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Study of samples geometry to analyze mechanical properties in Fused Deposition Modeling process (FDM)

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Abstract

Parts manufactured by Fused Deposition Modeling (FDM) present anisotropic properties, which have influence in tensile test results. In this paper, test samples of Polylactide (PLA) are manufactured by FDM according to geometries defined in UNE-EN ISO 527-2:2012 and ASTM D638-14:2014. Manufacturing parameters as wall thickness, orientation of building wall lines, and orientation of infill pattern have been studied. A nomenclature to define manufacturing direction of sample is also developed. Stress concentration can modify obtained results in tensile test, and it could be due to geometrical discontinuities, pressure points and thermal shock. Standard and no standard geometries have been evaluated to test FDM process. In order to avoid premature sample failure by stress concentration, different strategies have been developed: manufacturing samples with a rectangular geometry, an annealing treatment and to manufacture the samples as union of different parts. Last strategy has allowed to reduce stress concentration zones and to improve tensile strength values.

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1. Introduction

Additive manufacturing include different technologies to build 3D objects by adding layers of material. Fused Deposition Modeling (FDM), based on extrusion of materials with 3D printers, is one of the most popular additive manufacturing technology to obtain prototypes and plastic functional parts [1,2]. Some of the advantages of this technology, mainly used for rapid prototyping, are the possibility to get 3D complex parts, the accuracy reached, the short time to obtain the part and the low cost process. However, one of the disadvantages of FDM is the anisotropic properties of manufactured parts, which has influence in their mechanical properties [3,4].

Mechanical properties of parts manufactured with FDM process depend of several variables, as parameters related to the process conditions (temperature, feed rate, preheating, etc.), part orientation during manufacture, infill percentage, space between filaments, etc. [5-7]. Tensile strength is a common test to evaluate mechanical properties of parts manufactured by FDM and different studies have tried to relate these parameters with mechanical properties of parts [7-9]. On the one hand some of them evaluates the mechanical behaviour of two materials, ABS (acrylonitrile butadiene styrene) and PLA (polylactide) in order to study layer height, infill density and layer orientation, being the infill percentage the parameter more influent in mechanical behaviour [3,7]. On the other hand, tensile strength has been studied taking into account different parameters, as printing angles and layer thickness for each angle, concluding that tensile strength decreases if the printing angle is smaller or if the layer is thicker [10].

Different standards can be used to characterize tensile strength parameters. The most common standards are UNE-EN ISO 527-2:2012 [11] and ASTM D638-14:2014 [12]. In both standards, geometrical dimensions of test specimens are specified, but as the dimensions are not the same, results varying from one to other [13]. Otherwise, when standard geometries are used in FDM manufactured specimens, stress concentration points could be generated, allowing specimens break in these positions, and producing variation in tensile strength values obtained. Some studies have evaluated these stress concentration in samples, concluding that both standards are not totally adequate to study tensile stress [6,7]. Stress concentration is more evident in samples manufactured according to ISO 527 than in ASTM D638 samples [13], due to a smaller radius. In order to avoid stress concentration, studies propose to use geometries with a very large radius [14], but this implies to manufacture samples with small section area, without space to test infill patterns. Due to these difficulties, some studies propose to use a rectangular sample with an additional material extrusion to reinforce the section where the grip is in contact with the sample [6]. Stress concentration also depends on how samples are manufactured. For instance, if the sample is manufactured following longitudinal lines, stress concentration appears due to discretization of radius. To avoid stress concentration in this zone, offset contours can be used, but stress concentration is already present in another zones [8].

In this paper, test samples of PLA are manufactured using Ultimaker Cura software modifying different geometrical parameters. PLA used in this study has been choose without colour, in order to visualize concentration stress zones. Standards ISO 527 and ASTM D638 have been evaluated. Rectangular sample has also been manufactured to compare the obtained results of all geometries. Geometrical discontinuities, pressure points and thermal shock have been identified as causes of stress concentration. In order to avoid stress concentration, an annealing treatment of the samples and some samples as union of different parts are studied. Manufacturing parameters evaluated are wall thickness, orientation of building wall lines, and orientation of infill pattern. A nomenclature to define manufacturing geometries of samples are also developed.

2. Procedures and Methods

2.1. Test sample code

Parts manufactured by FDM present anisotropic properties. In FDM, manufacturing layer orientation and building line orientation in every layer of test samples have influence in tensile strength results. Standard UNE-EN ISO/ASTM 52921:2017 [15] defines orthogonal layer orientation respect to the coordinate system of the 3D printer machine (Fig. 1). Layers are manufactured in plane XY, and Z axis is defined orthogonal to the layers plane.

In each layer, orientation of building lines is not defined in standard UNE-EN ISO/ASTM 52921:2017. The currently work stablishes a nomenclature to code each test sample, considering orientation of building layers.

Orientation of building lines is defined respect to axis X, showing rotating angle with respect to this axis, having positive value from the axis X to axis Y. If orientation of building lines in a layer has a variable direction, they will be defined with P, to indicate that the direction is parallel to the perimeter of layer XY (Fig. 2).

Some test samples are manufactured with different infill pattern. Infill pattern is coded using the Cura software code (Grid, Line, etc.). Infill line direction is manufactured in XY plane. Axis X direction is defined as 0 ° orientation, being a positive value to axis Y. Different infill line direction in each layer can be used. In this case, a different orientation will be chosen for each layer (Fig 3).

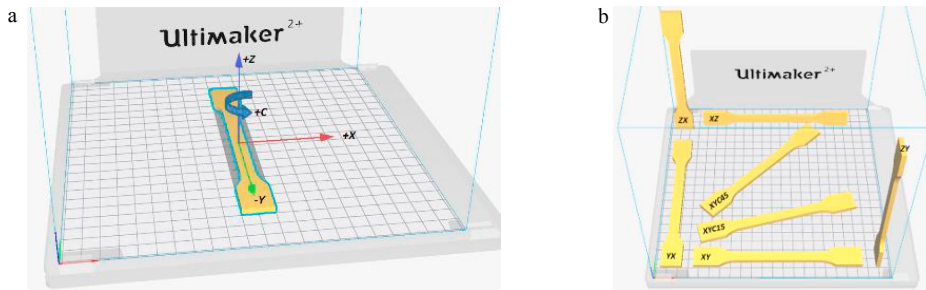


Fig. 1. (a) Orthogonal orientation of test sample; (b) Code for test sample.

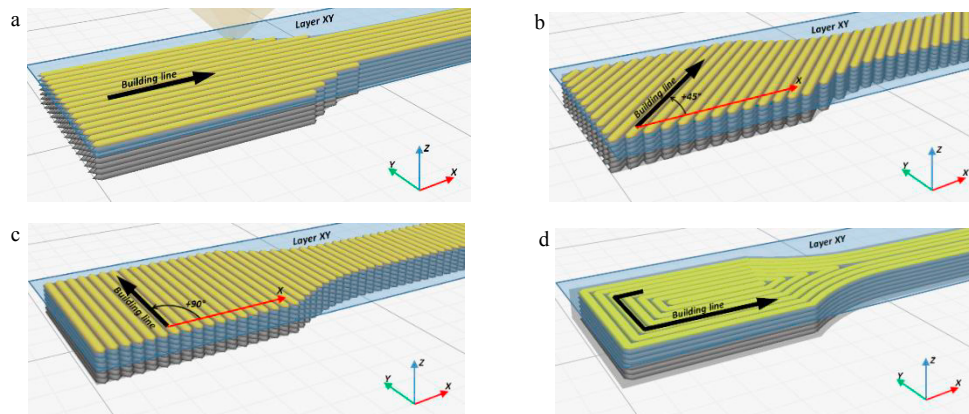


Fig. 2. (a) XY+0; (b) XY+45; (c) XY+90; (d) XY+P.

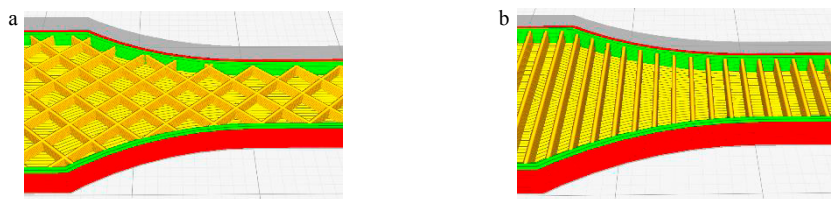


Fig. 3. (a) Grid+45 (G45); (b) Line +90 (L90).

2.2. Experimental method

Poly lactide samples geometries manufactured by FDM 3D printer were evaluated. The commercial 3 mm (1/8") NATURAL PLA FILAMENT PLA3x1 (VELLEMAN NV., Belgium) was used. Typical values of the main mechanical properties of PLA materials are presented in Table 1.

Table 1. Mechanical properties for PLA materials.

Properties	PLA
Tensile strength (MPa)	47-70
Tensile modulus (GPa)	3.3-3.6
Elongation at break (%)	2.5-6

PLA samples are manufactured using an Ultimaker 2+ printer (Ultimaker B.V., Netherlands). A nozzle of 0.4, a height layer of 0.15 mm, a printing temperature of 210 °C and a build plate temperature of 60 °C, were used. In the currently study, Cura software (Ultimaker B.V., Netherlands) was used to generate G-code files and to command and control all the process parameters. The geometry of the 3D printed samples were modelled using Inventor software (Autodesk, Inc., USA) and imported to Cura as STL file.

Tensile test were performed to analyze the mechanical properties. An Instron 5967 (Illinois Tool Works Inc., USA) of 30 kN load cell at a loading rate of 1 mm/min was used. The experimental data were processed to obtain the stress-strain curves graphs, and to calculate the maximum tensile strength.

Twelve samples have been evaluated (Table 2). PLA manufactured sample set consisted of five specimens for each group. Average and standard deviation strength values of the five specimens were taken as the results (Average \pm Standard Deviation). Tests were carried out according to the standards for room temperature.

Samples from 1 to 6 (Type 1A) are based in standard UNE-EN ISO 527-2, while samples from 7 to 9 (Type I) are based in standard ASTM D638-14. Sample 10 shows a non-standard rectangular geometry (Fig. 4). Samples 11 and 12 show the same geometry than sample 7. In order to decrease stress concentration, an annealing treatment of 45 °C during 5 hours has been applied in the sample 11. Sample 12 geometry has been obtained as the union of different parts (Fig. 5) using silicone-based adhesive.

Samples have been manufactured varying different geometrical parameters. Each sample has been code with these parameters separated by underscore to recognize how it was manufactured (Table 2). The first parameter coded is the orthogonal and wall lines orientation. Second parameter is ‘wall thickness’ and it has been identified by *e* followed by thickness value (in mm). Infill parameters have been identified with the first letter of pattern, followed by infill density percentage and infill lines angle (raster angle). Only a infill density pattern of 25% value has been used. As sample thickness is 4 mm, if thickness wall line is 2 mm, there is not infill pattern in the sample.

Table 2. Experimental sample.

Sample	Geometry	Code	Orthogonal orientation	Wall lines orientation	Thickness wall lines (mm)	Infill pattern	Infill lines angle
1	Type 1A	XY+P	XY	P	2	-	-
2	Type 1A	XY+P_e1_G25+45	XY	P	1	Grid	45
3	Type 1A	XY+P_e1_L25+90	XY	P	1	Line	90
4	Type 1A	XY+0	XY	0	2	-	-
5	Type 1A	XYC45+0	XYC45	0	2	-	-
6	Type 1A	YX+0	YX	0	2	-	-
7	Type I	XY+0	XY	0	2	-	-
8	Type I	XY+P_e1_G25+45	XY	P	1	Grid	45
9	Type I	XY+P	XY	P	2	-	-
10	Rectangular	XY+P	XY	P	2	-	-
11	Type I	XY+0	XY	0	2	-	-
12	Type I	XY+0	XY	0	2	-	-

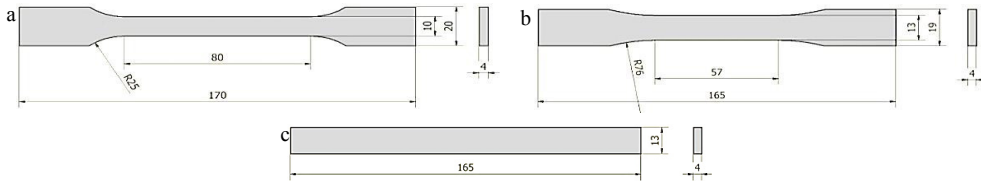


Fig. 4. (a) Type 1A geometry; (b) Type I geometry; (c) Rectangular geometry.



Fig. 5. Geometry formed as union of different parts (sample 12).

3. Results

3.1. Tensile test analysis

Stress-strain curves of the samples evaluated have been calculated and are showed in Fig. 6. These results are consistent with those reported in the literature for PLA material manufactured under different printing conditions [5–7]. Sample with Type 1A geometry exhibits a maximum stress of 49 ± 4 MPa, nevertheless samples 5 and 6 hardly reach 17 ± 3 and 31 ± 6 MPa, respectively. These low mechanical values are due to the direction of the fibers respect to the tensile test direction.

Type I samples present similar curves, being able to appreciate lack of plastic deformation in all of them, except in sample 8. Stress average value is 53 ± 6 MPa, slight higher than Type 1A.

Samples 7, 11 and 12 show the same geometry. Sample 11 has suffered an annealing treatment, which has incurred a decrease in maximum stress, as we expected, although plastic deformation does not increase. Sample 12, manufactured as union of different parts, presents a light change in maximum stress and plasticity.

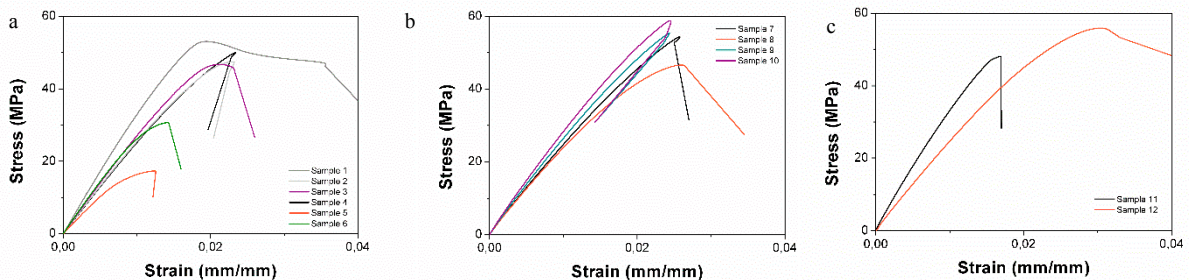


Fig. 6. Stress strain curves of (a) Samples 1 to 6; (b) Samples 7 to 10; (c) Samples 11 and 12.

3.2. Fracture position analysis

Representative samples after the tensile test are showed in Fig. 7. Fracture position has been observed in most of analyzed geometries near of the narrow section, when section changes in geometries based on standards (UNE-EN ISO 527-2 and ASTM D638-14), and at the end of the grip fix in rectangular geometry samples (sample 10). Typical stress concentration marks have been observed in these positions (Fig. 8). These marks coincide with the fracture position of the samples (Fig. 7 and Fig. 8), having relationship with stress concentration zones. Only in some sepecimens of samples 5 and 12 breaking has been observed in the length of the narrow section.

Stress concentration modifies obtained results in tensile test, being necessary to analyze their causes and to develop solutions to avoid them. Stress concentration may be due to geometrical discontinuities, pressure points and thermal shock.

- Geometrical discontinuities

Geometry of standard samples has an enough high fillet radius to avoid stress concentration in injection molding plastics samples. In this way, Type 1A geometry samples present a smaller fillet radius than Type I geometry samples. In FDM samples, manufacturing process has influence in properties of final parts. In stress-strain curves, a little plastic zone has been observed (Fig. 6), this is an indication that PLA has become brittle during the manufacturing process. Visually, a brittle rupture is observed in specimens (Fig. 7). Fragility increases stress concentration, so that the sample fillet radius could not be enough to avoid it, or that another causes could provoke stress concentration.

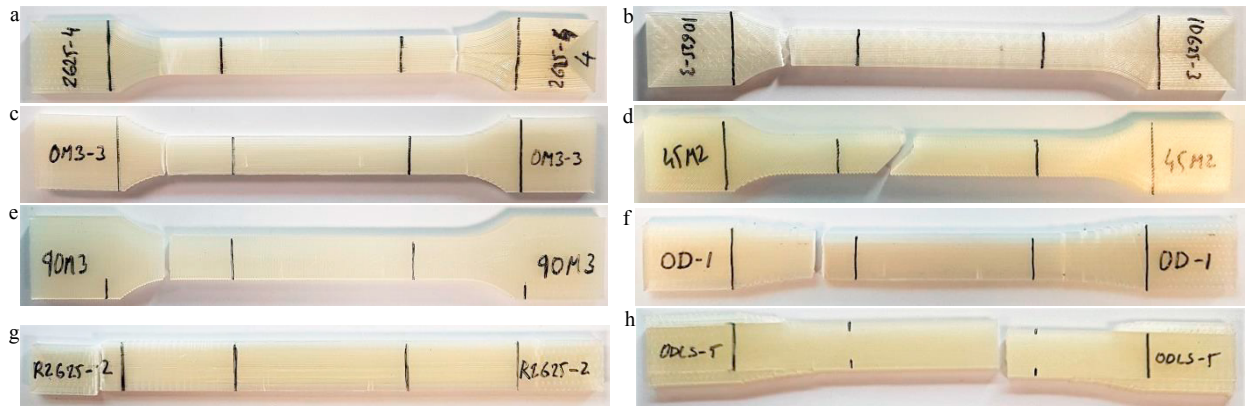


Fig. 7. (a) Sample 1; (b) Sample 2; (c) Sample 4; (d) Sample 5; (e) Sample 6; (f) Sample 7; (g) Sample 10; (h) Sample 12

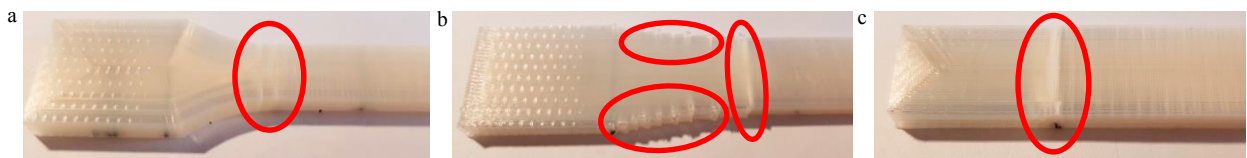


Fig. 8. Stress concentration in (a) Sample 1; (b) Sample 7; (c) Sample 10.

In samples with Type 1A and Type I geometries, fracture has been observed when section changes, but tensile strength is lower in samples with Type 1A geometry (Fig. 6a and Fig. 6b). It is due to the stress concentration effect is more important in geometries with lower fillet radius, as in Type 1A geometry.

In samples with infill pattern (Fig. 3), stress is supported by wall thickness, and as it is closer to stress concentration points, a major percentage of area is subjected to the effect of stress concentration. This causes lower tensile strength in samples with wall thickness of 1 mm (sample 3 versus sample 1, and sample 8 versus sample 9).

In XY+P samples (Fig. 2d), where lines keep the direction of the perimeter, it could be expected a significant stress concentration than in XY+0 samples. Nevertheless, tensile strength is similar in samples with Types I geometry (sample 1 vs sample 4), and in samples with Type 1A geometry (sample 9 vs sample 7). Comparing XY+P samples with both geometries (sample 1 vs sample 9), values of stress do not present meaningful differences taking into account fillet radius.

In XY+0 samples (Fig. 2a), where all lines are in X direction, it could be expected a smaller stress concentration because the building lines do not follow fillet radius, but stress values are similar, even a little lower, to XY+P samples (sample 1 vs 4 and sample 9 vs 7), and breaking also appears when section changes (Fig. 7c and Fig 7f). It is due to that in the raster edges the unions with the adjacent line form notches (Fig. 9a), creating concentration points, as observed in Fig. 8b.

In XY+45 sample (Fig. 2b), breaking frequently does not appear close to stress concentration zone, so that in this sample, stress concentration effect is lower than in others samples.

In XY+90 sample (Fig. 2c) fracture appears when section changes. In this case, stress concentration is due to notches formation between adjacent lines in the fillet radius zone.

Rectangular geometry samples have been manufactured to remove the effect of fillet radius. All tested specimens have broken at the end of the grip fix (Fig. 7g), because at this point there is a stress concentration, not a geometrical one, but due to the pressure difference between the specimen in contact with the grip and the rest of the specimen (Fig. 11). In stress-strain curves (sample 10 vs sample 7) can be appreciated that tensile strength is superior in the sample with rectangular geometry. It could be said that the effect of pressure in the grip is lower than the change of section in others geometries.

- Pressure points

Pressure points can appear due to external forces, e.g. pressure between grip and the specimen (Fig. 11), as showed in Fig. 8c. Besides, pressure points can appear during FDM manufacture process. Every manufactured layer generates pressures in the adjacent layer, due to the nozzle width is bigger than the width of the final line. This effect allows the union between lines of the same layer (Fig. 9b and Fig. 9c). This difference of size generates a pressure point between lines (Figure 10a).

Pressure point effect has been observed in rectangular geometry sample and it could be another cause of the stress concentration in XY+0 samples. In order to reduce notches and pressure points influence, in sample 12, Type I specimens have been manufactured as union of different parts (Fig. 5), using a silicone-based adhesive, to avoid brittle union. Two of five of tested specimens have not broken close to stress concentration zone (Fig. 7h), which indicates a reduction of stress concentration. Sample 12 has a tensile strength superior than sample 7, which evidence a decreasing of the negative effect of stress concentration.

- Thermal shock

Besides, every manufactured line of the layer generates a sudden temperature change in the adjacent line, generating residual stress and stress concentration (Fig. 10b). Low ductility of PLA samples manufactured by FDM increases these effects.

In order to evaluate them, an annealing treatment has applied in a sample (sample 11) with Type I geometry and XY+0. Although all tested specimens have broken when section changes, no stress concentration marks are appreciated. In stress-strain curves, a decreasing in tensile strength with respect to sample 7 is observed, due to annealing treatment, therefore a heat treatment is not adequate.

Sample 12 has been assembled with a non-exothermic silicone-based adhesive, eliminating thermal shock influence.

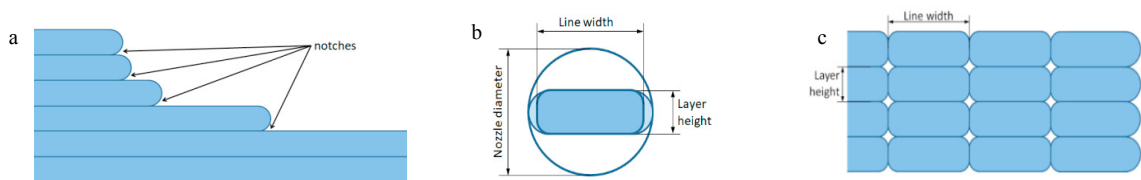


Fig. 9. (a) Notches between lines of the same layer; (b) Line section; (c) Layers sections



Fig. 10. (a) Pressure point between lines; (b) Heat transmission between lines.

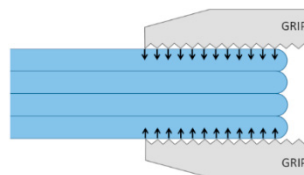


Fig. 11. Pressure between grip and specimen.

4. Conclusions

In this paper, test samples of Polylactide are manufactured by FDM according to geometries defined in ISO 527 and ASTM D638. PLA without colour has allowed to visualize concentration stress zones. Geometrical discontinuities, pressure points and thermal shock have been identified as causes of stress concentration. To avoid stress concentration, an annealing treatment of the samples and some samples as union of different parts are studied.

PLA samples are manufactured varying different geometrical parameters: sample geometry and orthogonal orientation, wall thickness, orientation of building wall lines, infill pattern density and direction, in order to test standards to evaluate tensile stress test results in FDM. In order to define orientation of building lines in each layer, which is not define in standard UNE-EN ISO/ASTM 52921:2017, a nomenclature to code each test sample is developed, taking into account not only this parameter but another ones used.

Mechanical properties of PLA samples are consistent with those reported in the literature. FDM manufacturing process of PLA, compared with another processes as injection molding plastic, fragile parts, increasing stress concentration effects generated during manufacturing. PLA fragility drives to a decrease in the plastic zone. Standards do not solve this problem with the proposal geometries. In Type 1A geometry samples, a maximum stress of 49 ± 4 MPa is reached and in Type I geometry samples an average value of 53 ± 6 MPa is obtained.

Stress concentration can modify obtained results in tensile test and it could be due to geometrical discontinuities, pressure points and thermal shock. Although Type 1A and Type I geometries present stress concentration and sample breaks in this zone, sample with non-standard rectangular geometry does not solve the problem.

An annealing treatment has been applied to avoid stress concentration, but although no stress concentration marks are appreciated, a decrease in tensile strength is observed. Another sample has been manufactured as union of different parts, observing that stress concentration zone is reduced. Standard Type I samples with wall lines orientation P and manufactured as union of different parts exhibit higher results. Type I geometries, due to an increasing section versus Type 1A, allow testing a wide wall line thickness and infill pattern range values.

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