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Additively Manufactured PLA under static loading: strength/cracking behaviour vs. deposition angle

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Abstract

This paper aims to assess the existing interactions between strength/fracture behaviour and infill angle in additively manufactured PLA subjected to static loading. Plain specimens and samples containing crack-like notches of 3D-printed PLA were manufactured horizontally by making the deposition angle vary from 0° to 90°. A direct inspection of the fracture surfaces revealed that, irrespective of the infill orientation, static failures were caused by two mechanisms, i.e.: (i) initial shear-stress-governed de-bonding between adjacent filaments and subsequent normal-stress-governed breakage of the filaments themselves. The results being generated demonstrate that, from an engineering point of view, the influence of the deposition angle on the overall strength/fracture resistance of additively manufactured PLA can be neglected with little loss of accuracy. The profile of the stress vs. strain curves being obtained experimentally suggests also that the mechanical behaviour of the 3D-printed PLA being investigated can be modelled accurately without requiring the use of complex non-linear material models, with this resulting in a great simplification of the design problem.

Keywords: Additive Manufacturing, PLA, deposition angle, static loading, strength, fracture resistance

1. Introduction

Additive Manufacturing (AM) allows objects from three-dimensional numerical models to be fabricated by joining materials layer upon layer. Therefore, AM is an "additive" process that permits components having complex shape to

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Nomenclature

a	notch depth
t	thickness
w_g	gross width
w_n	net width
E	Young's modulus
K_C	fracture toughness
α	shape factor
θ_p	angle defining the manufacturing direction
$\sigma_{0.2\%}$	0.2% proof stress
σ_f	nominal failure stress referred to the gross area
σ_{UTS}	ultimate tensile strength

be manufactured in a more effective way than conventional "subtractive" technologies, with this being done by reaching a remarkable level of accuracy in terms of both shape and dimensions.

Plastics can be additively manufactured from powders, wires and flat sheets that are melted using a variety of different technologies. Compared to the large variety of plastic materials that can be manufactured by adopting conventional processes, a limited numbers of plastics can be additively manufactured effectively, with acrylonitrile butadiene styrene (ABS) and polylactide (PLA) being the most commonly employed polymers. Other plastic materials such as polyphenyl sulfone and polycarbonate can also be additively manufactured, even though the fabrication processes being required are based on more sophisticated technological solutions.

PLA is a biodegradable, absorbable and biocompatible polymer that is used to manufacture a variety of components/objects that include, amongst other, biomedical devices (Hamad et al., 2015). One of the most important features of PLA is that it can be additively manufactured very easily by using low-cost commercial 3D-printers.

Examination of the state of the art shows that the mechanical properties of additively manufactured PLA are markedly affected by different technological variables such as: nozzle size, layer thickness, infill percentage, filling pattern, filling speed, and manufacturing temperature (de Ciurana et al., 2013; Fernandez-Vicente et al., 2016). It is interesting to observe that other parameters as well are seen to play an important role during the manufacturing process: for instance, given the basic chemical composition of the material being used, pigments affect not only its mechanical properties, but also its level of crystallinity (Wittbrodt and Pearce, 2015).

In this context, certainly the infill orientation is one of the most important variables affecting the overall mechanical, strength, and fracture behaviour of additively manufactured plastics. In particular, by testing unidirectional fused deposition specimens of both PLA and ABS, Lanzotti et al. (2015) have observed that the material ultimate tensile strength decreases by 50% as the infill angle varies from 0° to 90°. Further, on average, the strength along the vertical direction (i.e., along a direction perpendicular to the build-plate) is seen to be about 30% lower than the strength that is obtained along horizontal directions.

From a structural integrity view point, the fact that 3D-printed components can contain very complex geometrical features results in localised stress concentration phenomena, with stress raisers reducing markedly the overall strength of the components themselves (Susmel & Taylor, 2008a, 2008b, 2010; Yin et al., 2015). Accordingly, accurate and simple design techniques are required in order to perform the static assessment of 3D-printed materials accurately.

In this challenging scenario, the aim of the present paper is to investigate whether, under static loading, the deposition angle influences not only the static strength, but also the fracture resistance of additively manufactured PLA.

2. Fabrication of the specimens

Via 3D-printer Ultimaker 2 Extended+, both plain specimens and samples containing crack-like notches were additively manufactured using as parent material white filaments of New Verbatim PLA having diameter equal to