Applying fracture toughness test methods to specimens additively manufactured by filament-deposition methods

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Abstract

This paper presents illustrations of collecting and using fracture toughness testing methods to characterize compact-tension C(T) specimens printed to nominal dimensions by filament deposition melt (FDM) methods. This additive manufacture process has become the most well-known and popular solution for 3D printing, due to the small size, simplicity, and affordability of equipment. Nonetheless, that does not diminish its commercial importance, especially with more recent extension into producing metallic parts.

For the tests, a fracture mechanics approach was used, and different analysis approaches are presented, with discussion of their suitability and validity according to the well-established fracture toughness test methods ASTM E399 and ASTM E1820.

Specimen production

Specimen dimensions were chosen as around the smallest typically used for conventional materials (12.5mm thick, 30mm total width), produced as nominally 100% dense material. Two orientations were examined: applied load in build direction, with the crack propagating between layers in the print plane (Z-Y); applied load parallel to the deposition plane, with crack propagating orthogonally across the build (X-Y). A common poly-lactic acid extrusion compound was used first, as a rapid, low-cost demonstration, to provide some scope of whether the test procedure might need to be modified with orientation. This illustrated the expected high level of anisotropy, and a group of specimens were post-processed to induce crystallization, creating deliberate change in performance. Specimens were then obtained in FDM-printed A13 tool steel, and tested in a congruent manner.

Testing and analyses

Test methodology was based on conventions for metallic materials: collecting some basic fatigue resistance data while generating a fatigue precrack, followed by pull-to-failure and post-test analysis of resistance to fracture. The data from these tests can be dissected and analysed in various fashions.

For example, the initial crack growth, when cutting across layers can offer an indication of how homogeneous the material is. In Fig.1, the fatigue crack growth rate, under a constant amplitude of stress intensity, can be seen to fluctuate, with a spatial periodicity which appears to be matching the bead width of the print raster.

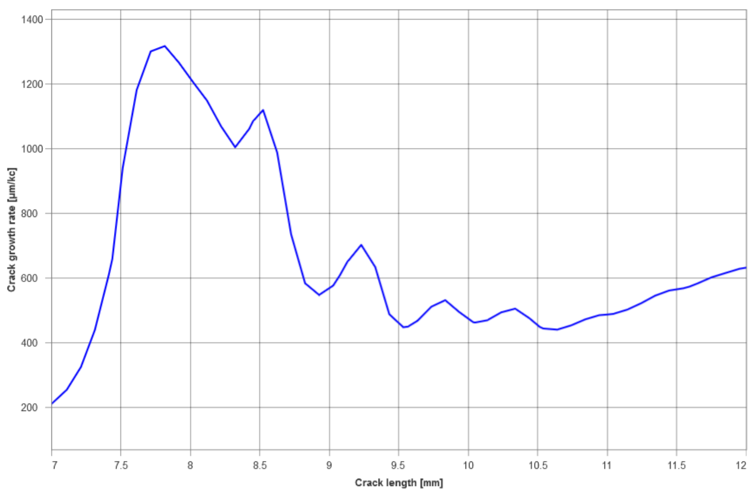

Figure 1: crack growth rate of PLA in X-Y direction (perpendicular to deposition plane) under fatigue loading at constant ΔK

Meanwhile loading to critical failure, to determine fracture toughness, reveals significantly different behaviour depending upon orientation to the building direction. In Fig.2, the contrast can be seen, between a highly brittle failure in one orientation, and a much more ductile behaviour at significantly higher toughness in another.

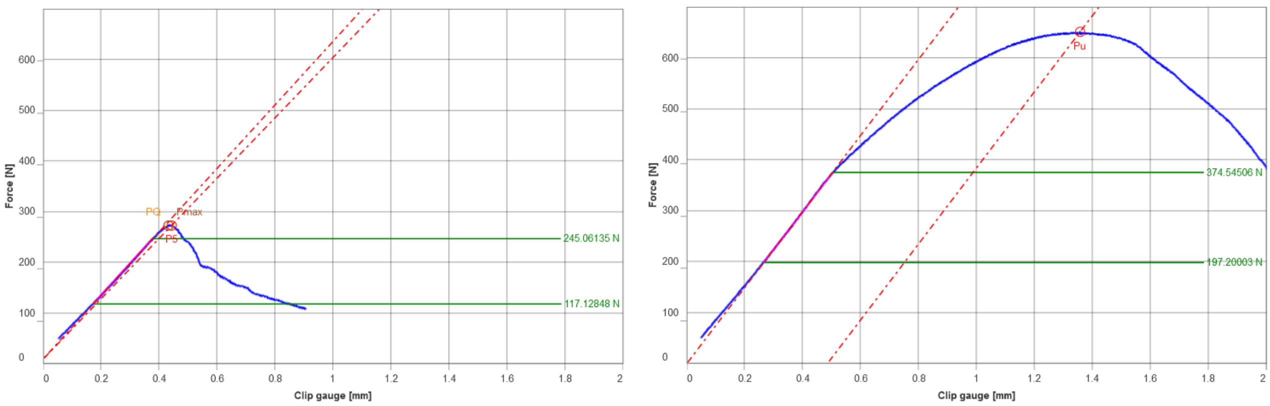

Figure 2: Loading to failure Force-vs-CMOD plots for a compact tension specimen of FDM-PLA in (left) Z-X direction, the plane of the deposition and (right) X-Y direction, cutting across layers

Relevance of analyses

The material morphology resulting from FDM processes cannot be considered homogeneous. Any exposure to additive manufacturing technology will inform the reader that resulting parts commonly have microstructures resembling multi-pass weldments, and that nominally fully-dense material often suffers much greater void content than any conventional production process. Faced with specimens with an inherent degree of meso-structure, it is recognised that conventional fracture mechanics should strictly demand some revised consideration. However, this paper seeks to show that there is some value in using established methods to parameterize toughness in order to assess structural integrity.

Furthermore, while many articles are ultimately likely to be designed for fabrication as a shell, with some form of internal lattice structure, the question must remain about how to evaluate the quality that results from process parameters and feedstock in use. Common tensile tests are often not particularly probing of behaviour that will affect durability in service, so using tests derived from a fracture mechanics approach may offer greater insight, for relatively little greater effort.