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Mechanical properties of polyamide 12 manufactured by means of SLS: Influence of wall thickness and build direction

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Abstract

The wall thickness and build direction of PA 12 parts manufactured via SLS are currently being investigated for applications requiring low weight and good mechanical properties (ultimate tensile strength, elongation at break, elastic modulus, and hardness). Current design guidelines for the SLS process include recommendations about the influence of build direction on the mechanical properties of the part; however, the recommended minimum wall thickness only considers the process's manufacturability, so this study aims to determine the wall thickness and build orientation conditions that present the slightest difference in mechanical properties, considering different conditions as vertical, horizontal, and transverse build directions and wall thicknesses of 2.0, 2.5 and 3.0 mm. Statistical differences were found between build direction, ultimate tensile stress, and elongation at break and hardness. It was observed that the significant differences in the direction of impression were between the vertical direction versus the transverse and horizontal directions. The differences were between the values of 2.0 mm versus 2.5 and 3.0 mm for the wall thickness. The mechanical properties between these last two thicknesses do not present significant differences, so it is suggested that parts manufactured with PA 12 by SLS with thicknesses of 2.5 mm could have the same tensile mechanical properties as those of 3.0 mm. The horizontal and transverse directions with a 2.5–3.0 mm thickness showed the highest mechanical properties with an ultimate tensile stress of ≈ 43 MPa, a modulus of elasticity of 2.2 GPa, and an elongation at break of 16%–18% and a hardness of ≈ 75 Shore D.

Introduction

Additive manufacturing via the selective laser sintering (SLS) technique has applications in many fields, such as the automotive, pharmaceutical, aerospace, and biomechanics industries [1–5]. SLS has advantages over traditional processes because it facilitates the manufacture of parametric and nonparametric parts and reduces production costs compared to conventional manufacturing techniques since it allows the manufacture of pieces without extensive tooling and can use virgin and recycled materials [6–10]. Nylon 12 (PA 12) is the most widely used material for SLS, it is of great interest in engineering research due to its excellent mechanical properties such as tensile strength, compressive strength, and hardness [7, 11–13].

On the other hand, it has been reported that parts manufactured using SLS exhibit variability in their mechanical properties, which is closely related to manufacturing factors such as the build direction and the wall thickness. For example, Ajuko *et al* [14] studied the influence of the build direction on the tensile and flexural mechanical properties in PA 12 specimens fabricated via SLS. The results indicated that the build direction affected the ultimate tensile stress (UTS), elastic modulus (EM), and elongation at break (Eab). The authors observed that the UTS of the materials was highest when the build direction was horizontal, followed by

transverse and vertical. Finally, the authors suggested that the changes observed were associated with the particle fusion process.

Mehdipour *et al* [15] examined the mechanical properties of PA 12 as a function of the printing direction in SLS and multijet fusion (MFJ) techniques using cross-head speeds of 5 mm min^{-1} and 50 mm min^{-1} . The results showed that the transverse build direction exhibited the highest UTS and EM values, followed by the horizontal and vertical build directions. At the same time, Eab did not indicate a defined behaviour. The low ductility in these directions may be associated with porosity and poor particle fusion. Furthermore, the mechanical properties in PA 12 did not change at the two strain rates evaluated, indicating that the material's nature was unaffected.

Cooker *et al* [16] evaluated the mechanical properties of PA 12 as a function of the build direction and the storage conditions. The material's mechanical properties after fabrication and exposure to ambient humidity were evaluated, showing that the transverse build direction exhibited the highest UTS and EM values. In comparison, Eab exhibited higher values in the transverse and horizontal build directions, which were close. The horizontal build direction showed the lowest anisotropy value, followed by the transverse and vertical directions.

Faes *et al* [17] obtained samples from a mixture of virgin and recycled powder without specifying the mixing ratio and determined that the EM values tended to be homogeneous in the horizontal and transverse build directions. At the same time, the vertical build direction exhibited the most striking differences, mainly in its fracture mechanism.

Majewski *et al* [18] studied the influence of wall thickness and build direction on tensile mechanical properties using 2, 3, 4, 5, 6, and 7 mm wall thicknesses. The results suggested that the wall thickness did not influence the UTS, Eab, or EM, while the vertical build direction exhibited the lowest UTS value. Tasch *et al* [19] studied the variability of the mechanical properties of tensile specimens as a function of wall thickness (0.6 to 2.0 mm). As the wall thickness increased, the UTS and EM increased. In addition, the strain at break increased nonlinearly as a function of thickness.

Sigfrid-Laurin *et al* [20] evaluated the influence of wall thickness and build direction on the UTS, Eab, and EM values. The results showed that specimens with smaller wall thicknesses (0.6 mm and 1.0 mm) exhibited mechanical properties with lower values of those properties. Upon comparison to those obtained using samples with thicknesses of larger magnitude (2.0 mm and 4.0 mm), it was suggested that this behaviour is due to the porosity ratio as a function of thickness. In addition, it was shown that specimens manufactured using the vertical build direction exhibited the worst mechanical properties compared to the horizontal and transverse directions.

According to ISO/ASTM 52900:2015 [21], the mechanical properties of a part must be coupled with the process parameters to be accurately predictable. Design guidelines for SLS parts [22–24] inform the designer about the effect of the build orientation on the part's mechanical properties, but the minimum wall thickness is only related to the process manufacturing capabilities. The minimum thickness is also essential in applications requiring low weight and high strength, mainly when the designer uses computational-driven design tools such as topology optimisation or generative design to create slender parts with organic shapes [25]. Although previous studies mostly detail the study of a single variable, mainly the effect of the build direction on the tensile mechanical properties of SLS-sintered PA 12, research evaluating these two factors is uncommon, focusing on tensile mechanical properties and leaving aside hardness, one of the essential qualities in mechanical parts with an excellent resistance to wear, such as automotive housing parts. Furthermore, previous research mainly performed ANOVA comparisons but not Pairwise tests, which allowed us to observe differences between each variable level, in this case, wall thickness and build direction.

For these reasons, in the present study, the influence of build direction and wall thickness on the mechanical properties of SLS-sintered PA 12 was evaluated qualitatively and quantitatively. Specimens were characterised by hardness and tensile tests, and the mechanical properties (ET, UTS, and Eab) were determined. Analysis of significant differences by factor and levels was performed to identify the most influential variables concerning the mechanical properties of PA 12.

Materials and methods

Sintering process

Uniaxial tensile specimens were fabricated on a commercial EOS Formiga P110 Velocid machine with the manufacturer's recommended criteria, following ISO 257-Type I guidelines. The samples were manufactured with a CO_2 laser power of 30 W, a scan speed of 5 m s^{-1} , a layer thickness of 0.12 mm, and a build rate of 1.2 l/h. An EOS polyamide 12 mixture of virgin powder and recycled powder (30:70) was used, and the machine predetermined the scanning strategy. The CAD specimens were randomly distributed throughout the chamber volume (figure 1(B)) so that the variability of the mechanical properties of the specimens was not a consequence

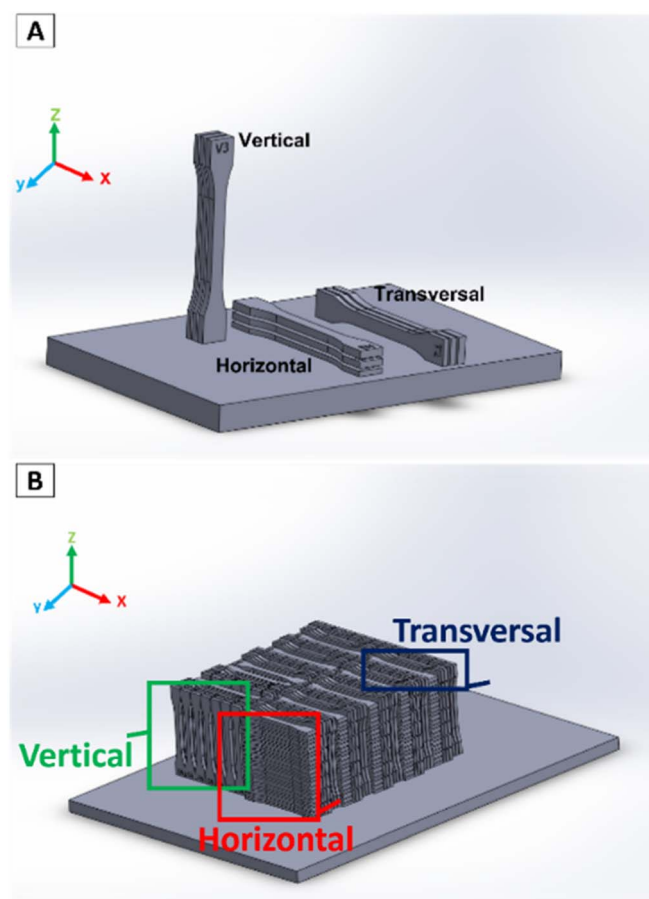


Figure 1. (A) Vertical (V), horizontal (H), and transverse (T) build directions. (B) Build directions of the manufactured specimens: vertical (V), horizontal (H) and transversal (T). (B) Distribution of CAD specimens randomly placed in the sintering chamber volume. (ONE COLUMN).

Table 1. Experimental design in the manufacture of specimens from the mechanical test. (ONE COLUMN).

Group	Experiment	Experimental parameters	
		Build direction	Thickness (mm)
1	H2.0	Horizontal	2.0
2	H2.5	Horizontal	2.5
3	H3.0	Horizontal	3.0
4	T2.0	Transversal	2.0
5	T2.5	Transversal	2.5
6	T3.0	Transversal	3.0
7	V2.0	Vertical	2.0
8	V2.5	Vertical	2.5
9	V3.0	Vertical	3.0

of the equipment or the heterogeneity of the powdered material. The wall thicknesses were 2.0, 2.5, and 3.0 mm, and the build directions were vertical (V), horizontal (H), and transverse (T) (figure 1(A)). For wall thickness, values from 0.6 to 4 mm were studied.

Experimental design and statistical analyses

The experimental design (table 1) was factorial 3^2 , and the variables considered were build direction and wall thickness. The number of replicates was calculated with a significance of 0.05 and an expected error of 2.5 MPa in UTS ($n = 8$). The mean value of UTS was 45.7 MPa, obtained from previous results.

Table 2. The particle size of the overall and individual measurements. (One Column).

Description	Powder sample	Powder populations			
		A	B	C	D
Mean (μm)	47.69	47.54	48.69	47.27	47.28
Max (μm)	91.51	82.03	91.51	74.14	86.75
S.D (μm)	11.10	10.48	11.68	10.07	12.07

Randomness

Thirty specimens were fabricated for each experiment, as shown in table 2. Each experiment evaluated a combination of wall thickness and build direction values. The 270 specimens were sorted into nine groups according to each experiment. Then, the 30 specimens from each group were manually mixed for 15 min, and 15 specimens were randomly selected and numbered from 1 to 15. These 15 specimens were manually mixed for 15 min, and eight samples were randomly assigned (8 replicates per experiment) and stored at room temperature in a desiccator with silica until use (table 2).

Statistical analysis

The Anderson–Darling and Levene tests evaluated the assumptions of normality and homoscedasticity. One-way and two-way ANOVA tests were applied to assess significant differences. Nonparametric data were evaluated using the Kruskal–Wallis test and pairwise comparisons were performed using the Bonferroni adjustment test. A q-norm transformation was used to determine the normality for the hardness, UTS, and EM properties. An Ameijeiras-Alonso bimodality test was performed on the particle size. Statistical analysis and visualisation of all the experimental data were performed using Python and RStudio software.

Ultimate tensile stress (UTS)

The uniaxial tensile test was conducted per ISO 527–1 at a 2 mm min^{-1} speed. A Shimadzu universal testing machine AG IS- 5KN with an SLBL-5K load cell capacity of 5 kN was used.

Elongation break (Eab) and transversal area

The specimens' gauge distance, thickness, and width were measured with a Mitutoyo calliper before and after the tensile test. The stress was calculated over the entire area of the manufactured specimens. The tensile tests were conducted below $25\text{ }^{\circ}\text{C}$ and 50% relative humidity, as the ISO 527 guidelines recommended.

Elastic modulus (EM)

The modulus of elasticity was measured based on the following formula:

$$EM = \frac{V_{lon}^2 - \rho(1 + \nu)(1 - 2\nu)}{1 - \nu}$$

V_{lon} is the longitudinal wave velocity (m s^{-1}), ρ is the material density (kg m^{-3}), and ν is the material's Poisson ratio.

The sound velocity of the material was measured with an SIUI model CTS59 Ultrasonic thickness gauge probe. A dual frequency 1 MHz Ultrasonic Thickness Gauge Probe TC110 of 12 mm was used. The material density value and Poisson's ratio were taken from the research by Judawisastra *et al* [26].

Stress-strain curves

The strain values for the stress-strain curves were measured with a Shimadzu contact extensometer SES 1000, with a 25 mm gauge adapted to the extensometer. The comparison was carried out using the loess method with the smoothing functions of the ggplot2 package in rstudio.

Hardness test (Shore D)

The hardness was measured on a D-06752 RX tester on the Shore D scale and according to ASTM D2240 with the maximum hardness criterion.

Cryogenic fracture

The specimens under tension were wrapped in aluminum foil and immersed in liquid nitrogen for 2 min, then the specimens were fractured by means of metal tweezers in flexion in a time not exceeding 3 s.

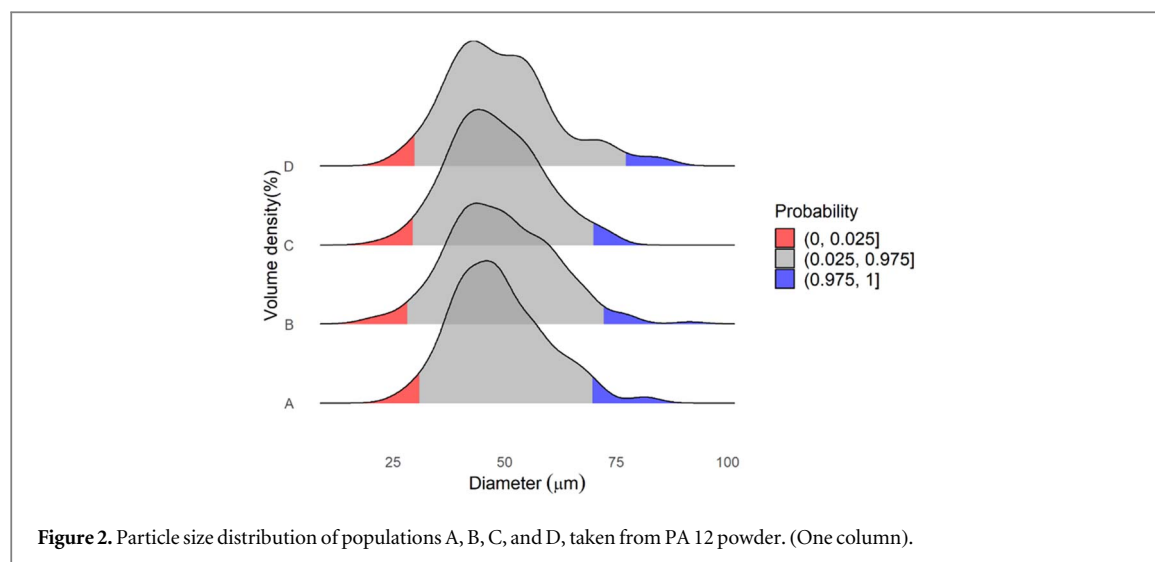


Figure 2. Particle size distribution of populations A, B, C, and D, taken from PA 12 powder. (One column).

Particle and pore size

The particle size was determined by measuring 800 particles using SEM Vega 3 tescam equipment with a gold metallised specimen. The particle size and pore diameter were evaluated using ImageJ software with four SEM images. The PA12 powder was divided into four parts (A, B, C, and D), and three sections were fractured under liquid nitrogen to avoid most of the deformation corresponding to the SEM images.

Results and discussion

Particle size

The particle size of the PA12 powder used in manufacturing the specimens was close to an average value of approximately $47.69 \mu\text{m}$ with a standard deviation of $11.10 \mu\text{m}$ approx. On the other hand, the difference between the maximum and the average particle size was approximately $43.82 \mu\text{m}$ in all samples (table 2).

It was found that the distributions did not exhibit bimodal behaviour, only one powder population; however, a shoulder was observed when analysing figure 2 in distributions B and D. This would indicate two primary particle diameter values, close to $30 \mu\text{m}$ and $60 \mu\text{m}$.

No significant differences between each measurement ($p = 0.798$) were observed between the particle sizes in the nonparametric distributions (figure 2). However, it has been observed that particle size dramatically influences the sintering process, and this amount of particles in two sizes can affect some mechanical properties of the manufactured specimens. Ajoku *et al* [14] mentioned that the sintering process occurs under the Frankel model, which is related to the particle radius. In this case, having two populations of radio would lead to a variation in the sintering necks and, therefore, in the porosity and defectology of the sample, as explained in the research of Benedetti *et al* [27] and Dadbakhsh *et al* [28].

Cross-sectional area analysis

The cross-sectional area exhibits an error depending on the specimens' thickness and build direction. It seems that the error generally increases as the thickness decreases. In addition, the vertical direction causes more significant errors than the horizontal and traverse directions. The highest error values (6.22%, 4.15%, and 4.46%) were observed at a thickness of 2.0 mm in the vertical, horizontal, and transverse directions, respectively. The area values for this thickness are 14.05, 14.49, and 14.57 mm^2 for the vertical, horizontal, and transverse directions, respectively (table 3). Furthermore, the error variability increased as the thickness decreased and was higher in the horizontal and vertical directions than in the transverse direction (figure 3).

Comparisons of the cross-sectional area values for each specimen's wall thickness are shown in table 4. It was observed that the cross-sectional area values of the samples fabricated with the horizontal and transverse build directions were significantly larger than those fabricated with the vertical build direction, which greatly influenced the cross-sectional area of the manufactured specimens [29].

The SEM image of specimen H2 (figure 4) shows the external surface and the fracture zone. The surface contained particles that appeared not well fused, suggesting that the energy density of the laser that formed the outer layers may have been too low to allow proper sintering. On the other hand, the fracture section shows good particle fusion, with differences between the surface and the nucleus of specimens in the sintering process.

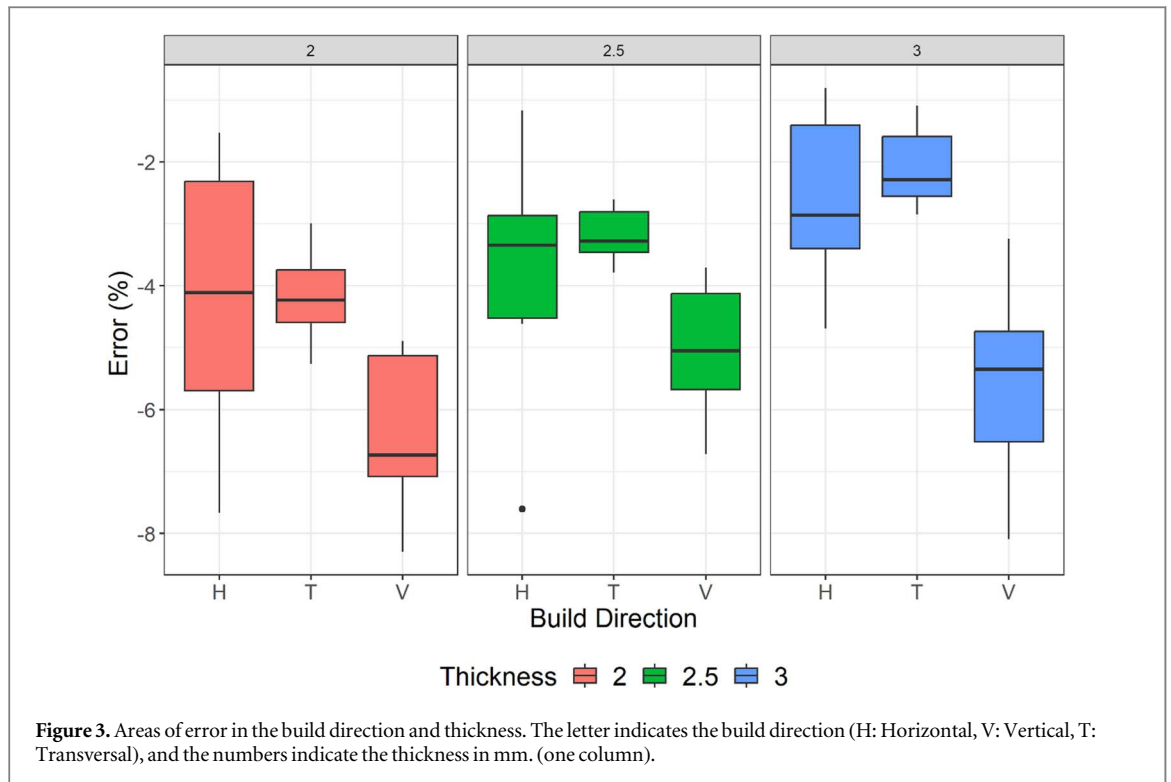


Table 3. Cross-sectional area and error values on a function to build direction and thickness wall measurements. (One Column).

Dimensional cross-section area average values					
Build direction	Wall thickness (mm)	Cross-sectional area (mm ²)	S.D	Error (%)	S.D
Vertical	2.0	9.378	0.12	−6.22	1.24
	2.5	11.84	0.13	−5.28	1.04
	3.0	14.05	0.25	−6.29	1.66
Horizontal	2.0	9.58	0.22	−4.15	2.25
	2.5	12.01	0.24	−3.95	1.89
	3.0	14.49	0.20	−3.37	1.33
Transversal	2.0	9.55	0.08	−4.46	0.79
	2.5	12.10	0.05	−3.22	0.42
	3.0	14.57	0.09	−2.86	0.62

Table 4. Parametric ANOVA statistical test of the transverse area as a function of the wall thickness and build direction parameters.

P values of the ANOVA test				
Wall thickness (mm)	Normality	Homoscedastic	Statistical differentials	Post hoc
2.0	0.915	0.015*	0.0296*	T versus H→ 1 V versus H→ 0.035* V versus T→ 0.030*
2.5	0.079	0.082	0.028*	T versus H→ 1 V versus H→ 0.21 V versus T→ 0.028*
3.0	0.806	0.146	3.6 e−05**	T versus H→ 1.0 V versus H→ 4.0e−04** V versus T→ 6.4e−05**

T-H is the transverse versus horizontal direction; V-H is the vertical versus horizontal direction; V-T is the vertical versus transverse direction. *Significant differences; **Very significant differences.

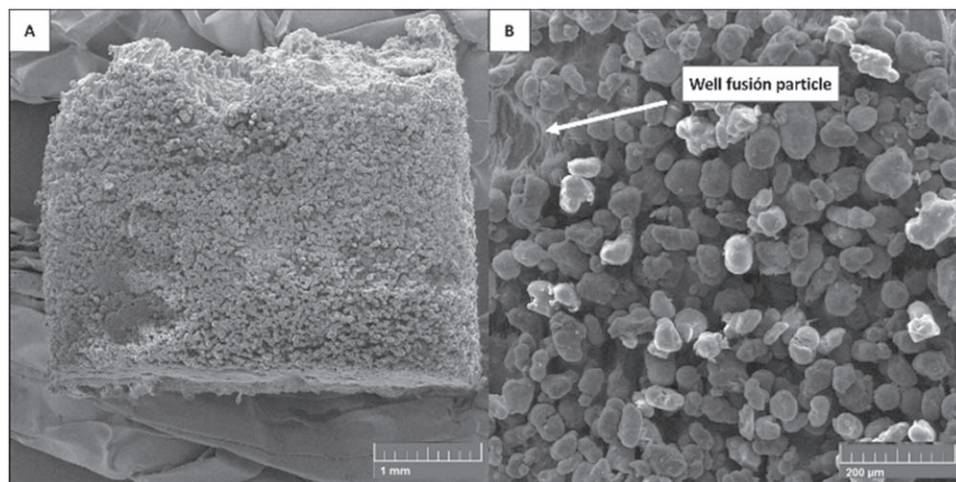


Figure 4. SEM image of the H2 specimen surface. (A) Surface with particle non-well fusion. (B) Well-sintered section particle near the surface.

A possible explanation for this phenomenon could be the thermic behaviour in the sintering of PA 12. In manufacturing, the laser passes through the powder, and the material absorbs that energy and transforms it into heat, joining the particles. When the laser generates the geometry of the layer, a process of energy dissipation begins. The diffusion could be much slower with larger areas and volumes, causing a partial fusion of surrounding particles and increasing the part's mass. The partially melted particles on the surface could be the product of remanent heat in the consequent layers after sintering the last layer. This behaviour could explain the large cross-sectional area in the horizontal and transverse directions with the vertical build construction and changed mechanical and superficial properties.

Pavan *et al* [33] evaluated the accuracy of the cross-sectional area in tensile specimens manufactured in the vertical build direction via SLS. Their investigation suggested that the highest density energy increased the cross-area of the samples. However, the authors found variability in the cross-sectional area of tensile specimens' necks with the same density energy, build direction, and thickness. The present study also found variability in the cross-sectional area of the tensile specimens, but it occurs mainly at low wall thicknesses, probably because the thinner parts cool faster than, the thicker ones. Another factor possibly affecting this property is the type of area measurement. For example, in contact area measurement methods, the force exerted by the measuring instrument can remove poorly fluted particles from the surface, resulting in measurement error variability in the cross-sectional area.

Hardness test

The hardness of PA12 specimens sintered via SLS increased slightly with the wall thickness and was affected by the direction of construction (table 5). The average hardness of the 3.0 mm thickness exhibited the highest value (75.16 Shore D), followed by the 2.5 mm thickness (75.08 Shore D) and the 2.0 mm thickness (74.78 Shore D). The build direction that exhibited the highest average hardness in all thicknesses was the horizontal direction, with a hardness of 75.20 Shore D, followed by the transverse direction, with 74.93, and the vertical direction, with 74.88 Shore D. Although the directions exhibited different values, their magnitudes were very close.

On the other hand, the standard deviation in hardness values was similar in most sintering directions. However, the standard deviation of thickness showed more noticeable changes, with smaller thicknesses showing more significant variation (figure 5).

The nonparametric ANOVA statistical test showed that the variances in mean hardness values were significantly different between the variables, related to the increase in the wall thickness values of the specimens. Significant differences in hardness values were observed at lower wall thickness values (2.0 versus 2.5 and 2.0 versus 3.0 mm). No significant differences in hardness values were found when comparing the 2.5- and 3.0-mm thicknesses (table 6).

The hardness values were significantly different for specimens manufactured in the horizontal direction compared to the other direction values used (vertical and transverse directions) (table 6). Note that the change in hardness magnitude was small. However, these changes were statistically significant in all cases.

The hardness values were similar to those found by Yu *et al* [30]. Table 6 shows that the value of the 2.0 mm thickness in the vertical and horizontal directions differed significantly. This behaviour could be associated with the particle fusion phenomena explained by Ajoku *et al* [14]. The low particle fusion rate in the vertical direction would indicate low cohesion in the material, affecting the hardness. However, in magnitude, the change would be minimal.

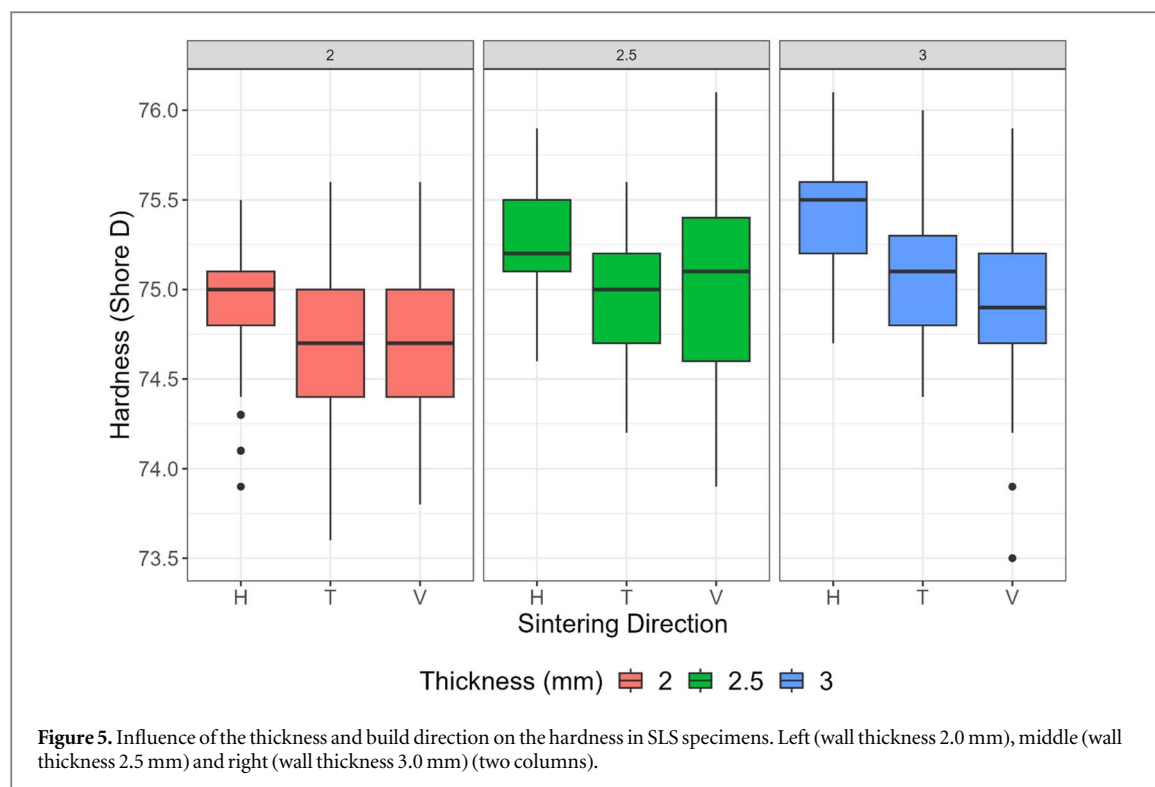


Table 5. Hardness values as a function of the build direction and thickness wall measurements. (One Column).

Hardness average values			
Condition	Thickness wall (mm)	Hardness (Shore D)	S.D
Vertical	2.0	74.74	0.38
	2.5	75.02	0.32
	3.0	74.90	0.29
Horizontal	2.0	74.90	0.38
	2.5	75.26	0.32
	3.0	75.46	0.30
Transversal	2.0	74.70	0.46
	2.5	74.96	0.38
	3.0	75.13	0.40

Table 6. Nonparametric ANOVA statistical test of the hardness as a function of wall thickness and build direction parameters.

P Values of the ANOVA test					
Factor	Normality	Homoscedastic	Statistical differentials	Post hoc test	
Hardness	0.4981	0.277	BD: 2.68×10^{-05} **	Build direction	Thickness (mm)
			Th: 6.2×10^{-05} **	T versus H $\rightarrow 1.4 \times 10^{-04}$ *	2.0 versus 2.5 $\rightarrow 9.0 \times 10^{-03}$ *
			BD Th: 0.055	V versus H $\rightarrow 9.5 \times 10^{-04}$ *	2.0 versus 3.0 $\rightarrow 2.0 \times 10^{-05}$ **
				V versus T $\rightarrow 1.0$	2.5 versus 3.0 $\rightarrow 0.841$

T-H is the transverse versus horizontal direction; V-H is the vertical versus horizontal direction; V-T is the vertical versus transversal direction. *Significant differences; **Very significant differences.

Mechanical properties

Tensile mechanical properties correlated with the build direction and wall thickness variables showed the stress-strain diagram with the average curve for each combination of variables (figure 6). It was observed that the samples sintered in the vertical direction showed a lower Eab and UTS (5.47% and 40.6 MPa) compared to the horizontal (19.3%, 42.5 MPa) and transverse directions (16.63%, 42.76 MPa), indicating an anisotropic

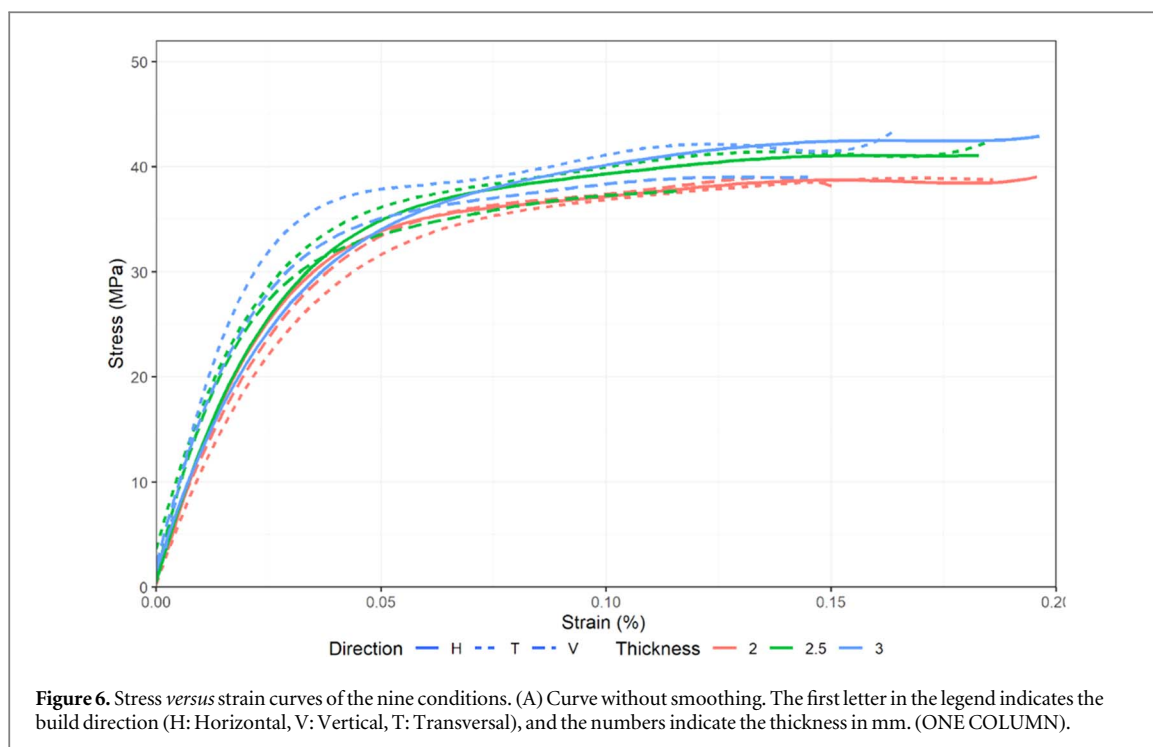


Figure 6. Stress versus strain curves of the nine conditions. (A) Curve without smoothing. The first letter in the legend indicates the build direction (H: Horizontal, V: Vertical, T: Transversal), and the numbers indicate the thickness in mm. (ONE COLUMN).

Table 7. Mechanical property values (UTS, EM and Eab) on a function to build direction and thickness wall measurements. (One Column).

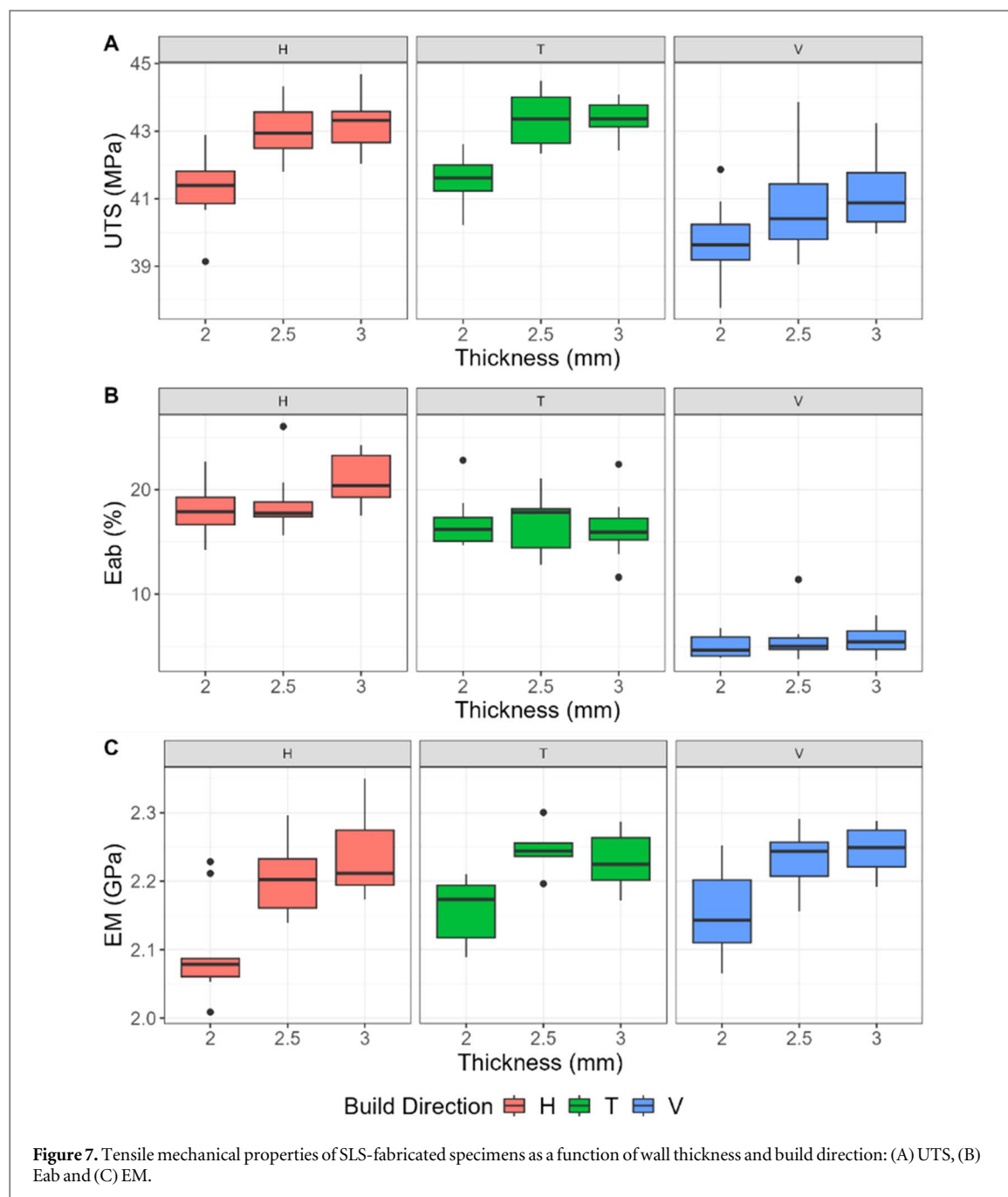
Mean mechanical tensile properties							
Build direction	Wall thickness (mm)	UTS (MPa)	S.D	EM (GPa)	S.D	Eab(%)	S.D
Vertical	2.0	39.8	1.23	2.13	0.025	5.03	1.17
	2.5	40.8	1.69	2.23	0.051	5.78	2.38
	3.0	41.2	1.21	2.24	0.067	5.62	1.42
Horizontal	2.0	41.3	1.10	2.06	0.026	18.2	2.66
	2.5	43.0	0.83	2.20	0.051	18.8	3.23
	3.0	43.3	0.82	2.24	0.067	20.9	2.51
Transversal	2.0	41.5	0.77	2.17	0.048	16.9	2.73
	2.5	43.4	0.79	2.23	0.037	16.7	2.88
	3.0	43.4	0.540	2.23	0.043	16.3	3.19

behaviour of the UTS with the vertical direction compared with the other two directions. For Eab, anisotropic behaviour was observed in all directions.

The increase in UTS is related to the increase in thickness. The rate of change between 2.0 mm thickness and 2.5 mm thickness was 2.45 % in the vertical, 3.95 % in the horizontal and 4.38 % in the transversal direction. On the other hand, the rate of change between 2.5 mm thickness and 3.0 mm thickness was 0.97% in the vertical, 0.69% in the horizontal and 0.52% in the transverse direction. This behaviour indicates that the UTS stabilises at one value as the wall thickness increases in all directions. On the other hand, the average UTS value increased with higher thickness in all directions. The EM did not exhibit significant changes, and the value oscillated at approximately 2.2 GPa at thicknesses higher than 2.0 mm. However, unlike the UTS (table 7), the EM did not show a defined behaviour as a function of thickness.

The variability of the UTS was constant under each condition, except for the 2.5 mm UTS in the transverse direction (figure 7(A)). The EM presented a higher variability without a defined behaviour, which could be associated with the uncertainty related to the equipment (figure 7(C)). Finally, the Eab exhibited minimal variability in each of its directions. The vertical direction showed the highest homogeneity (figure 7(B)).

Table 8 shows the significant differences between the mechanical properties of UTS, Eab, and EM of the SLS-manufactured specimens as a function of build structure and wall thickness. It is observed that all output variables are affected by the printing direction, the wall thickness or otherwise both.



Porosity

Figure 8 shows the cross sections obtained by cryogenic cutting for each condition of the specimens. It was observed that the porosity tends to be circular, with random patterns of location in each of the samples. It was observed that most of the pores were concentrated in the centre because the laser trajectory sweeps several times the outer zone, improving the particle fusion and reducing the porosity.

In addition, the effective stress area ($A_{\text{Effective}}$), void area (A_{Hollow}), transverse area density in percent, and the ratio of wall thickness (t) to pore diameter (d) (figure 9) were obtained and listed in table 9.

The density of the cross-section did not show notable changes in its mean value. Table 9 shows no significant difference in this property, indicating that the printing direction and wall thickness did not affect the cross-sectional area density. On the other hand, it was observed that in each thickness, the vertical direction presents the highest average value of pore diameter. In addition, it was observed that as the thickness increases, the pore diameter also increases. Finally, the wall thickness-pore diameter ratio increases as the thickness increases.

Figure 10 shows the distribution of the pore diameter data and its relationship with wall thickness. It can be seen that the vertical direction shows a shift towards larger diameter values at all thicknesses. On the other hand, in the wall thickness-pore diameter ratio, an increase is observed in all directions of construction as the wall thickness increases. The directions of the most significant increase are horizontal and transverse.

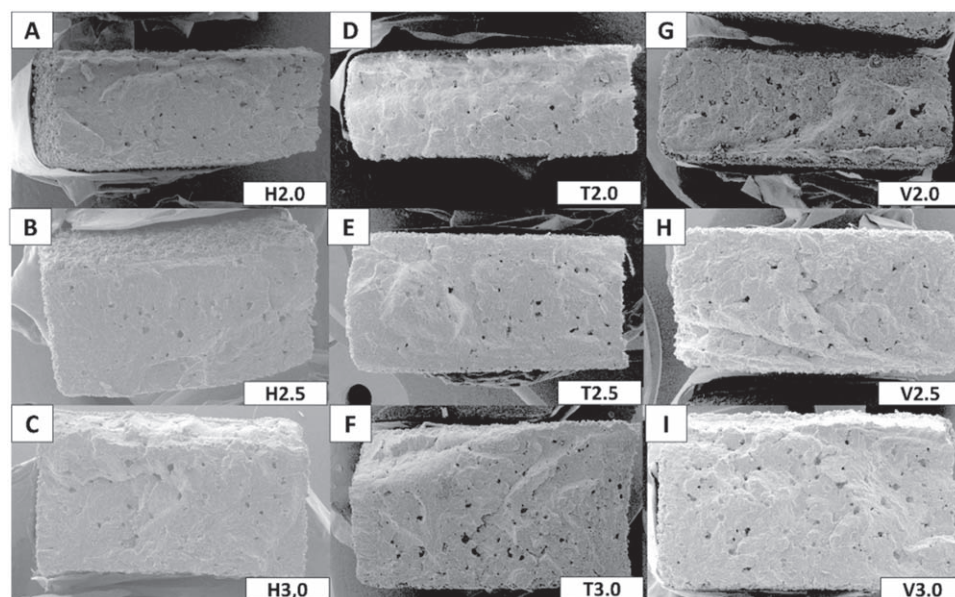


Figure 8. Transverse section of tensile specimens with cryogenic fracture. (A), Horizontal –2.0 mm (B) Horizontal –2.5 mm, (C) Horizontal –3.0 mm, (D) Transverse –2.0 mm, (E) Transverse –2.5 mm, (F) Transverse –3.0 mm, (G) Vertical –2.0 mm, (H) Vertical –2.5 mm, (I) Vertical –3.0 mm.

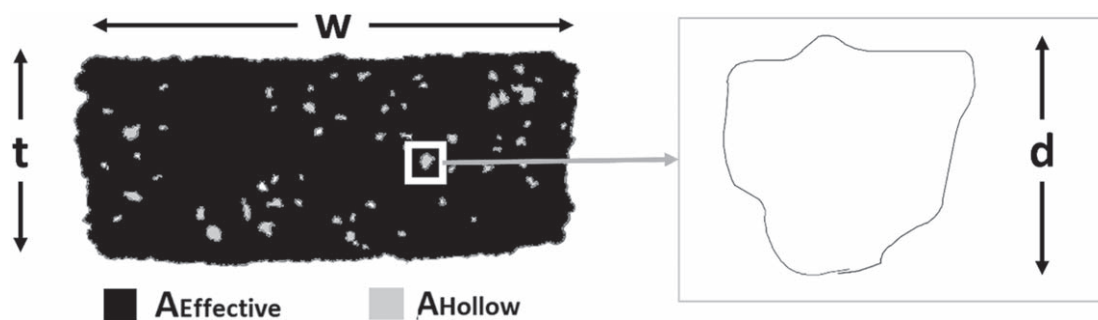


Figure 9. Effective stress area in the printed specimens ($A_{\text{Effective}}$), the void area corresponding to pores or manufacturing defects (A_{Hollow}), specimen thickness (t), specimen width (w), and maximum pore diameter in the thickness direction (d).

Table 8. Parametric and nonparametric two-way ANOVA statistical test of the UTS, Eab, and EM as a function of wall thickness and build direction parameters. (Two columns).

Factor	P values of the ANOVA test				
	Normality	Homoscedastic	Statistical differentials	Post hoc	
UTS	0.454	0.375	BD: $5.3 \times 10^{-07}^{**}$	Build Direction T versus H $\rightarrow 1.0$ V versus H $\rightarrow 7.5 \times 10^{-06}^{**}$ V versus T $\rightarrow 5.9 \times 10^{-07}^{**}$	Thickness 2.0 versus 2.5 $\rightarrow 8.9 \times 10^{-05}^{**}$ 2.0 versus 3.0 $\rightarrow 1.6 \times 10^{-05}^{**}$ 2.5 versus 3.0 $\rightarrow 1.0$
			Th: $1.6 \times 10^{-07}^{**}$		
			BD Th: 0.835		
Eab	0.342	0.835	BD: 3.3×10^{-16}	T versus H $\rightarrow 1.7 \times 10^{-04}^{**}$ V versus H $\rightarrow 2.0 \times 10^{-16}^{**}$ V versus T $\rightarrow 2.0 \times 10^{-16}^{**}$	2.0 versus 2.5 $\rightarrow 1.0$ 2.0 versus 3.0 $\rightarrow 1.0$ 2.5 versus 3.0 $\rightarrow 1.0$
			Th: 0.36		
			BD Th: 0.39		
EM	0.131	0.8045	BD: 0.09	T versus H $\rightarrow 0.34$ V versus H $\rightarrow 0.24$ V versus T $\rightarrow 1.00$	2.0 versus 2.5 $\rightarrow 1.2 \times 10^{-04}^{**}$ 2.0 versus 3.0 $\rightarrow 1.6 \times 10^{-08}^{**}$ 2.5 versus 3.0 $\rightarrow 1.0$
			Th: $3.7 \times 10^{-08}^{**}$		
			BD Th: 0.45		

T-H is the transverse versus horizontal direction; V-H is the vertical versus horizontal direction; V-T is the vertical versus transverse direction. *Significant differences; **Very significant differences.

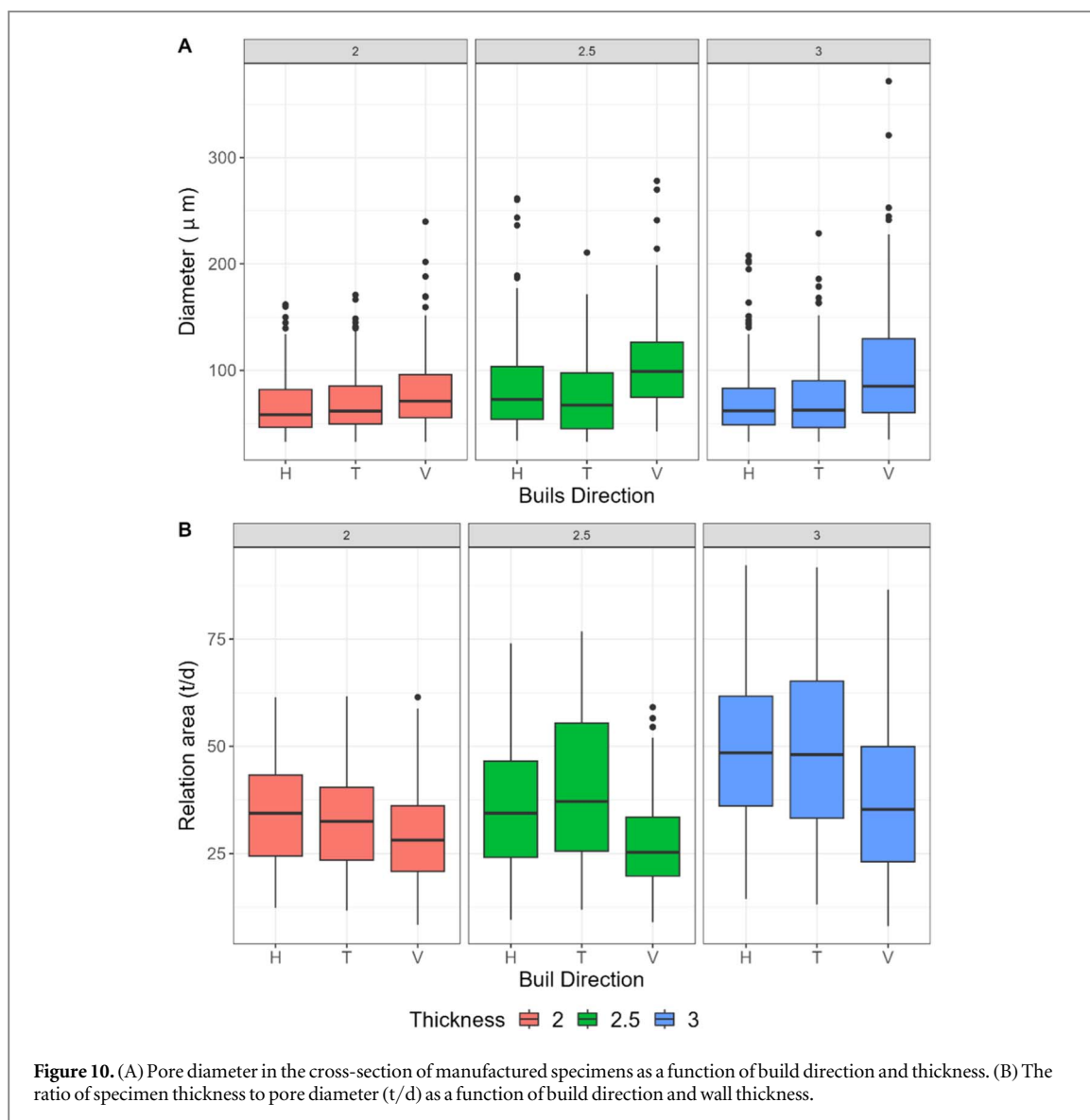


Figure 10. (A) Pore diameter in the cross-section of manufactured specimens as a function of build direction and thickness. (B) The ratio of specimen thickness to pore diameter (t/d) as a function of build direction and wall thickness.

Table 9. Average pore diameter values, cross-sectional area density and wall thickness-pore diameter relationship as a function of wall thickness and build direction. (Two columns).

Build direction	Thickness (mm)	The mean of density properties					
		Transverse area density (%)	S.D	Relation t/d	Sd	Pore diameter (μm)	Sd
Vertical	2.0	96.1	0.8	28.0	11.0	81.3	35.4
	2.5	96.1	0.7	28.8	11.0	104.0	42.1
	3.0	96.1	0.5	38.8	18.0	100.0	54.5
Horizontal	2.0	96.9	0.5	34.0	11.2	66.9	26.5
	2.5	96.4	0.3	35.8	15.0	85.7	44.0
	3.0	96.0	0.8	49.3	17.6	71.3	32.4
Transverse	2.0	97.4	0.6	32.8	11.5	70.5	29.8
	2.5	96.9	0.6	40.7	17.3	75.4	36.1
	3.0	96.6	0.2	50.7	20.5	71.7	35.0

Statistical tests in table 10 showed that pore diameter and its relationship to wall thickness significantly differed depending on the input variables. The pore diameters presented significant differences, indicating that each thickness illustrates a different pore distribution. On the other hand, the build direction showed variations when comparing the vertical direction versus the transverse and horizontal directions.

Table 10. Parametric and nonparametric two-way ANOVA statistical test of the transverse density, pore diameter, and relation between wall thickness and pore diameter as a function of wall thickness and build direction parameters. (Two columns).

P values of the ANOVA test					
Factor	Normality	Homoscedastic	Statistical differentials	Post hoc	
Transverse Density	0.278	0.951	BD: 0.132 Th: 0.073 BD Th: 0.970	Build Direction _____ _____ _____	Thickness _____ _____ _____
t/d	$3.2 \times 10^{-12} **$	$2.2 \times 10^{-16} **$	$2.20 \times 10^{-16} **$	T versus H $\rightarrow 1.00$ V versus H $\rightarrow 2.2 \times 10^{-16} **$ V versus T $\rightarrow 2.2 \times 10^{-16} **$	2.0 versus 2.5 $\rightarrow 3.6 \times 10^{-03} *$ 2.0 versus 3.0 $\rightarrow 2.2 \times 10^{-16} **$ 2.5 versus 3.0 $\rightarrow 2.2 \times 10^{-16} **$
Pore diameter	$2.2 \times 10^{-16} **$	$2.2 \times 10^{-16} **$	$2.239 \times 10^{-09} **$	T versus H $\rightarrow 1.00$ V versus H $\rightarrow 2.2 \times 10^{-16} **$ V versus T $\rightarrow 2.2 \times 10^{-16} **$	2.0 versus 2.5 $\rightarrow 1.7 \times 10^{-10} **$ 2.0 versus 3.0 $\rightarrow 8.4 \times 10^{-05} **$ 2.5 versus 3.0 $\rightarrow 1.2 \times 10^{-04} **$

T-H is the transverse versus horizontal direction; V-H is the vertical versus horizontal direction; V-T is the vertical versus transverse direction. *Significant differences; **Very significant differences.

Table 11. Ultimate tensile strength values of some relevant research. (One Column).

Experiment	Mean UTS values (MPa)					
	This study	Lammes <i>et al</i> [31]	Razaviye <i>et al</i> [32]	Tomanik <i>et al</i> [33]	Rosso <i>et al</i> [34]	Olejarczyk <i>et al</i> [35]
H2.0	41.3	48.3	43.80	N/A	46.93	50.6
H2.5	43.0					
H3.0	43.3					
T2.0	41.5	49.4	N/A	42.5	N/A	52.9
T2.5	43.4					
T3.0	43.4					
V2.0	39.8	45.9	N/A	17.1	N/A	52.2
V2.5	40.8					
V3.0	41.2					

Ultimate tensile strength

The mean ultimate tensile strength (UTS) was 41.9 MPa with a standard deviation of 1.34 MPa and was affected by the specimen's thickness and position. The average UTS value increased in all directions as a function of wall thickness. The directions with the highest UTS values were the horizontal and transverse directions, with values of 43.0 MPa. On the other hand, the UTS values in the vertical direction were lower, at 41.0 MPa.

Tables 11, 12, and 13 compare the results of this investigation with other similar ones, such as Lammens *et al* [31], Razaviye *et al* [32], Tomanik *et al* [33], Rosso *et al* [34], and Olejarczyk *et al* [35]. It was observed that specimens with wall thicknesses greater than 3.0 mm in the present investigation showed near UTS values, suggesting that the UTS values may be similar in samples of a broad range of wall thickness values. However, the sintering conditions used by these authors were different, which affects the mechanical properties, as suggested by Yan *et al* [36].

The UTS values were related to the percentage of crystallinity, porosity, and defectology [20]. The first two conditions were strongly linked to the sintering conditions. However, no significant differences in crystallinity were found under the same parameters used in the present investigation, which found differences [37, 38].

The horizontal and transverse sintering directions showed a higher significant tensile strength than the vertical direction when comparing table 7. The difference in strength is mainly due to the cross-sectional area behaviour of the tested specimens. It was observed that the directions that exhibited significant changes in the cross-sectional area of the samples under tension were the same and showed a higher mechanical strength. By associating the thermal sintering process, specimens with a larger sintering surface area exhibited the highest UTS.

On the other hand, although the specimens have the same transverse area density, the ultimate tensile strength in the vertical direction is always lower. In some investigations, such as that of Dewulf *et al* [39], it is mentioned that its mechanical resistance is lower compared to the other directions due to the direction of the interlayer bonding. In addition to this behaviour, it can be associated that this direction of printing presented the highest mean value of pore diameter, which would lead to a higher stress concentration and explain the drop in mechanical strength in this condition. In addition, when studying the pore diameter-wall thickness ratio, it is

Table 12. Elastic modulus values of some relevant research (One column).

Experiment	Mean EM values (GPa)					
	This study	Lammes <i>et al</i> [31]	Razaviye <i>et al</i> [32]	Tomanik <i>et al</i> [33]	Rosso <i>et al</i> [34]	Olejarczyk <i>et al</i> [35]
H2.0	2.06	2.16	1.26	N/A	1.87	1.92
H2.5	2.20					
H3.0	2.24					
T2.0	2.17	2.15	N/A	0.86	N/A	1.99
T2.5	2.23					
T3.0	2.23					
V2.0	2.13	2.21	N/A	0.43	N/A	1.96
V2.5	2.23					
V3.0	2.24					

Table 13. Elongation at break values of some relevant research (One column).

Experiment	Mean Eb values (%)					
	This study	Lammens <i>et al</i> [31]	Razaviye <i>et al</i> [32]	Tomanik <i>et al</i> [33]	Rosso <i>et al</i> [34]	Olejarczyk <i>et al</i> [35]
H2.0	18.2	15.07	5.17	N/A	10.3	24.6
H2.5	18.8					
H3.0	20.9					
T2.0	16.9	15.46	N/A	13.1	N/A	24.6
T2.5	16.7					
T3.0	16.3					
V2.0	5.03	8.741	N/A	6.0	N/A	15.2
V2.5	5.78					
V3.0	5.62					

observed that its magnitude tends to fall at lower thickness values, so the amount of mass that would resist the stress is lower. This behaviour would explain why the vertical impression conditions and the 2.0 mm thickness presented statistically significant differences compared to the other states.

Elastic modulus

The mean elastic modulus was 2.19 GPa, with a standard deviation of 0.06 MPa, and was affected by specimen thickness. The average EM was constant: it did not vary in thicknesses greater than 2.0 mm. Besides, the build directions did not show a significant change in the magnitude of the EM.

Different authors cited in table 12 reported EM values of a lower magnitude than those of all specimens evaluated in the present study. This difference may be due to the measuring instrument used. The other authors used an extensometer, except Lammes *et al* [33], which was measured with ultrasound equipment [20, 26, 37, 40].

The results in table 8 show that the build direction had no significant influence on the EM property [17]. That change was minor, suggesting that this property showed isotropic behaviour in the elastic region [19, 31] and that the EM values determined by ultrasound exhibited no significant differences according to the build direction.

On the other hand, the elastic modulus showed significant differences as a function of thickness. As the thickness increased, there was a higher ratio between wall thickness and pore diameter (t/d). This behaviour indicates that at lower thicknesses (2.0 mm), the amount of material concerning the hollow zones is less, and therefore, there is a drop in the ultrasonic wave and hence a drop in the magnitude of the elastic modulus value.

Elongation at break

The mean elongation at break was 13.8% with a standard deviation of 6.33% and was affected by the build direction. The high standard deviation value indicates anisotropic behaviour in each build direction compared to the other two properties. Table 13 shows that, in general, the vertical direction presents the lowest elongation values at the break. However, there is considerable variation between each of the studies. The closest to the present work is the one by Lammes *et al* [31].

It was observed that the elongation at break is not affected by wall thickness. This behaviour could be related to the fact that the transverse area density is equal in all thicknesses in each build direction. On the other hand, it

was observed that printing direction significantly impacts the elongation at break. This behaviour can be related to the thermal phenomenon associated with sintering since each direction presents a different value of the transverse area and, therefore, different cooling times. The directions with a greater sintering area showed a more ductile behaviour, indicating that slower cooling times lead to a greater connection between the sintered particles. Due to its construction method, the vertical direction has the smallest surface area and is expected to have a much faster cooling and, therefore, a behaviour with slight elongation.

Some investigations [20, 28, 41–43] suggest that elongation at break is strongly related to the printing direction. Some researchers, such as Stichel *et al* [44, 45], indicate that the vertical direction has the lowest porosity value. In the present study, under the conditions mentioned in the materials and methods section, it was identified that the cross-sectional area density is the same in all printing directions and wall thicknesses. This behaviour suggests that the elongation at break varies with powder mixture conditions and machine laser parameters.

Conclusions

This study allowed us to understand the mechanical behaviour of Nylon PA 12 manufactured through SLS, considering the wall thickness and build direction. It was observed that the mechanical properties vary significantly as a function of input variables. This conduct allows us to understand better the mechanical behaviour of 2.0, 2.5 and 3.0 mm thicknesses manufactured in the vertical, horizontal and transverse directions and to implement it in part design guides. Although parts generally work under different types of loading, not only axial loading, the design criteria are based on the material's UTS, Em and Eab properties under a given manufacturing process. Therefore, this work shows each input variable's behaviour, variation, and effect in these design criteria.

The founded variations can come from raw material conditions. Differences in particle size can vary the process of particle neck generation and, in turn, the defectology of the sample. It was identified that, in this case, the sample did not have a bimodal behaviour. However, several populations of the powder (B, D) presented two dominant particle sizes, which could affect some properties of the piece. On the other hand, it was found that the UTS is significantly affected because the cross-sectional area and pore size vary as a function of the printing direction and wall thickness. The modulus of elasticity was affected only by the thickness since the wall thickness to pore diameter ratio increases at lower thicknesses. Finally, Eab showed changes as a function of the printing direction, probably due to the thermal behaviour at the time of sintering.

Future research should further investigate the comparison between the 2.0- and 2.5-mm thicknesses to find the best mechanical strength-to-weight ratio. In addition, we propose that thermal annealing treatments be carried out to check if this process, together with the other variables, exhibits higher mechanical values.

Data availability statement

The data is associated with a doctoral thesis, it will be made available to the public when it is published. The data that support the findings of this study are available upon reasonable request from the authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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