Streamlining the development of failure surfaces for Fused Filament Fabrication

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Abstract

Fused Filament Fabrication (FFF) is arguably the most widely available Additive Manufacturing technology at the moment. Offering the possibility of producing complex geometries in a compressed product development cycle and in a plethora of materials, it comes as no surprise that FFF is attractive to multiple industries, including the automotive and aerospace segments. However, the high anisotropy of parts developed through this technique implies that part failure prediction is extremely difficult —a requirement that must be satisfied to guarantee the safety of the final user. Application of a Failure Criterion to predict part failure can solve this issue. However, a large number of mechanical tests performed under a variety of loading conditions are required to populate the parameters of the function that describes the failure envelope - a process that is extremely time consuming. This research proposal describes a method by which the development of the failure surface can be streamlined, and the number of mechanical tests can be significantly reduced.

Keywords: FFF, FDM, Failure Criteria, Mechanical Testing, Machine Learning.

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Introduction

Additive Manufacturing (AM) is an umbrella term that encompasses all fabrication techniques where the final geometry of the part is obtained through superposition of material in a layer-by-layer basis [1]. Developed in the 1980s, this manufacturing technique permits immensely shorter part development cycles, since the transition from a 3D *Computer Aided Design* (CAD) to part fabrication only requires one intermediate step: the use of a slicing engine that converts the geometry of the object into machine instructions [1]. For this reason, AM technologies were initially employed exclusively for prototype development and were referred to as *Rapid Prototyping techniques* (RP). However, recent innovations in the field have caused AM to be considered as a legitimate manufacturing technology since it is also capable of reproducing complex geometries unattainable through traditional methods [1].

While offering great advantages over traditional part fabrication methods, AM comes with its own set of limitations and disadvantages: First and foremost, the use of a stratified build approach tends to produce extremely anisotropic parts. Secondly, the geometric accuracy of the object produced is highly dependent of process parameters, particularly, the thickness of the layers. Finally, as of the time of this writing, AM lacks the standardization and scrutiny that are associated to most traditional manufacturing techniques [1].

Fused Filament Fabrication (FFF), also known under the trademark *Fused Deposition Modeling* (FDM™), represents perhaps the most prevalent AM technique in the market due to the advent of low-cost, desktop 3D printers in the early 2010s [2]. Due to the broad availability of machines and relatively low costs of material, there is a surging interest in optimizing FFF to produce small batches of end-user grade parts. Success stories are varied, but examples include vacuum form molds, fixtures, jigs, and tools used to aid assembly lines in the automotive industry [3, 4, 5]. However, this technology still faces the challenges and limitations that currently affect the field of AM as a whole. Namely, anisotropy introduced through the layer-by-layer build approach makes it difficult to assess the expected mechanical behavior of FFF parts when subjected to important mechanical stresses [2]. For these reasons, multiple attempts have been made to characterize the anisotropy of FFF manufactured objects, such as the studies performed by Koch *et al.* [6] and Rankouhi *et al.* [7], which show that the ultimate tensile strength of FFF coupons is sensitive to process parameters such as the layer thickness and, in particular, the orientation in which the plastic strands are laid during the build process -henceforth referred to as the bead orientation. Literature related to preventing failure through the use of failure criteria in the design stages is scarce, given the difficulty of using commercially available FFF machines to produce test coupons with unconventional bead orientations, as well as the limitations inherent to development of failure envelopes. The large number of coupons required to properly characterize the failure behavior of parts is one of the main culprits for the small number of research articles on the topic. However, recent efforts include the developments of failure envelopes for Polyamide 12 (PA12) used in Selective Laser Sintering (SLS) [8], and more importantly for this body of work, a failure surface for Acrylonitrile Butadiene- Styrene (ABS) used in FFF [9].

This research applies a novel criterion, tailored for anisotropic materials, to develop a failure surface for FFF parts through mechanical testing of coupons under various types of loading conditions. Certain test specimens were produced using a unique off-axis 3D printer developed in-house that allows production of coupons in unconventional configurations. Such a surface can be an invaluable tool in part design, since catastrophic failure can be prevented in the early stages of part development. This could potentially allow a broader embrace of FFF as a legitimate manufacturing technique in highly demanding engineering fields, such as the aerospace or automotive industries where part failure is to be avoided at all costs.

This work offers a comprehensive overview of AM technologies, FFF and shortcomings of current failure criteria in Chapter **??**. Chapter **??** details the failure criterion used throughout this work, as well as outlining its advantages over similar models. Chapters **??** through **??** detail the experimental setup followed, as well as outlining noteworthy results. Finally, conclusions and recommendations are given in Chapter **??** in the hopes of guiding future work on the topic.

Bibliography

[1] Ian Gibson, David Rosen, and Brent Stucker. *Additive Manufacturing Technologies*. 2nd Ed. Springer, 2015. ISBN: 978-1-4939-2112-6. DOI: 10.1007/978-1-4939-2113-3. URL: http://link.springer.com/10.1007/978-1-4939-2113-3.

[2] G A Mazzei Capote, A Redmann, C Koch, and N Rudolph. "Towards a Robust Production of FFF End-User Parts with Improved Tensile Properties". In: *Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium*. Austin, TX, 2017, pp. 507–518.

[3] Cole Hartman and Veronica de la Rosa. *Benefits of 3D Printing Vacuum Form Molds*. 2014. URL: http://studiofathom.com/wp-content/uploads/Vacuum-Forming-White-Paper-F001-5-1-2014.pdf (visited on 02/06/2018).

[4] Luke Van Hulle. "Robotic Off-Axis Fused Filament Fabrication". Master Thesis. University of Wisconsin-Madison, 2017.

[5] Caspar de Vries. *Volkswagen Autoeuropa: Maximizing production efficiency with 3D printed tools, jigs, and fixtures*. 2017. URL: https://ultimaker.com/en/stories/43969-volkswagen-autoeuropa-maximizing-production-efficiency-with-3d-printed-tools-jigs-and-fixtures (visited on 02/02/2018).

[6] Carsten Koch, Luke Van Hulle, and Natalie Rudolph. "Investigation of mechanical anisotropy of the fused filament fabrication process via customized tool path generation". In: *Additive Manufacturing* 16 (2017), pp. 138–145. ISSN: 22148604. DOI: 10.1016/j.addma.2017.06.003. URL: http://dx.doi.org/10.1016/j.addma.2017.06.003.

[7] Behzad Rankouhi, Sina Javadpour, Fereidoon Delfanian, and Todd Letcher. "Failure Analysis and Mechanical Characterization of 3D Printed ABS With Respect to Layer Thickness and Orientation". In: *Journal of Failure Analysis and Prevention* 16.3 (2016), pp. 467–481. ISSN: 15477029. DOI: 10.1007/s11668-016-0113-2.

[8] P. Obst, M. Launhardt, D. Drummer, P.V. Osswald, and T.A. Osswald. "Failure criterion for PA12 SLS additive manufactured parts". In: *Additive Manufacturing* 21.March (2018), pp. 619–627. ISSN: 22148604. DOI: 10.1016/j.addma.2018.04.008. URL: http://linkinghub.elsevier.com/retrieve/pii/S221486041830099X.

[9] Gerardo A Mazzei Capote, Natalie M Rudolph, Paul V Osswald, and Tim A Osswald. “Failure surface development for ABS fused filament fabrication parts”. In: *Additive Manufacturing* 28.April (2019), pp. 169–175. ISSN: 2214-8604. DOI: 10.1016/j.addma.2019.05.005. URL: https://doi.org/10.1016/j.addma.2019.05.005.