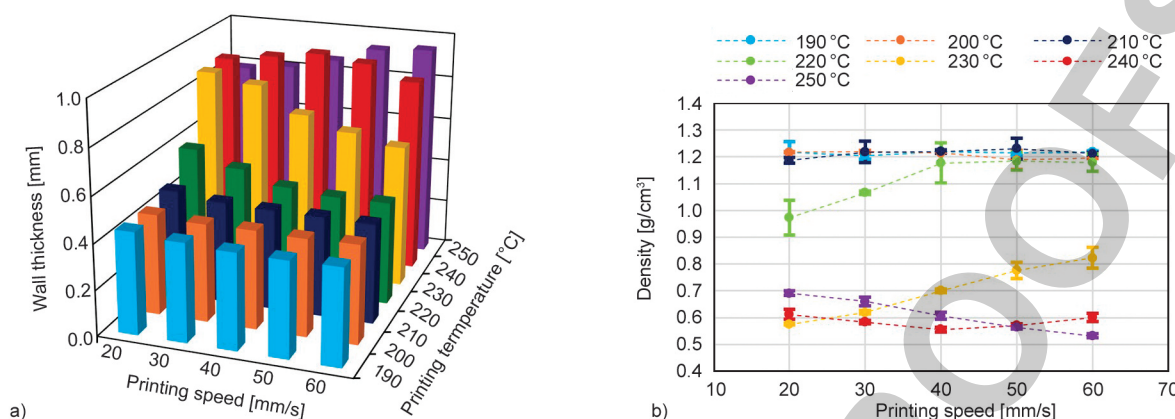


Figure 4. Wall thickness (a) and density (b) of hollow cubes printed with different temperature and speed settings.

For temperatures of 220 °C and 230 °C, increasing the speed resulted in a significant increase in density. This can be explained by the fact that at higher speeds, the residence time of the material in the heated nozzle decreases (see Figure 3). Due to the low thermal conductivity of polymers, heat transfer becomes insufficient for complete decomposition of the blowing agent, reducing the extent of foaming.

At 240 °C, the effect of speed on foaming follows a more complex tendency. Initially, increasing speed enhances the degree of foaming, leading to a decrease in density. Suppose the residence time is still sufficient for full decomposition and gas dissolution (as observed at 20, 30, and 40 mm/s). In that case, higher speeds provide an additional benefit by increasing the internal pressure within the nozzle. This leads to a more significant pressure drop at the nozzle exit [35], promoting both cell nucleation and growth. However, beyond a certain threshold (above 40 mm/s at 240 °C), the residence time becomes too short for complete gas dissolution, causing a decline in foaming efficiency.

As the printing temperature increases further, the optimal printing speed for maximum foaming shifts toward higher values. At 250 °C, for instance, the highest speed tested (60 mm/s) resulted in the greatest reduction in density. This suggests that despite the high temperature, the reduced residence time prevented excessive heat exposure, avoiding a severe reduction in melt strength. Additionally, the higher speed contributed to an increased pressure drop at the nozzle exit [35], further facilitating cell nucleation and growth.

To support the findings and analyze the cellular structure, scanning electron microscopy (SEM) images were captured for the cross-sections of printed samples at each parameter setting. Since previous

results indicated that foaming was only initiated at 220 °C and above, no images were taken for temperatures below this threshold. The collected images are summarized in Table 1.

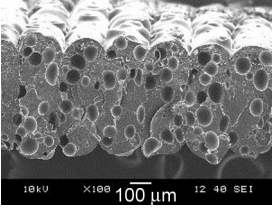
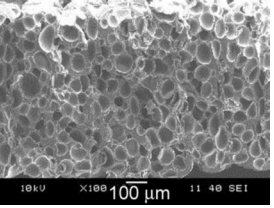
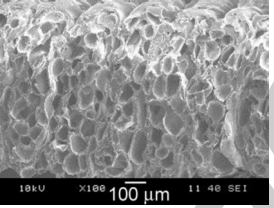
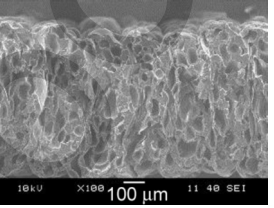
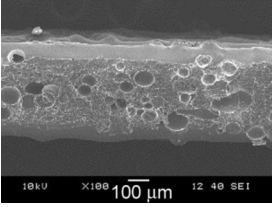
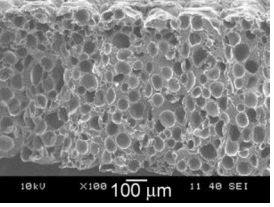
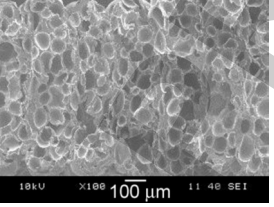
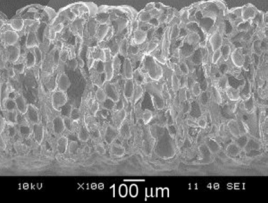
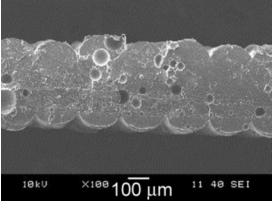
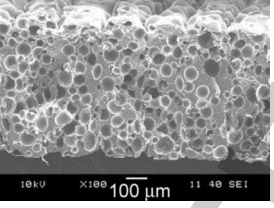
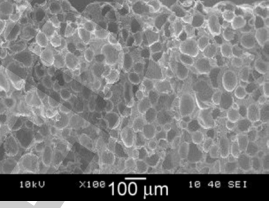
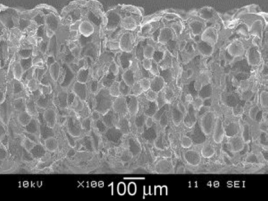
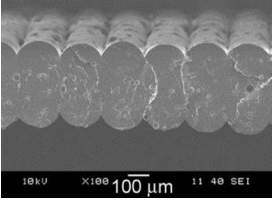
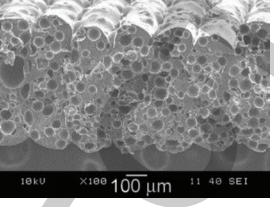
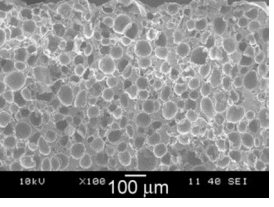
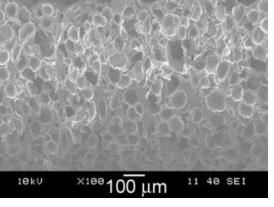
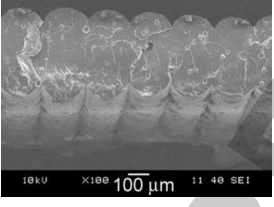
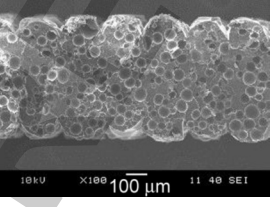
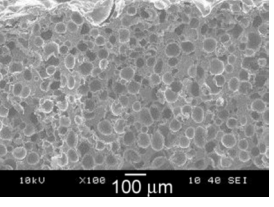
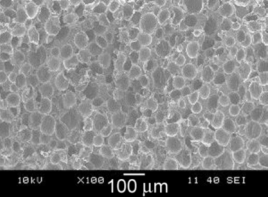
The SEM images reveal that all the printed specimens have a closed-cell structure, allowing further investigation of the influence of printing parameters on cell formation.

At 220 °C, increasing the printing speed drastically reduced the number of visible cells. At a low temperature of 220 °C and high speed of 60 mm/s, no visible pores were detected in the SEM images, which is consistent with the density measurements, indicating that foaming did not occur under these conditions.

In contrast, the cell morphology appeared increasingly irregular at higher temperatures (240 and 250 °C) and low speeds (20 and 30 mm/s). This supports the earlier conclusion that the combination of high temperature and low speed exposed the polymer to excessive thermal loading. The lower melt viscosity at elevated temperatures, combined with the longer residence time, allowed for increased gas diffusion before solidification. Moreover, the faster decomposition rate of the blowing agent at high temperatures, coupled with prolonged residence time, likely resulted in partial gas loss from the system and increased occurrences of cell collapse and coalescence.

Examining the SEM images of samples printed at higher temperatures but at increased speeds revealed a notable difference in structure. The irregular morphology observed at low speeds disappeared, and instead, the cellular structure exhibited well-defined, circular pores with higher cell density, forming a more homogeneous foam morphology. This indicates that at elevated speeds, the reduced residence

Table 1. SEM images of the structures printed with different temperature and speed settings.

Printing speed [mm/s]	220 °C printing temperature	230 °C printing temperature	240 °C printing temperature	250 °C printing temperature
20				
30				
40				
50				
60				

L1 time minimized excessive heat exposure, preserving
L2 the polymer’s melt strength while simultaneously
L3 benefiting from the increased pressure drop, which
L4 enhanced cell nucleation.
L5 The structural trends observed in the SEM images
L6 are further supported by quantitative image analy-
L7 sis of the cellular structure (see Figure 5). Cell den-
L8 sity, defined as the number of cells per unit volume,
L9 increased with printing speed across all conditions
L10 except for the lower temperature (220 and 230 °C)
L11 prints. At 220 °C, foaming was limited due to
L12 insufficient gas evolution. At 230 °C, no clear trend
L13 was observed, as higher printing speeds reduced the

amount of gas released during the initial stage of
foaming due to shortened residence time (Figure 3),
while simultaneously enhancing cell nucleation
through increased pressure drop [36]. At higher tem-
peratures, the correlation between printing speed and
cell density became more apparent, supporting the
previously discussed role of pressure drop at the noz-
zle exit in promoting the formation of nucleation
sites.
Cell size generally increased with printing tempera-
ture, indicating that higher temperatures allowed for
a more extensive expansion phase before the struc-
ture was solidified by cooling. However, increasing

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R12
R13

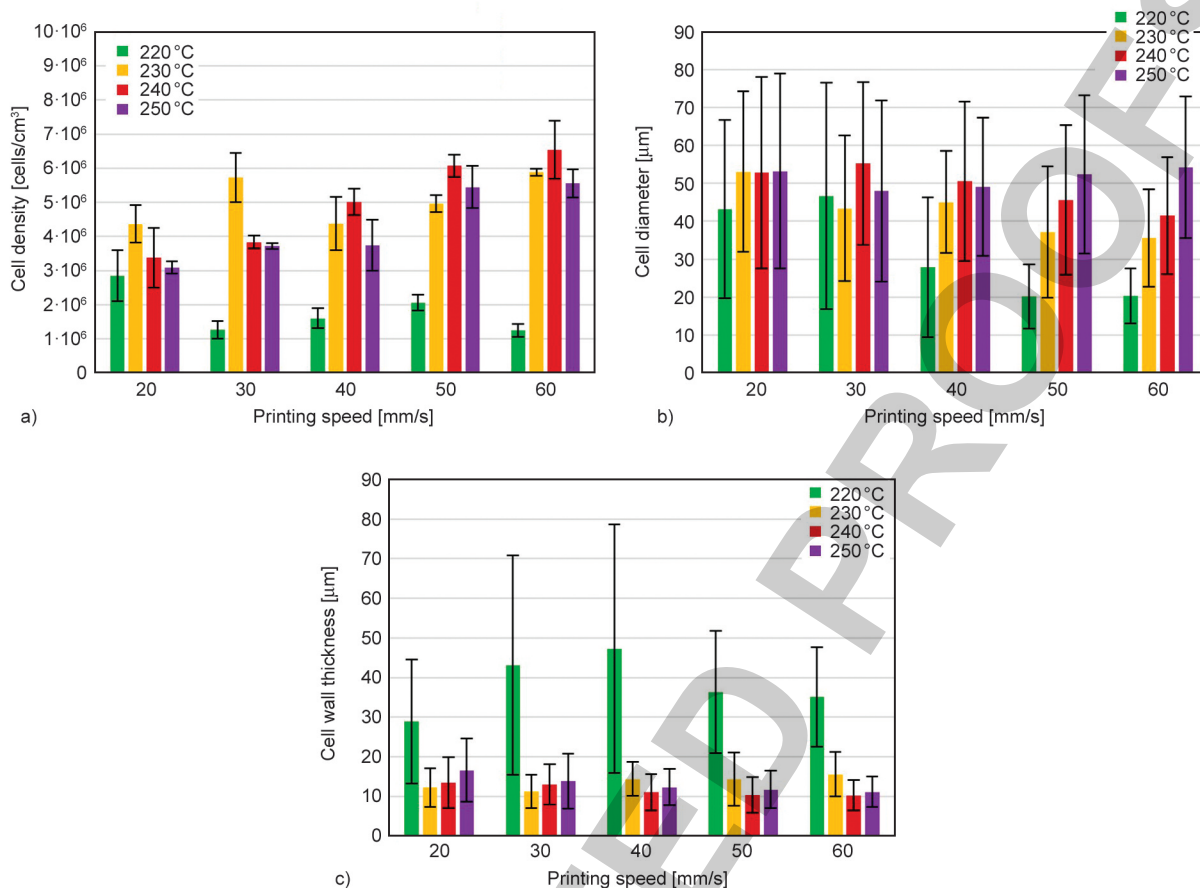


Figure 5. Cell density (a), cell size (b) and cell wall thickness (c) characteristics of the foam structures printed with different temperature and speed settings.

printing speed led to a slight reduction in average cell size. This trend can be attributed to two factors: (1) reduced expansion time before solidification at higher speeds and (2) the increased number of nucleated cells, which resulted in a finer cellular structure due to a more distributed gas phase. Finally, cell wall thickness remained relatively constant across the samples where significant foaming occurred. This suggests that while printing parameters influenced the number and size of cells, they did not cause significant variations in their cell wall dimensions.

3.2. Effect of nozzle diameter on foam structure and density

To investigate the influence of nozzle diameter on the foaming process, specimens were printed using 0.4, 0.6, and 0.8 mm nozzles at constant printing speed while varying the temperature between 220 and 250 °C. The SEM images of the printed samples are summarized in Table 2, illustrating the effect of nozzle diameter on foaming.

The results indicate that, in terms of maximizing foaming efficiency, smaller nozzle diameters are preferable. Despite many filament manufacturers recommending the use of larger nozzles for *in-situ* foaming PLA due to the pre-expanded nature of these materials, our findings suggest that a smaller nozzle leads to greater expansion and porosity. This phenomenon can likely be attributed to two key factors. First, with a reduced cross-sectional area, the filament requires less time to reach the target temperature across its cross-section. At the same time, smaller nozzle diameters result in longer residence times (see Figure 3), allowing the blowing agent more time to decompose and the gas to dissolve into the polymer matrix more effectively. Second, a smaller nozzle subjects the material to greater shear forces, which enhances internal friction and heat generation due to viscous heating [37]. Additionally, the increased shear may contribute to a higher pressure inside the nozzle, resulting in a more significant pressure drop upon exit from the nozzle [35], which promotes cell nucleation [36].

Table 2. SEM images of the structures printed at different temperatures using different nozzle diameters.

Printing temperature [C°]	Nozzle diameter [mm]		
	0.4	0.6	0.8
220			
230			
240			
250			

L1 The density measurement results (Figure 6) also
L2 confirm this trend, showing that at each tested tem-
L3 perature, the lowest density – and consequently, the
L4 highest expansion – was achieved with the smallest
L5 nozzle. An exception to this tendency was observed
L6 at 220 °C, where the density values remained high
L7 regardless of the nozzle diameter, indicating that the
L8 temperature was insufficient to initiate effective foam-
L9 ing. This observation is supported by the SEM im-
L10 ages shown Table 2, where only a minimal number
L11 of pores – or in some cases, none – can be observed.
L12 Although the 0.4 mm nozzle provided higher shear

rates, the total thermal input – resulting from the
combination of residence time and viscous heating
– was still inadequate to trigger the decomposition
of the blowing agent and initiate cell nucleation at
this low temperature.
The cell structural characteristics extracted from SEM
images (Figure 7) reveal that above 230 °C, smaller
nozzle diameters led to an increased number of nu-
cleated cells per unit volume, resulting in higher cell
density. This is a direct consequence of the greater
pressure drop, which promotes bubble nucleation.
Furthermore, while cell diameter remained relatively

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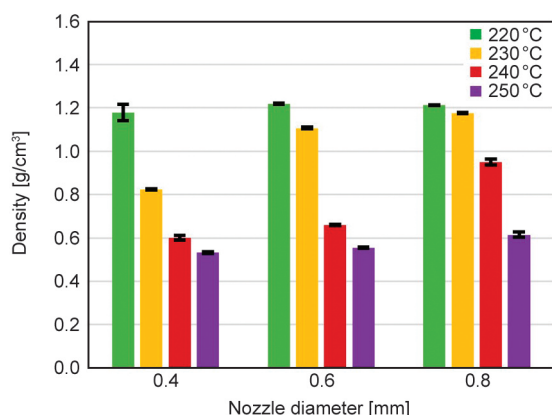


Figure 6. Density results of the structures printed at different temperatures using different nozzle sizes.

stable across different nozzle sizes, a slight increase was observed for smaller nozzles. This is presumably related to the longer residence time (see Figure 3), which may have led to more gas formation, and to the fact that the material likely reached the target temperature more uniformly across the cross-section, allowing for a longer cell growth period before the polymer solidifies and stabilizes the foam structure.

While these effects were still observable at 250 °C, the influence of nozzle diameter on density and structure became less distinct compared to lower

temperatures (Figure 6). As shown in Figure 7, cell density was still higher for smaller nozzle diameters, suggesting enhanced nucleation. The average cell size remained relatively stable, but SEM images (Table 2) indicate that samples printed with larger nozzles exhibited a more heterogeneous cell distribution, including a few larger pores, regions lacking visible cells, and areas with only partially expanded structures. These structural irregularities balanced each other out, resulting in similar average cell sizes despite the visible differences in foam morphology. At this elevated temperature, the reduced pressure drop associated with larger nozzle diameters may shift the balance between nucleation and growth, resulting in fewer nucleated cells. These cells, however, can grow larger as more gas diffuses into them [38, 39]. The lower internal pressure in these expanding bubbles facilitates additional gas uptake, amplifying cell growth over nucleation and forming larger, more isolated pores.

These findings highlight that selecting an appropriate nozzle diameter is a crucial parameter for optimizing *in-situ* foaming efficiency, as it directly influences the extent of expansion, cell nucleation, and final cellular morphology.

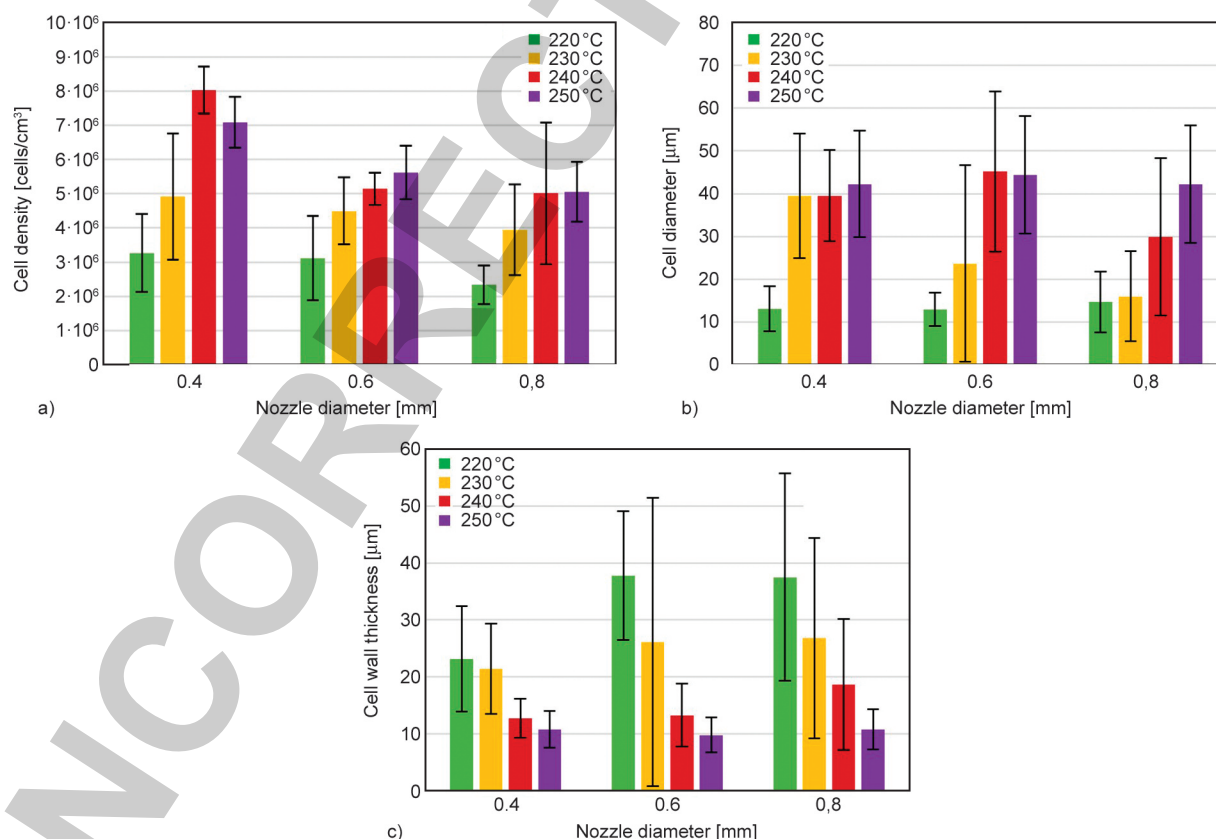


Figure 7. Cell density (a), cell size (b) and cell wall thickness (c) characteristics of the foam structures printed at different temperatures using different nozzle sizes.

3.3. Functionally graded foams: Effect of temperature-controlled layering on mechanical properties

3.3.1. 3D-printing

According to the method described in Section 2.2.3., we created 4-layer graded structures, in which the porosity of each layer were controlled by modifying the printing temperature and compensating the change in volume due to foaming with the extrusion multiplier. The SEM images taken from the cryogenic fracture surfaces of each configuration are presented in Figure 8.

As shown in Figure 8, some minor voids can be observed between the layers, especially in the non-foamed regions. These are likely due to the lack of expansion, which generally helps to fill small gaps between layers. It is important to note that increasing the flow rate could help eliminate these interfacial

voids, as more material would be deposited in each layer. In this study, however, we adjusted the extrusion parameters only to maintain the same overall dimensions and mass for each configuration, so that the effect of layer arrangement could be compared directly.

3.3.2. Three-point bending

The results of the three-point bending tests are summarized in Figure 9, illustrating the force-deformation curves, the flexural strength and modulus for each graded structure. The results clearly show the influence of the layer configuration on the mechanical performance, demonstrating that the control over porosity by adjusting the printing parameters can significantly enhance flexural resistance.

The 210–250–250–210 configuration, which has dense outer layers and a porous core, exhibited the

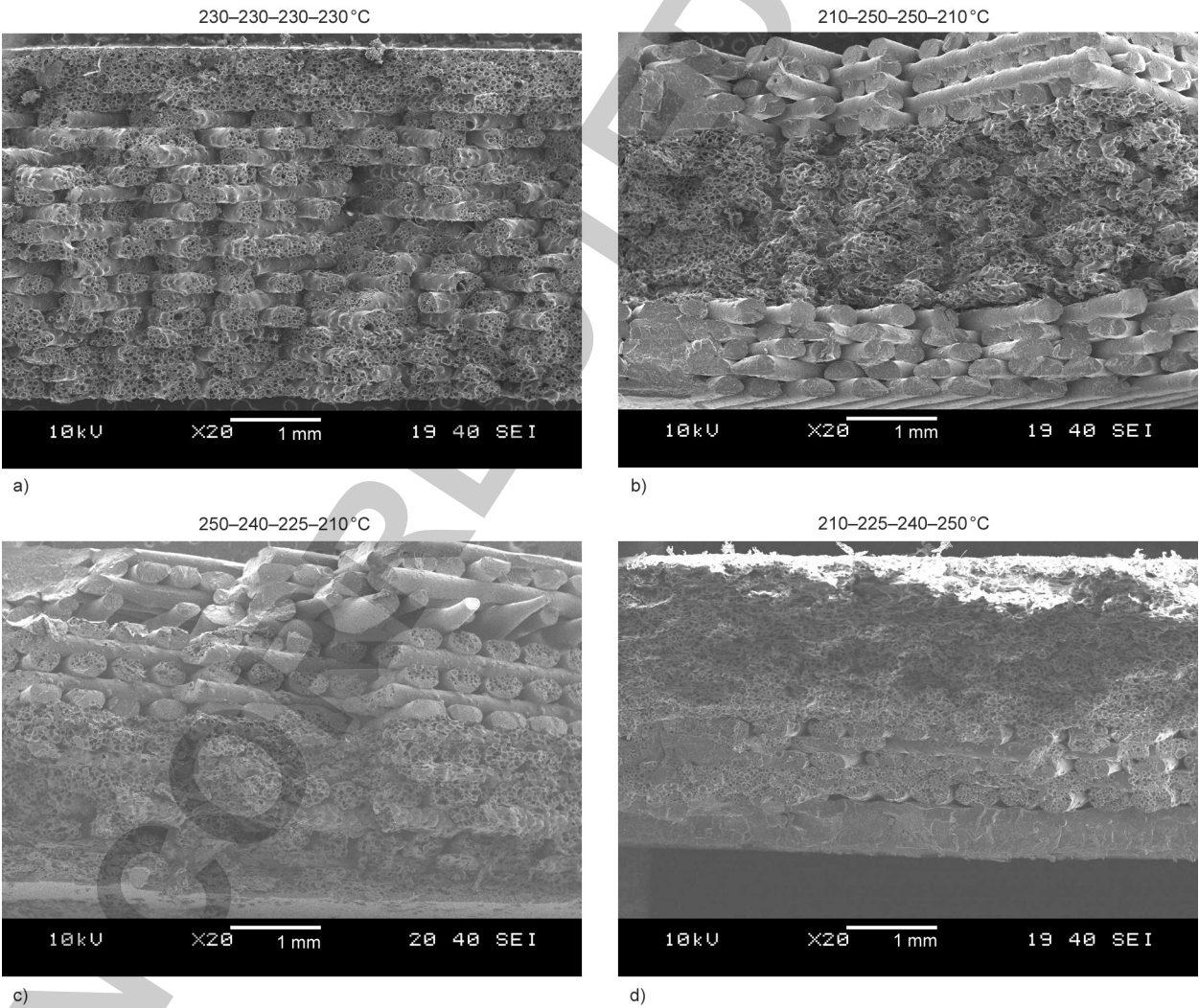


Figure 8. SEM images of the four-layer graded structures printed with different temperatures applied to each layer. a) printed with 230–230–230–230 °C, b) with 210–250–250–210 °C, c) with 250–240–225–210 °C and d) with 210–225–240–250 °C.

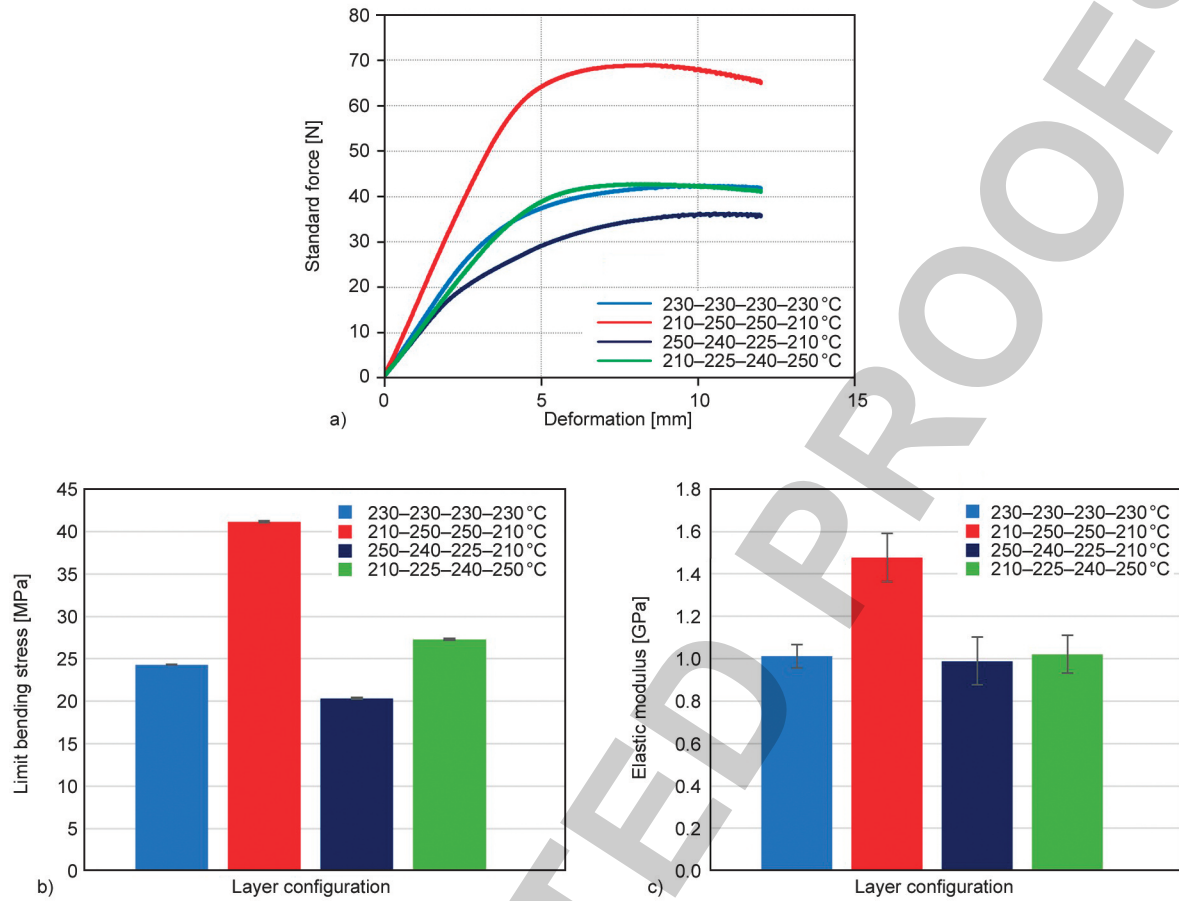


Figure 9. Force-deformation curves (a), limit bending stress (b) and elastic modulus (c) results obtained from the 3-point bending test.

highest flexural strength (41.15 ± 1.955 MPa) and modulus among all tested structures. This outcome can be explained by the general stress distribution in bending, where the top and bottom layers experience the highest compressive and tensile stresses, respectively. Since these layers had the highest density, they provided enhanced resistance to deformation, while the porous core reduced weight without significantly compromising stiffness. This design maximized mechanical performance while minimizing mass, demonstrating the efficiency of a shell-core-shell design for bending loads. The deformation remained largely elastic up to relatively high loads, with visible deflection but no sudden failure, indicating stable load-bearing behavior of the dense outer layers.

In contrast, the homogeneous structure (230–230–230–230) exhibited a significantly lower flexural strength (24.3 ± 1.022 MPa). In this case, the stress was evenly distributed throughout the sample, preventing localized strengthening in the most highly stressed regions. This confirms that material grading plays a

crucial role in optimizing bending performance by reinforcing the areas subjected to the highest loads. For graded structures with progressively changing density, the flexural strength varied depending on the direction of the density gradient. The 210–225–240–250 configuration, where the upper layers were more porous and the lower layers denser, exhibited higher strength (27.296 ± 0.836 MPa) than its inverse counterpart (250–240–225–210, 20.351 ± 1.193 MPa). This trend is closely related to the general mechanical behavior of cellular materials, as foams tend to be more resistant to compressive loads than tensile loads. In bending, the top layer undergoes compression, while the bottom layer is subjected to tensile stress. In the 210–225–240–250 structure, the densest layer was positioned at the bottom, reinforcing the region most sensitive to tensile loads, while the upper porous layer was able to deform progressively and withstand stress under compression. In contrast, in the 250–240–225–210 structure, the bottom layer was more porous, reducing its ability to withstand tensile loads, which led to lower flexural strength.

3.3.3. Impact testing

The results of the impact tests are presented in Figure 10, which shows the peak force, perforation energy, and ductility index for each tested layer configuration.

The data indicate that modifying the layer order consistently increased the force required to initiate crack propagation and the energy needed for complete perforation compared to the homogeneous structure (printed at 230 °C). However, the ductility index decreased, suggesting that functionally graded structures exhibited a more brittle failure than the homogeneous reference specimen. To better understand these differences, we analyzed the force-time curves (see Figure 11) recorded during the tests.

The impact response of the different layer configurations varied significantly, as reflected in their force-time curves and derived mechanical parameters. The homogeneous structure (230–230–230–230) exhibited the lowest peak force (461.9 ± 53.9 N) and the highest ductility index ($80.6\pm11.4\%$). The force reached its maximum within 1 ms and then gradually

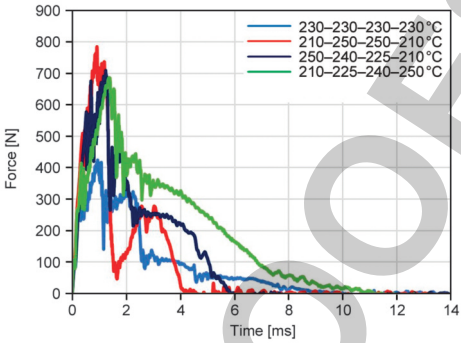


Figure 11. Typical force-time curves recorded during the impact tests.

declined over 8 ms, indicating a relatively extended failure duration. This suggests a failure mechanism, where energy dissipation occurs gradually throughout the structure. However, despite its ability to undergo gradual deformation, this configuration had the lowest perforation energy (0.89 ± 0.17 J/mm), highlighting its limited capacity to resist impact due to the lack of energy-dissipating effects provided by the graded structures. The failure occurred through gradual crack initiation and propagation through the

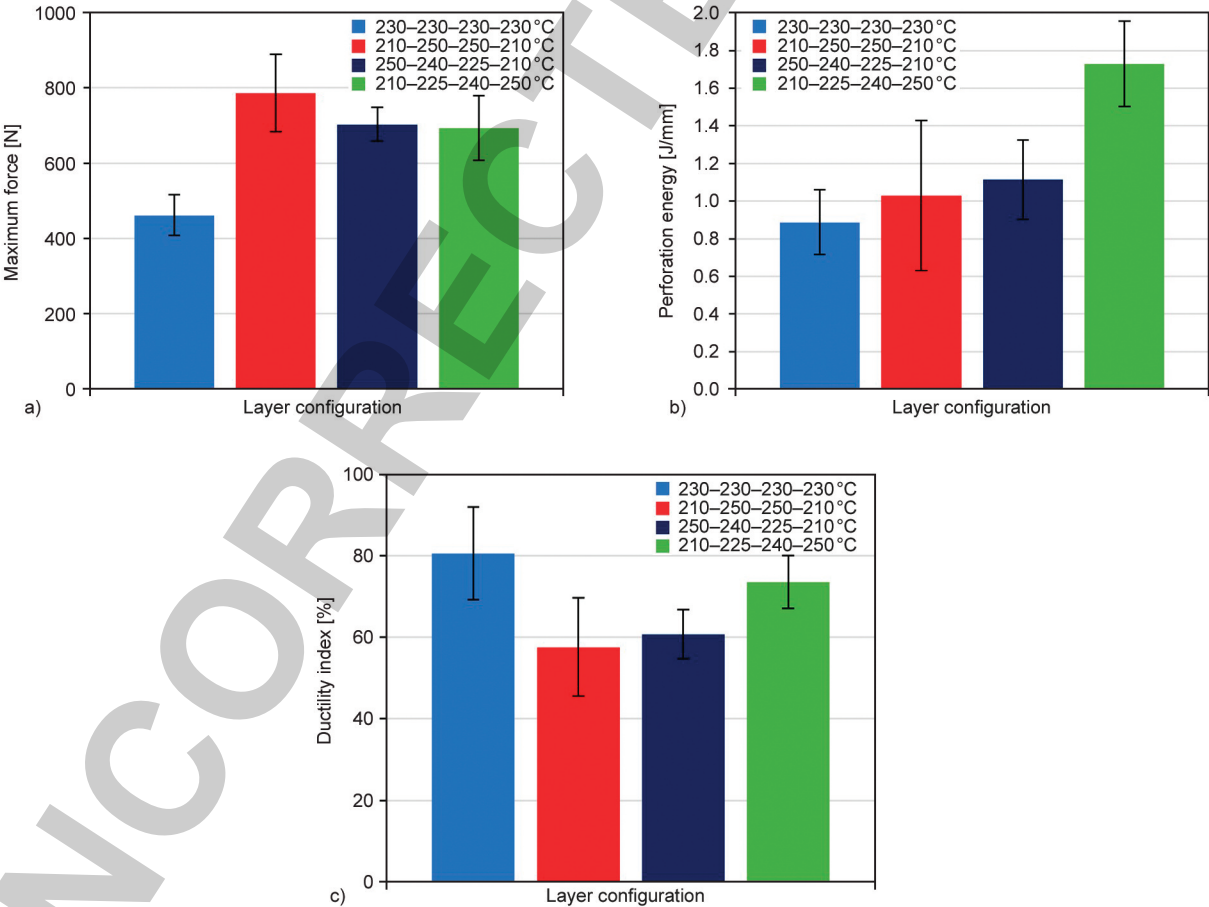


Figure 10. Impact testing results of the density-graded printed samples: maximum force (a), perforation energy (b), and ductility index (c).

thickness, with less pronounced brittle fracture surfaces observed compared to graded structures.

In contrast, the configuration with denser outer layers and a porous core (210–250–250–210) exhibited the highest peak force (785.6 ± 103.1 N), which was reached within 1.1 ms. However, this was followed by the most rapid failure progression, with complete perforation occurring in just 4 ms. The force-time curve demonstrated a steep increase in force, followed by a rapid drop, suggesting that the stiff outer layers initially provided significant resistance, but the weak, porous core collapsed quickly, leading to brittle failure. The low ductility index ($57.6 \pm 12.0\%$) further confirms that while this configuration effectively resisted the initial impact, it facilitated early structural failure due to insufficient energy dissipation.

A different trend was observed in the configuration where porosity increased toward the top (210–225–240–250). This structure exhibited the highest perforation energy (1.73 ± 0.23 J/mm), indicating superior energy absorption capacity. The force-time curve revealed a delayed force drop, with the peak force (692.3 ± 86.2 N) occurring at 1.5 ms, followed by a gradual decline over 11 ms before complete perforation. The extended failure duration suggests that energy was dissipated progressively through the increasingly stiff lower layers, which delayed crack propagation and structural collapse. The fracture surface showed progressive damage development, with visible crushing and compaction of the porous top layers prior to final rupture.

The configuration with decreasing porosity toward the top (250–240–225–210) exhibited a similar peak force (703.3 ± 44.5 N) to its counterpart with increasing porosity, yet its perforation energy (1.11 ± 0.21 J/mm) was notably lower. The force-time curve showed a sharp initial force increase followed by a relatively rapid drop, with complete perforation occurring within 6 ms. This behavior suggests a more sudden failure, likely due to the inability of the porous bottom layer to provide sufficient resistance and slow down crack propagation. These trends are in good agreement with the literature, which highlights that the density of the top layer – being the first to contact the impactor – has a dominant influence on the initial slope of the force-time curve. A decreasing density gradient in the loading direction results in weaker lower sections, offering less resistance and allowing deformation to progress more

rapidly toward the end of the impact event [19]. The lower ductility index ($57.6 \pm 12.0\%$) further supports this observation, indicating that while peak resistance remained similar, the overall energy absorption capacity of this configuration was decreased.

These results clearly demonstrate that the layer order and orientation have a significant influence on the impact behavior of the printed structures. By properly adjusting the density gradient, it is possible to optimize the strength–weight balance for a given application. In addition to the orientation, the exact shape of the density profile (e.g., linear, concave, convex) may also affect the mechanical performance, as suggested by previous studies [19, 40, 41], and could be the subject of future investigations.

4. Conclusions

In this study, we systematically investigated the influence of processing parameters on the foaming behavior and cellular structure of *in-situ* foam 3D-printed specimens. By analyzing the combined effects of printing temperature and speed, we identified their roles in the four key stages of the foaming process: gas dissolution, cell nucleation, cell growth, and stabilization. Our results demonstrated that increasing the printing temperature generally enhances foaming by promoting greater gas evolution and expansion. However, excessive heat exposure at low printing speeds led to irregular cell structures due to premature cell collapse and coalescence. Conversely, higher printing speeds improved cell nucleation efficiency by increasing the pressure drop at the nozzle exit, but at the same time, excessively high speeds limited foaming due to the reduced residence time, which was insufficient for complete gas dissolution in the polymer matrix.

We also explored the effect of nozzle diameter, an aspect previously unexamined in the context of *in-situ* foam 3D printing. Our findings revealed that smaller nozzle diameters enhance foaming efficiency by improving heat transfer, increasing shear-induced nucleation, and promoting higher internal pressures, which lead to a greater pressure drop when the melted polymer exits the nozzle.

To further demonstrate process-controlled foaming, we fabricated functionally graded four-layer structures by varying the printing temperature per layer. Mechanical tests showed that layer order significantly influences the bending and impact resistance of the graded structures. Specimens with dense outer

layers and a porous core exhibited superior bending strength. At the same time, structures with an increasing porosity gradient from bottom to top provided the best balance between strength and energy absorption under impact loading. These results highlight the potential of *in-situ* foam 3D printing for producing lightweight cellular materials with tailored mechanical properties.

Our findings contribute to a deeper understanding of process-controlled foaming in additive manufacturing and provide valuable insights for optimizing *in-situ* foam 3D printing for structural applications. Future research may focus on refining nozzle geometries, developing custom filament formulations – including foaming filaments made from recycled polymers – and exploring advanced strategies to enhance foaming efficiency. In addition, the influence of flow rate and extrusion volume on the foaming process should also be investigated, as these parameters may significantly affect layer adhesion. These results have potential applications in medical technology, particularly in the development of orthotic devices and implants, as well as in energy-absorbing systems for the automotive and sports equipment industries. Additionally, they contribute to improving the functionality of FDM-printed parts, thereby supporting the broader adoption of this technology in various engineering fields.

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