Different infill geometry influence on mechanical properties of FDM produced PLA

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Abstract. Fused Deposition Modelling (FDM) is one of the most widespread additive manufacturing technologies due to its relatively low cost and simplicity. Usually, printed parts have an internal structure (infill) that is not produced with 100% material density. This strategy is adopted to save material and time thanks also to the fact that when a component is loaded, stress are concentrated on its skin rather than in the internal section. Furthermore, infill structure can have different densities and topology. Slicer software have various configurations that can be exploited to produce internal structures: according to All3DP [1], some are intended for functional parts while others are more indicated to prototypes only. Aim of this work, is to compare the effect of different infill topologies produced using Ultimaker CURA [2] slicing software on material mechanical properties. Preliminary experimental activity has been carried out in order to determine the most suitable printing temperature. MaCh3D, an innovative miniaturized universal testing machine [3] was used to perform uniaxial tensile tests. Results underline the difference between different kind of infill in term of mechanical properties, given the same infill density across all specimens. Additionally, in order to evaluate infill percentage effect on mechanical properties, some of the most performing infill from the characterisation activity have been selected and specimens produced with 20%, 50%, 80% infill percentage. In the end, both infill topology as well as density impacts on mechanical properties.

1. Introduction
Amongst polymer-based AM processes, FDM is the most widespread. Known with the commercial name of FDM, the process was patented by Stratasys in 1989 [4] and is based on the mechanisms of extrusion, the material “being selectively dispensed through a nozzle or orifice” [5]. Amid other extrusion techniques, FDM provide material melting which uses a spool of thermoplastic filament of various diameters, such as PC, ABS and PLA, extruded through a heated nozzle. In more recent time, different companies developed processes to produce objects using high performance polymers with elevated melting temperatures, such as PEEK [6].

Analysis of mechanical properties of FDM parts represents an important subject of interest, with some of the first studies on this topic dating back to 1996 [7]. Most influencing FDM process parameters can be categorized as in the work of Popescu et al. [8]:

- Slicing parameters: layer thickness, nozzle diameter, road width, flow rate, deposition speed, infill geometry, raster orientation, raster pattern, air gaps (raster to raster, perimeter to raster), number of contour/perimeters, top thickness, bottom thickness;
Building orientation: usually testing specimens are oriented horizontally, vertically or laterally, but other orientations can be also used;

Temperature conditions: environment (or envelope) temperature, extrusion temperature, bed or platform temperature.

All these affect the mechanical behaviour of the printed parts, at different levels: not all FDM parameters have the same effect on the final material, the most important being raster to raster air gap, building orientation, raster angle, layer thickness and infill percentage.

The interaction between these parameters play a fundamental role in determining mechanical behaviour as well [9,10]. At the same time, an attempt was made to classify the influence of the different parameters in order of importance, as in the work of Durgun et al. [11]. Onwubolu et al. [12] determined that to maximize tensile strength of ABS specimens, layer thickness and raster width should be minimal: the finding is corroborated in various other works. Li et al. [13] showed that in the case of PLA specimens, as well, mechanical performances are improved when layer thickness possess the least values. Ziemian et al. [14] determined, that in the case of ABS specimen, highest tensile strength is reached having raster aligned to specimen axis. The same author studied flexural strength, showing through experimental testing that the ultimate strength value is the best for 0° raster orientation in respect to specimen axis. Chacón et al. [15] characterized the effect of build orientation, layer thickness and feed rate on PLA samples through tensile as well as three points bending tests: upright orientation shows the lowest mechanical properties. On the other hand, on-edge and flat orientation show the highest strength and stiffness. From a layer thickness and feed rate point of view, they observe that ductility decreases as layer thickness and feed rate increase. In addition, the mechanical properties increase as layer thickness increases and decrease as the feed rate increases for the upright orientation.

Another important aspect that must be addressed is the difference between the mechanical properties of bulk polymers (as sometimes indicated by producers in the material specification sheet), the mechanical properties of testing specimens and the mechanical performance of manufactured end-parts. Bellini and Güçeri [16], in determining mechanical behaviour of ABS specimens, compared bulk filament tensile testing properties and printed material ones, showing great difference between the two.

A typical characteristic of FDM produced objects is to have solid exterior walls, made by one or multiple adjacent rasters, whilst the internal region presents material density below 100%, having geometrical structures defined as "infill" to sustain loads and external walls. Usually, slicer software allow to select infill percentage and geometry, as indicated in Figure 1 in function of printed object purpose, printing time and material.

![Figure 1. Different common infill geometries at various densities [17].](image_url)

Infill percentage and geometry influence over mechanical properties has been discussed in several studies [18–22]. Aim of this work is to evaluate material mechanical properties given the infill geometries provided by a widespread slicing software such as Ultimaker CURA and its variations by changing the density.
2. Experimental campaign

The experimental campaign was divided into three main phases: the aim of the first one was to determine the printing temperature which allowed to obtain highest mechanical properties, using specimens with 100% nominal infill percentage. Starting from filament manufacturer indications, specimens were produced at different temperatures in the range 210°C – 240°C (temperature interval has a maximum 10°C higher than the manufacturer recommendations), with 5°C increase for each configuration, resulting in seven different sets. In this case, the default CURA infill (grid) was used, consisting in subsequent layers having ±45° rasters orientation.

Once best temperature was determined, the second phase saw the production of specimens having all thirteen infill topologies, adopting a nominal infill percentage equal to 20%. In the end, the three most performing infill topologies and the one used to produce the 100% specimens, were selected to print specimens with different infill percentage (20%, 50%, 80%) in order to evaluate mechanical properties response at infill percentage variation: as emerges from the work of Fernandez et al. [18], infill density heavily affects mechanical properties. In the end, given three repetitions for each configuration of the different phases, a total of 84 specimens have been produced.

2.1. Materials and methods

All specimens were produced using an AnyCubic I3 Mega (AnyCubic, Shenzhen, China) FDM printer, with grey polylactic acid (PLA) filament from SUNLU (Zhuhai SUNLU Industrial co., Zhuhai, China) having a diameter of 1.75 mm. The used slicer software was Ultimaker CURA v4.6.1 whilst the specimen STL file was generated using Autodesk Inventor 2020.

Common printing parameters used in CURA for all specimens are reported in Table 1. The three specimens needed for each configuration were printed in a unique batch, maintaining orientation as well as printing position on the build plate as illustrated in Figure 2. All specimens were fabricated in the horizontal plane, where the orientation of the fibres and their bonding is better than in other [23]. One factor that determined this situation was the infill pattern, as until now, it cannot be oriented in planes different than X-Y. Only one orientation of specimens was used, along the y-axis, to obtain results dependent upon the fibre-to-fibre fusion, and consequently the internal mesostructure [23].

| Parameter                  | Value       |
|----------------------------|-------------|
| Material                   | Grey PLA    |
| Layer height               | 0.2 mm      |
| Specimens on build plate   | 3           |
| N.º of walls               | 2           |
| Infill overlap             | 15%         |
| Printing speed             | 40 mm/s     |
| Infill printing speed      | 40 mm/s     |
| Wall printing speed        | 40 mm/s     |
| Build plate adhesion type  | Skirt       |
| Orientation                | On X-Y plane, along Y |

2.2. Specimens geometries and infill types

Specimen geometry is the same for all tests, being MaCh3D proprietary tensile testing specimen [3].

Two different thicknesses have been used for specimen production: for 100% infill specimens, adopted in the first phase of the experimental campaign, a nominal thickness of 3 mm was chosen. For all subsequent tests, where the infill was less than 100%, an increased thickness of 9 mm was used: comparison between specimen sections is reported in Figure 3. This was done to obtain specimens with wider cross-section, allowing to have full developed infill topologies.
Different infill topologies are reported in Figure 4 divided according to All3DP’s [1] scheme: each infill kind has been associated with a letter.

![Infill topologies](image)

Figure 3. MaCh3D specimen and different thickness.

**Figure 4.** Different infill topologies categorized according to object final function.

### 2.3. Experimental setup

The machine used to perform all the test is MaCh5 (MaCh3D srl, Parma, Italy), a miniaturized universal testing machine [3]. In order accurately to acquire gauge length deformation during tests, an MTS 632.12F-24 (MTS Systems Corporation, Eden Prairie, USA) was connected to the machine, as depicted in Figure 5.

Test speed was set to be 5 mm/min, according to ASTM D638 [24] and sample rate was 5 Hz.
3. Results and discussion

3.1. Determination of printing temperature

Temperature is one amongst the most influential parameters in FDM [15,25–28], affecting both mechanical resistance and other factors such as dimensional accuracy. From Figure 6, it can be seen how elongation at break \((A_t)\) decreases with higher temperatures, whilst ultimate tensile strength \((R_m)\) and specimen rigidity \((E)\) increase.

Figure 6. Stress-strain curves for different printing temperatures.

In Table 2 detailed results breakdown is reported, presenting average values with standard deviation (in round brackets). It is clear how best mechanical properties are obtained in correspondence 235°C printing temperature with \(E = 2362\) MPa and \(R_m = 35.08\) MPa. To be compliant to filament manufacturer indications, however, it has been chosen to print all subsequent specimens with a temperature of 230°C, the maximum recommended: hence reference mechanical properties are \(E = 2198\) MPa and \(R_m = 31.11\) MPa, respectively.
Table 2. Average mechanical properties for different printing temperatures.

| Configuration | $E$ [MPa] | $R_m$ [MPa] | $A_t$ [mm/mm] |
|---------------|-----------|-------------|--------------|
| AA00 - 210    | 1507 (2.9)| 22.97 (0.3) | 0.0760 (0.008) |
| AA00 - 215    | 1909 (10.3)| 27.57 (0.5) | 0.0616 (0.009) |
| AA00 - 220    | 1935 (20.8)| 28.30 (0.5) | 0.0521 (0.012) |
| AA00 - 225    | 1976 (36.5)| 29.08 (1.1) | 0.0540 (0.008) |
| AA00 - 230    | 2198 (61.2)| 31.11 (0.8) | 0.0461 (0.015) |
| AA00 - 235    | 2362 (43.9)| 35.08 (1.3) | 0.0426 (0.011) |
| AA00 - 240    | 2310 (66.2)| 33.17 (0.9) | 0.0404 (0.004) |

Specimens have been weighted after rupture, carefully collecting any ejected debris. From Figure 7 (a) results that higher temperature implies heavier weight. These results are in agreement with those obtained by previous studies [18,25]: in particular, higher temperatures make the molten material more fluid, allowing better slipping inside printer nozzle. Despite the fact that the rotation speed of the extruder motor does not depend on the temperature of the heating element, extrusion resistance decreases with increasing temperature, so that the plastic passes faster through the feeder due to decrease in parasitic slides and filament strains. The only exception is the 240°C specimens series, which present a lighter weight in respect to the others: this may be caused by some under extrusion due to Bowden tube consumption [29].

Specimen resistance increases with weight, as reported in Figure 7 for all the considered specimens. The increase in the strength of the samples with increasing temperature is double-natured: in addition to changing the mass off the sample and, subsequently, the geometry of the interlayer boundaries, the strength increases due to an increase in cohesion between layers [25], depending on the temperature conditions for the formation of the boundary between the new and the previous layer.

Figure 7. Average weights for different specimens configurations (a) and $R_m$ vs specimens weight (b).
3.2. Determination of infill geometry influence

Adopting the temperature of 230°C, all specimens were printed with an infill density of 20%.

Comparing $E$ and $R_m$, it is possible to see from Figure 8 how infill type "H" (octet) outperforms other infill topologies, both in terms of mechanical strength as well as stiffness, having $E = 943$ MPa and $R_m = 13.33$ MPa.

![Figure 8](image)

**Figure 8.** Mechanical properties for different infill geometries. Stiffness, $E$ (a) and Ultimate Strength (b).

It was not possible to test infill type "M" (concentric) due to its excessive compliance: MaCh3D load transmission mechanism is based on the interference between specimens heads and grips seats [3]. In this case, the latter weren't stiff enough to sustain the applied load, as can be seen in Figure 9.

![Figure 9](image)

**Figure 9.** Experimental setup showing "M" infill type specimen being squeezed through MaCh3D fixtures.

As in different works from literature [8,15,25], it has been noted that high rigidity usually corresponds to high ultimate tensile strength, as emerges from Figure 10 (a) where superimposed values of $E$ and $R_m$ show the same trend varying specimen infill type.

It has also been verified that All3DP's classification of infills is compliant with measured mechanical properties, since the four most performing infills are indicated as suitable to produce functional parts. The only exception is the infill type "G" (cubic subdivision) which presents very poor mechanical properties compared with other geometries, as it is reported in Figure 10 (b).
From the slicer software, it is possible to estimate the material necessary \((Cm)\) to produce the specimen geometry: normalizing \(Rm\) and \(E\) in respect to material consumption, infill "H" (octet) results to be the most efficient, having the best mechanical properties with a fairly low material usage, as in Figure 11 (a) and (b) (higher values represent an higher infill efficiency).

3.3. Determination infill density effect

The three infill having the highest ultimate tensile strength, namely "H" (octect), "L" (gyroid), "F" (cubic), together with the one used to print 100% specimens, "C" (grid) were adopted to produce specimens at different infill densities (20%, 50%, 80%). In order to estimate specimen behaviour at 0% infill, as if its cross section would be constituted by external solid walls only, an analytical approach was adopted. Starting from 230°C, 100% infill mechanical properties, the corresponding values for the hollow section were determined by dividing the initial values by full \((A_f)\) and hollow \((A_h)\) section ratio \(\gamma\), as in Eq. 1, 2.
\[ E_h = E_{230\degree C,100\%} \frac{A_h}{A_f} = \frac{E_{230\degree C,100\%}}{\gamma} \]  

(1)

\[ R_{mh} = R_{m230\degree C,100\%} \frac{A_h}{A_f} = \frac{R_{m230\degree C,100\%}}{\gamma} \]  

(2)

Where \( E_h \) and \( R_{mh} \) are the hollow section stiffness and ultimate strength. Obtained value were 613 MPa for \( E_h \) and 8.68 MPa for \( R_{mh} \), respectively.

Normalized results respect 100% values, obtained during best printing temperature determination and corresponding to the 230\degree C - 100% infill density, are reported in Figure 12 (a), (b), (c), and (d).

**Figure 12.** Normalized results (E, Rm) for different infill types varying infill density. Grid (a), Octet (b), Cubic (c), Gyroid (d).

It must be noted that 100% material has been printed with only one infill kind, as specified in par. 2: it is not possible to produce fully dense parts with different infill geometry.

As already observed, both \( R_m \) and \( E \) present the same behaviour varying infill percentage: moreover, mechanical strength and stiffness increase according an almost linear rule (except in the case of infill type C), even if the best fit of data is obtained using a polynomial law.
Infill type C seems to be quite different from others, presenting almost the same values across 0%, 20% and 50% infill densities: in particular, for lower percentages, it seems that walls influence becomes more prominent.

Comparing all curves, as in Figure 13, it is possible to see how infill types H, F, L present almost the same behaviour varying infill percentage, whilst infill type C differs significantly. This may be due to infill topology, the former three being characterized by complex solid geometries, such as gyroids or hexahedrons, in contrast to the simple mesh constituting the latter one.

![Figure 13. Normalized curves comparison for different infill geometries in terms of E (a) and Rm (b).](image)

### 4. Conclusions

This work aimed to assess infill influence over FDM produced parts using PLA. Some of the results obtained can be summarized as follows:

- The optimum printing temperature has been found to be higher than filament manufacturer recommended maximum, being 235°C instead of 230°C.
- Infill topology does influence mechanical properties: in particular, $R_m$ and $E$ present the same trend varying infill topology.
- Infill classification in function of printed parts purpose turned out to be quite accurate, except for infill type "G" (cubic subdivision) which performed poorly compared to other geometries.
- It wasn't possible to test infill type "M" (concentric) due to its excessive compliance.
- Material nominal consumption is not proportional to mechanical properties.
- Varying infill percentage affects material mechanical properties, in particular values vary in an almost linear way.
- Also, in this case, $R_m$ and $E$ present the same behaviour varying infill density.

Some possible future developments include the repetition of the experimental campaign using different material and/or printers, thus determining the influence of those factor on the observed behaviours.

Another interesting experiment would be to perform three-point bending tests on the different infill geometries, to assess their behaviour under a different type of load.

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