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Influence of printing parameters on the eligibility of plane-strain fracture toughness results for PLA polymer

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Abstract

The majority of manufacturers of polymer filaments for FDM technology rely their datasheets only on tensile tests, so their documentation usually lacks any data concerning fracture mechanics parameters. Having in mind the importance of fracture mechanics parameters in material design and application e.g., plane-strain fracture toughness, and the fact that it can be measured using only standard tensile grips, or three-point bending test fixture on a regular tensile testing machine, this practice offers vital information for AM components carrying the load. Anyhow, it is not always a simple task to satisfy all requirements of the standard for plane-strain fracture toughness assessment of plastic materials (ASTM D5045-14), as in the case of FDM technology due to many printing parameters that not only influence fracture toughness results, but also can question the eligibility of test results if crack propagation deviates from the expected path or if the specimens don't meet the size criterion necessary for achieving the plane-strain condition. These problems are tackled in this research on PLA polymer, a material widely used in FDM technology. For this research SENB specimens are prepared according to ASTM D5045-14 standard and tested on tensile testing machine using three-point bending test fixture.

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Keywords: Additive Manufacturing; Fracture Toughness; PLA; SENB specimen

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1. Introduction

Most commonly used AM technology is the extrusion process called FDM, which uses thermoplastic materials delivered in the form of filament wrapped around a spool. To begin the printing process filament end is inserted into an extruder mechanism that guides the filament through the hot-end where the thermoplastic material is melted after which the material is extruded through the nozzle onto a build platform. The whole process is executed using many stepper motors for horizontal movement of the extruder, vertical movement of the build platform, and filament passage through the extruder to the build platform. After each performed layer build platform lowers one step down to allow extrusion of another layer. The process is repeated until the whole part is printed [Milovanović et al. (2019); Milovanović et al. (2020)]. Fig. 1 shows three different FDM printing processes of SENB specimen batches with 10%, 50% and 100% infill density for fracture toughness assessment, from the left to the right-hand side respectively.

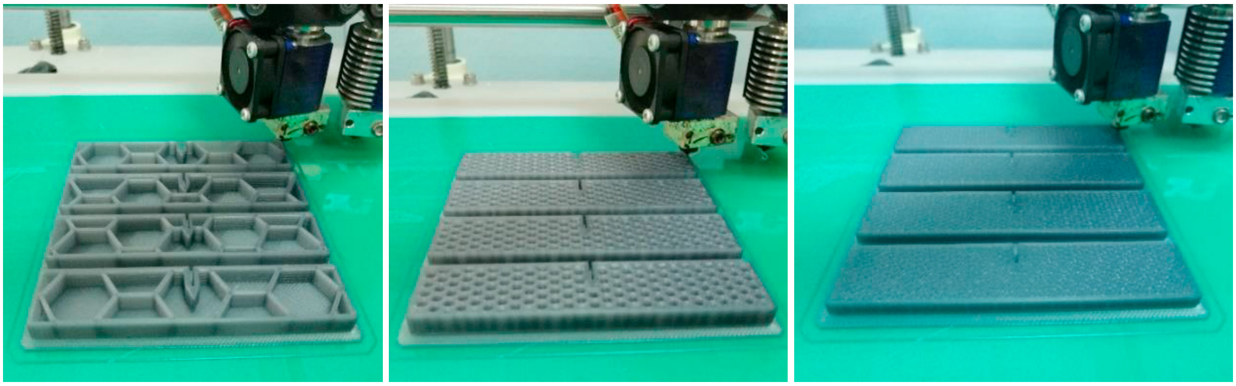


Fig. 1. SENB specimen batches during the FDM printing process (Left- 10% infill, Middle- 50% infill, Right- 100% infill density batch).

Most used FDM materials are PLA and ABS. Due to its environment friendly nature, since PLA originates from renewable resources such as corn starch and cassava roots, PLA is recently favored as the 1st material of choice for FDM 3D printing. Another advantage of PLA is the apparent ease in 3D printing since PLA has a low material shrinking during 3D printing [Milovanović et al. (2019)]. Main difference between PLA and ABS is in the area of mechanical properties, i.e., PLA has higher yield and ultimate stress and has less capacity to withstand larger deformations than ABS material. In AM, printing parameters have a significant impact on mechanical properties of the final product, and their effect on PLA material is shown in the previous researches [Milovanović et al. (2020); Valean et al. (2020a); Pandžić et al. (2019)]. Highest mechanical properties are in specimens with 100% infill density, which is due to the strong bonding between layers, according to Akhoundi et al. (2019). Conclusions of previously mentioned research papers show that infill density, layer height and infill pattern have the highest impact in mechanical properties of finished parts, in that particular order. Due to the large number of required specimens, this research includes only the influence of infill density variation, covering the whole range from minimal 10% up to 100% infill density, with identical layer height value and infill pattern shape in all specimens. Selected layer height value and infill pattern shape provide the best mechanical properties according to the literature findings [Milovanović et al. (2020); Valean et al. (2020a); Pandžić et al. (2019)], and they are presented in the following section.

The most common issue in mechanical testing of polymers concerns the amorphous nature of particular materials. Even more complications arise in AM of polymer materials due to a large number of printing parameters used in FDM technology. For example, the main issue in tensile testing is the uneven distribution of fracture cites on tested specimens [Pandžić et al. (2019)], thus requiring more specimens than the number specified in the standard BS EN ISO 527-2:2012. In order to attain proper test results, it is advisable to test at least one additional specimen per batch from the suggested number in particular standard. Mentioned tensile test results are important for fracture toughness assessment because the yield stress value is needed for the evaluation of the size criteria, in order for the plane-strain condition to be satisfied, according to standard ASTM D5045-14:2014.

Another issue concerns the specimens for bending loads since the crack path needs to follow an almost straight line from the crack initiation up to specimen failure. According to the ASTM D5045-14 standard, test results are valid if following conditions are fulfilled: sufficient specimen size for plane-strain state near the crack front, sharp crack to ensure linear elastic behavior until the force reaches its maximum, long enough crack to avoid excessive plasticity. As a result, a fracture toughness value represents a lower limit value used to estimate the relation between failure stress and defect size for a tested material.

Fracture toughness results were obtained in previous research on SENB and SCB specimens using bending test fixture on ultimate testing machine with constant stroke [Arbeiter et al. (2018); Linul et al. (2020); Stoia et al. (2020); Valean et al. (2020b); Ayatollahi et al. (2020)]. Arbeiter et al. (2018) created side-grooves on SENB specimens in order to ensure a straight crack path and to increase the plane-strain ratio near specimen surfaces. Hence, specimen thickness was measured at the position of the side-grooves. Four-point bending test has proven to be useful for the assessment of Mode I and Mode II fracture toughness results. Namely, symmetric four-point bending method was used for the assessment of Mode I results and asymmetric for the Mode II results [Linul et al. (2020); Stoia et al. (2020); Valean et al. (2020b)]. Also, one novel test fixture allows for the assessment of fracture toughness results for pure tensile mode to pure in-plane and out-of-plane shear Modes, i.e., Modes I, II and III respectively, and its vast variety of combinations on CTS specimens [Razavi et al. (2019a,b)]. Greatest concern for the SENB specimen preparation is the fabrication of the notch. According to Valean et al. (2020b), fracture toughness results are higher for specimens with directly 3D printed notches than milled ones. Also, a lower dispersion of results was present on specimens with 3D printed notches, which is associated to the better dimensional accuracy of 3D printed notches compared with notches inserted in specimens using a milling machine. The recommendation is to directly 3D print all geometrical features without further machining [Valean et al. (2020b)].

Nomenclature

FDM	Fused Deposition Modeling
AM	Additive Manufacturing
PLA	Polylactic Acid
SENB	Single Edge Notched Bending
ABS	Acrylonitrile Butadiene Styrene
SCB	Semi-Circular Bending
CTS	Compact Tension Shear

2. Fracture toughness testing

This research is focused on SENB specimens with different infill densities. Layer height is set at 0.2 mm, which is a lowest layer height value for the most commercially available 3D printers. Used infill pattern is a honeycomb structure (Fig. 1), which is a best pattern concerning mechanical properties [Pandžić et al. (2019)], available in "Simplify3D" slicer software ("Simplify3D" company, Cincinnati, OH, USA). Specimens include infills from 10% up to 100%, with 10% increment. Thus, ten batches are included in this research with four specimens per batch – three as mandatory defined by the ASTM D5045-14:2014 standard, and the fourth one served as potential replacement. In any case, results for all 40 specimens are included in this research. Nine out of ten specimen batches used in this research are depicted in Fig. 2. The image shows the specimens after the conducted tests.

Fig. 2. Nine out of ten SENB specimen batches used in this research.

All SENB specimens had the same dimensions: thickness B = 10 mm, width W = 20 mm and length L = 88 mm. ASTM D5045-14:2014 standard offers an individual to choose specimen thickness B, and all the other dimensions derive from it. Distance between supporting pins was set at 80 mm. According to the standard, SENB specimens are loaded on a regular tensile testing machine using three-point bending test fixture with a constant stroke speed, in this case 5 mm/min.

Crack length, a, being the full length of pre-crack plus notch, is 10 mm. Before application of a pre-crack, all specimens had a drawn red line at 10 mm width (Figs. 2 and 3) on both sides of the specimen. Pre-crack was applied with hammer tapping on a sharp razor placed in a notch. In that way, razor was inserted up until reached red line on both sides of the specimen.

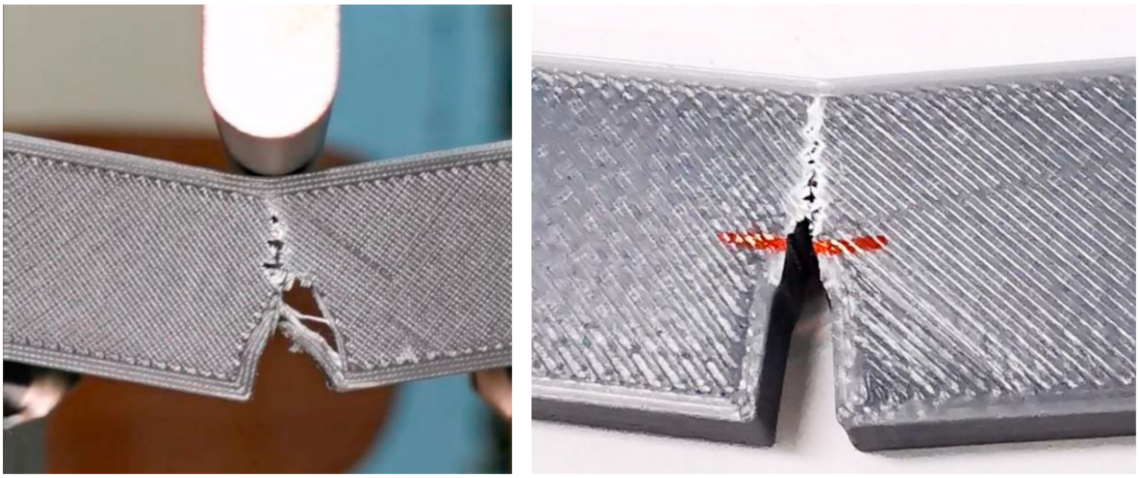


Fig. 3. Cracked SENB specimens after the fracture toughness test: with three outlines (Left); two outlines (Right).

During the fracture toughness tests crack propagates from the tip of the pre-crack up until certain point where failure occurs forming an almost straight path, which is mandatory for the eligibility of the test. Main issue with the fracture toughness tests is the delocalization of the crack from the expected crack propagation path. Unlike conventional extruded plastics, FDM components have certain structural constituents, such as top and bottom layers, infill structure and outlines. Top and bottom layers are printed in full density, and in-between these layers are the infill structures which have lower material percentage, with material arranged in particular pattern (hexagons, triangles, lines, etc.). Outlines are the solid lines that are 3D printed on the edges of each performed layer and their main purpose is to enclose the infill structure. Outlines are clearly visible on the top layer of every SENB specimen (Fig. 3). In our research, first specimens were printed with three outlines. For fracture toughness tests pre-crack length, inserted in the notch, needs to be longer than the outline thickness, in order for the pre-crack to reach the inside of the specimen, i.e., infill structure. If not, as in our case with specimens with three outlines crack will initiate and propagate from somewhere in-between outlines on the location with the highest stress concentration state where delamination of outlines would begin. From there the crack will find another path usually with an angulation form the predicted crack path (Fig. 3 - Left). In this research, pre-crack was 2.5 mm long and if three outlines are printed, which are approx. 3 mm thick, the delocalization of crack from predefined path is expected. In the next iteration the number of outlines is reduced to two, with which the pre-crack will breach the outlines resulting in the crack propagation along the expected path (Fig. 3 - Right).

Application of smaller outline number indicates in Force-Displacement diagrams that the pre-crack length will result in linear behavior, i.e., linear progression of force values on the test specimen (Fig. 4 - Left). Otherwise, force data will have local peaks before reaching the maximum value (Fig. 4 - Right), due to a presence of local stress concentrators in-between outlines. If non-linear behavior is present before reached maximum force such test is dismissed as invalid.

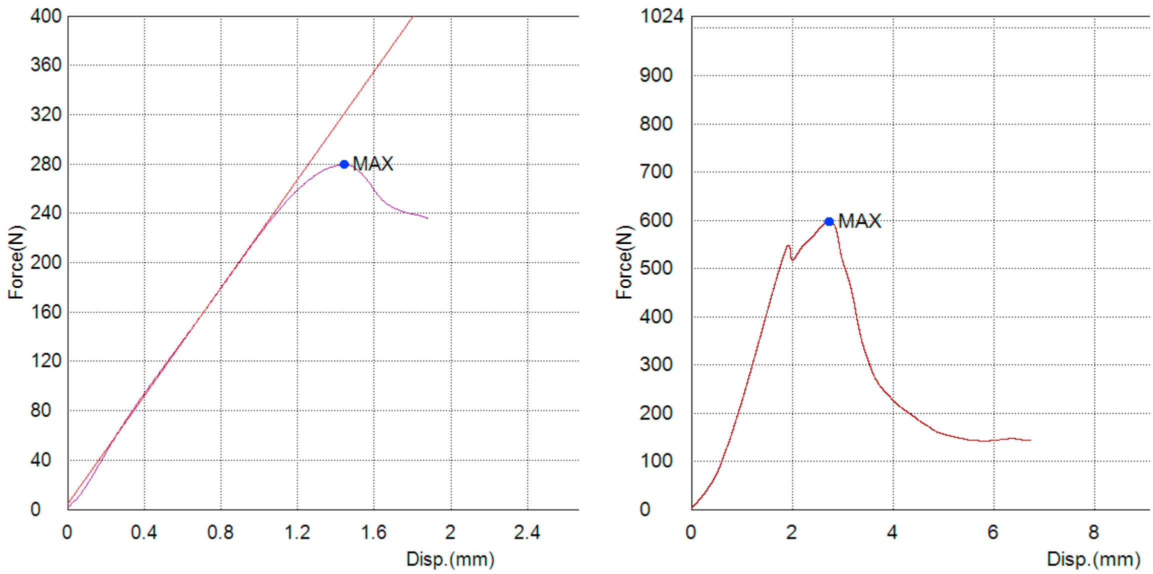


Fig. 4. Force-Displacement diagram examples for specimens with two outlines (Left); three outlines (Right).

According to the ASTM D5045-14:2014 standard, the maximum force value and specimen dimensions are needed (B and W) for the fracture toughness assessment, as well as the ratio between crack length and specimen width ($x=a/W$). First calculated fracture toughness value is conditional and has to satisfy the size criterion in order to be valid.

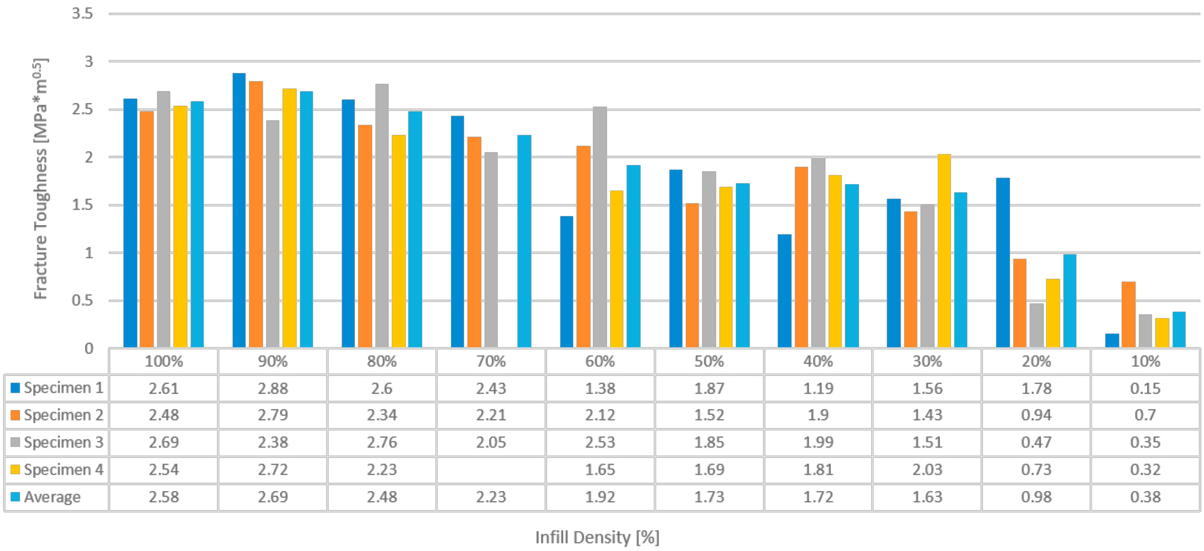
Results of this research are shown in the Fig. 5, with depicted individual fracture toughness values for each of the tested specimens and average values for every batch. The calculated K_{Ic} values are between 0.38 and 2.69 $MPa\sqrt{m}$, indicating that infill density has a significant impact on fracture toughness results. For the size criterion values, the yield stress (σ_y) values for every infill density have to be considered, since they are different. Values are acquired according to the BS EN ISO 527-2:2012 standard, and average results are shown in Table 1. Then, calculated conditional K_{Ic} value along with corresponding yield stress value for particular infill density is used in the formula from the before mentioned fracture toughness standard:

$$B,\ a,\ (W-a) > 2.5\left(\frac{K_{Ic}}{\sigma_y}\right)^2 \tag{1}$$

Table 1. Average yield stress values for every specimen infill density.

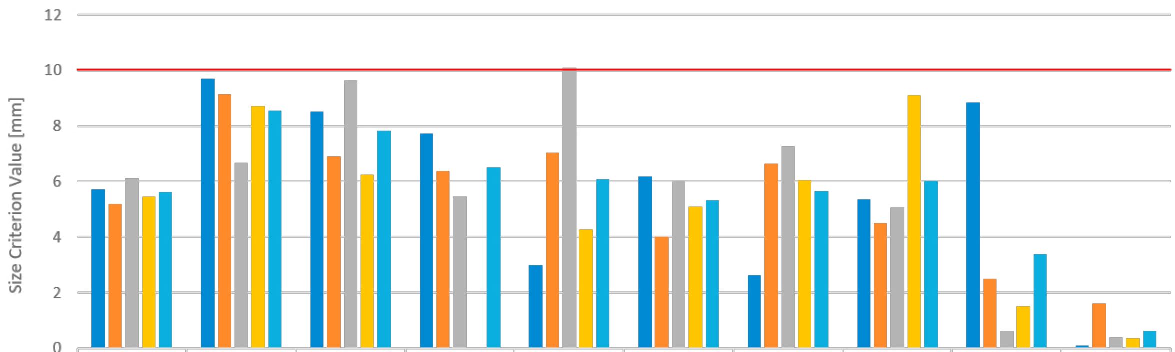
Specimen infill density (%)	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%
Yield Stress (MPa)	54.35	46.20	44.58	43.77	39.92	37.49	37.08	33.64	29.68	27.44

Calculated values have to be lower that the B, a and (W-a) length, which are the same. Results for the size criterion are shown in Fig. 6. In our case, the fracture toughness results and yield stress values for all the tested specimens meet the size criterion according to the ASTM D5045-14:2014 standard for the chosen specimen thickness (B = 10 mm), except for the specimen number 3 from the 60% infill density batch (Fig. 5). There, the size criterion value exceeds by just 0.08 mm (Fig. 6). As a reflection on fracture toughness results, particular specimen holds the substantially higher value than in all the other specimens from that particular batch (Fig. 5). Since the standard requires 3 specimens per batch, the quoted specimen may be deleted from the list. One of the conclusions from this research is that all specimens that have higher K_{Ic} values than the other specimens from their belonging batches have the size criterion value closer to the limit, i.e., in this case 10 mm (Figs. 5,6). Worth mentioning is that the batch with 70% infill density has only 3 mandatory specimens, due to the test failure on the replacement specimen. Comparing the results in-between tested batches can be seen that high force values achieved during the test in most of the higher infill density batches results in their size criterion value closer to the limiting 10 mm. Batches with lower infill densities have the size criterion results notably below the limiting 10 mm value. If size criterion was not satisfied, this test would prove to be invalid and for the next iteration larger specimens would be needed.



	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%
Specimen 1	2.61	2.88	2.6	2.43	1.38	1.87	1.19	1.56	1.78	0.15
Specimen 2	2.48	2.79	2.34	2.21	2.12	1.52	1.9	1.43	0.94	0.7
Specimen 3	2.69	2.38	2.76	2.05	2.53	1.85	1.99	1.51	0.47	0.35
Specimen 4	2.54	2.72	2.23		1.65	1.69	1.81	2.03	0.73	0.32
Average	2.58	2.69	2.48	2.23	1.92	1.73	1.72	1.63	0.98	0.38

Fig. 5. Fracture toughness values for all the tested SENB specimens with average values per each batch.



	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%
Specimen 1	5.73	9.71	8.53	7.73	2.98	6.17	2.64	5.36	8.85	0.08
Specimen 2	5.19	9.15	6.89	6.38	7.03	4.01	6.64	4.5	2.51	1.61
Specimen 3	6.13	6.67	9.63	5.46	$\boxed{10.08}$	6.03	7.28	5.07	0.63	0.39
Specimen 4	5.44	8.72	6.26		4.26	5.08	6.05	9.11	1.51	0.34
Average	5.62	8.56	7.83	6.52	6.09	5.32	5.65	6.01	3.38	0.61

Infill Density [%]

Fig. 6. Size criterion values for all the tested specimens with average values per each batch.

3. Conclusions

In FDM technology printing parameters have a significant effect on mechanical properties of 3D printed parts. Concerning fracture toughness assessment, printing parameters may not only have an impact on the final results, but may also question the eligibility of the test. In this paper the influence of printing parameters on the crack path direction and linear behavior was studied based on the number of applied layer outlines. It was shown that the smaller outline number results in linear behavior, i.e., linear progression of force values. Also, the estimation of infill density contribution (10% to 100%) to K_{Ic} values has been studied, as well as its influence on the size criterion estimation for the fulfilment of plane-strain condition. The K_{Ic} value was between 0.38 and 2.69 $MPa\sqrt{m}$, indicating that infill density has a significant impact on fracture toughness results.

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