

# Additively manufactured PLA: strength and fracture behaviour under static loading

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**Abstract.** This paper investigated the strength as well as the cracking behaviour of additively manufactured PLA subjected to static loading. In particular, plain and cracked specimens of PLA were tested under tension, with the samples being manufactured to investigate explicitly the effect of the infill orientation angle. The results of the systematic experimental investigation being performed seem to strongly support the idea that, as long as 3D-printed components of PLA are manufactured horizontally, the influence of the deposition angle on the overall material strength can be neglected with little loss of accuracy.

## Introduction

As far as additive manufacturing of plastics is concerned, acrylonitrile butadiene styrene (ABS) and polylactide (PLA) are the polymers that are most commonly used in situations of practical interest [1]. In particular, PLA is a biodegradable, absorbable and biocompatible material that is widely used to manufacture components for medical, dental, automotive, and aircraft applications. PLA can be 3D-printed by making use of powder, wires and flat sheets that are melted using a variety of different techniques. One of the most important peculiarities of additive manufacturing is that it allows objects having complex forms to be manufactured by systematically reaching a remarkable level of accuracy in terms of both shape and dimensions. In this context, aim of this paper is investigating the effect of the manufacturing orientation on the overall static strength as well as on the fracture resistance of additively manufacture PLA.

## Fabrication of the specimens and experimental testing

Specimens of white PLA (New Verbatim PLA having diameter of 2.85mm) were additively manufactured using 3D-printer Ultimaker 2 Extended+. The key manufacturing parameters were set as follows: nozzle size=0.4mm, nozzle temperature=240°C, build-plate temperature=60°C, layer height=0.1 mm, shell thickness=0.4mm, fill density=100 %, and print speed=30mm/s. The specimens were manufactured horizontally, with the filaments being always at  $\pm 45^\circ$  to the longitudinal axis of the specimens. The samples were fabricated by setting (with respect to the samples' longitudinal axis) the deposition angle,  $\theta_p$ , equal to  $0^\circ$ ,  $15^\circ$ ,  $30^\circ$ ,  $45^\circ$ ,  $60^\circ$ , and  $90^\circ$ . The plain samples had thickness equal to 4mm and net width to 15mm. Crack-like notches were fabricated by cutting the material via a sharp thin knife, with these rectangular section specimens having thickness equal to 4mm, gross width to 25mm, and notch depth to 4.8mm. The average length of the manufactured crack-like notch root radii was measured (via an optical microscope) to approach 0.05mm.

Tensile static tests were run under a constant displacement rate of 1 mm/min by using a Shimadzu universal machine. In the plain specimens, local strain were measured directly via a standard axial extensometer with gauge length equal to 50 mm. The tests were run up to the complete breakage of the specimens. Three different specimens were tested for any geometry/manufacturing configuration that was investigated.

## Experimental results

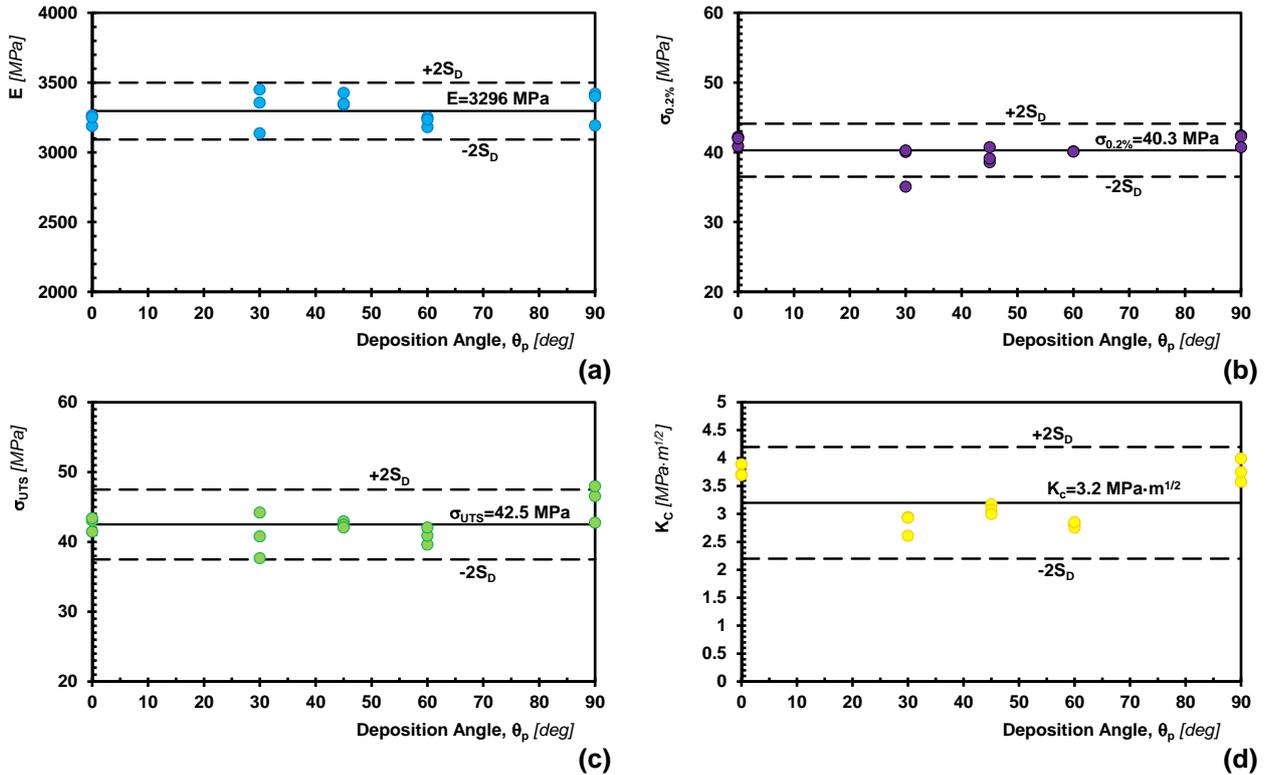
In terms of cracking behaviour, it was seen that, both in the presence and in the absence of crack-like notches, final breakage was caused by two prevailing failure mechanisms, i.e. (i) initial shear-stress-dominated debonding between adjacent filaments followed by (ii) normal-stress-governed rectilinear breakage of the filaments themselves.

As far as plain specimens are concerned, the stress vs. strain curves being generated were post-processed in order to determine Young's modulus,  $E$ , 0.2% proof stress,  $\sigma_{0.2\%}$ , and ultimate tensile strength,  $\sigma_{UTS}$ . The values of these material constants averaged from the 15 tests being run were as follows:  $E=3296$  MPa,  $\sigma_{0.2\%}=40.3$  MPa, and  $\sigma_{UTS}=42.5$  MPa. According to the charts reported Figures 1a, 1b, and 1c, the results generated by making deposition angle  $\theta_p$  vary from  $0^\circ$  to  $90^\circ$  were seen to fall within an error interval of  $\pm 2S_D$ , with  $S_D$  being the standard deviation characterising any material mechanical property being considered. According to these results, it is possible to conclude that deposition angle  $\theta_p$  had little effect on the overall mechanical behaviour of the PLA specimens being tested. Further, the fact that the difference between the average values of  $\sigma_{0.2\%}$  and  $\sigma_{UTS}$  was measured to be lower than 1% suggests that the mechanical behaviour of this PLA can be modelled effectively by directly using a simple linear-elastic constitutive law.

Subsequently, attention was focussed on the cracking behaviour displayed by the additively manufactured PLA being investigated. The chart of Figure 1d shows the existing interaction between deposition angle  $\theta_p$  and fracture toughness,  $K_C$ , determined for a thickness equal to 4 mm. In particular, the  $K_C$  values reported in this chart were determined according to the following standard formula [2, 3]:

$$K_C = \alpha \cdot \sigma_f \cdot \sqrt{\pi a} \quad (1)$$

where  $\alpha$  is the shape factor,  $\sigma_f$  is the nominal failure stress referred to the gross area, and  $a$  is the crack-like notch depth. By considering the 15 different experiments that were run to investigate the effect of  $\theta_p$ , the average value for  $K_C$  was seen to be equal to of  $3.2 \text{ MPa}\cdot\text{m}^{1/2}$ . In particular, the chart of Figure 1d makes it evident that the largest value for  $K_C$  was obtained for  $\theta_p$  equal to  $0^\circ$  and to  $90^\circ$ , whereas the lowest value for  $\theta_p=30^\circ$  and  $\theta_p=60^\circ$ . As to the results reported in Figure 1d, it is interesting to observe also that, overall, the measured values for  $K_C$  were seen to fall within an error interval of  $\pm 2S_D$ . This suggests that also in terms of fracture strength the effect of deposition angle  $\theta_p$  can be neglected with little loss of accuracy.



**Figure 1.** Influence of deposition angle  $\theta_p$  on the mechanical/cracking behaviour of the additively manufactured PLA being tested.

## Conclusion

From a structural integrity point of view, the generated experimental results demonstrate that both the mechanical and the cracking behaviour of the PLA being considered in the present investigation were not affected markedly by the deposition angle. Further, the fact that the difference between yield stress and ultimate tensile stress was seen to be lower than 1% strongly supports the idea that the mechanical behaviour of 3D-printed PLA can be modelled by using a simple linear-elastic constitutive law.

## References

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