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Junlan Wang · Bonnie Antoun · Eric Brown · Weinong Chen
Ioannis Chasiotis · Emily Huskins-Retzlaff
Sharlotte Kramer · Piyush R. Thakre *Editors*

Mechanics of Additive and Advanced Manufacturing, Volume 9

Proceedings of the 2017 Annual Conference on Experimental and Applied Mechanics

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ISSN 2191-5644 ISSN 2191-5652 (electronic)
Conference Proceedings of the Society for Experimental Mechanics Series
ISBN 978-3-319-62833-2 ISBN 978-3-319-62834-9 (eBook)
DOI 10.1007/978-3-319-62834-9

Library of Congress Control Number: 2017953418

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Printed on acid-free paper

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The registered company is Springer International Publishing AG
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Preface

Mechanics of Additive and Advanced Manufacturing represents one of nine volumes of technical papers presented at the 2017 SEM Annual Conference and Exposition on Experimental and Applied Mechanics organized by the Society for Experimental Mechanics and held in Indianapolis, IN, June 12–15, 2017. The complete Proceedings also includes volumes on: *Dynamic Behavior of Materials*; *Challenges In Mechanics of Time-Dependent Materials*; *Advancement of Optical Methods in Experimental Mechanics*; *Mechanics of Biological Systems, Materials and other topics in Experimental and Applied Mechanics*; *Micro- and Nanomechanics*; *Mechanics of Composite, Hybrid and Multifunctional Materials*; *Fracture, Fatigue, Failure and Damage Evolution*; *and Residual Stress, Thermomechanics and Infrared Imaging, Hybrid Techniques and Inverse Problems.*

Mechanics of additive and advanced manufacturing is an emerging area due to the unprecedented design and manufacturing possibilities offered by new and evolving advanced manufacturing processes and the rich mechanics issues that emerge. Technical interest within the society spans several other SEM technical divisions such as: composites, hybrids and multifunctional materials, dynamic behavior of materials, fracture and fatigue, residual stress, time-dependent materials, and the research committee.

In this inaugural track in SEM 2017, the topic of mechanics of additive and advanced manufacturing included in this volume covers design, optimization, experiments, computations, and materials for advanced manufacturing processes (3D printing, micro- and nano-manufacturing, powder bed fusion, directed energy deposition, etc.) with particular focus on mechanics aspects (e.g., mechanical properties, residual stress, deformation, failure, rate-dependent mechanical behavior, etc.).

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Chapter 1
Fracture Properties of Additively Manufactured Acrylonitrile-Butadiene-Styrene Materials

Kevin R. Hart and Eric D. Wetzel

Abstract Additively Manufactured (AM) parts exhibit orthotropic behavior when loaded as a result of the layer-by-layer assembly commonly utilized. While previous authors have studied the effect of layer orientation on the tensile, flexural, and impact response of AM parts, the effect of layer orientation on the fracture response is not well established. Here we explore the effect of layer orientation on the fracture properties of Acrylonitrile-Butadiene-Styrene (ABS) materials fabricated through the Fused Filament Fabrication (FFF) process. Critical fracture toughness values of Single Edge Notch Bend (SENB) specimens with a pre-crack oriented either parallel or perpendicular to the direction of layer-by-layer assembly were compared. Results show that the inter-laminar fracture toughness (fracture between layers) is approximately one order of magnitude lower than the cross-laminar toughness (fracture through layers) of similarly manufactured parts. Contrasting brittle and ductile fracture behavior is observed for inter-laminar and cross-laminar crack propagation, respectively, demonstrating that the elastic-plastic response of AM ABS parts is governed by the orientation of the layers with respect to the direction of crack propagation.

Keywords Additive manufacturing • J-integral • Fracture mechanics • Polymer • Single edge notch bend

SENB specimens measuring 100 × 20 × 10 mm were fabricated using a Taz 6 FFF desktop printer (Lulzbot; Loveland, Co), with ABS M30 filament (Stratasys; Eden Prarie, MN). Printed specimens are described as laminates, where each laminae is a layer of material constructed parallel to the print bed with a nominal thickness equal to the layer height (0.22 mm). Samples with variable crack-tip/laminae orientation angles, θ, were fabricated. Specimens for inter-laminar fracture testing were fabricated with the longest part edge oriented perpendicular to the build plate (vertically) and had a crack-tip/lamina orientation of $\theta = 0°$. Specimens for cross-laminar fracture testing were constructed with the longest part edge oriented parallel to the build plate (horizontally) and had a crack-tip/lamina orientation of $\theta = 90°$. Specimens to investigate crack kinking behavior were constructed with the longest edge oriented at an oblique angle of 75° relative to the vertical (oblique). Orientations of vertically, horizontally, and obliquely printed SENB samples are depicted in Fig. 1.1a.

Three-point SENB testing was performed on a benchtop load frame. Fracture response of the specimens varied depending on the crack-tip/lamina orientation angle, θ. Vertically printed samples with $\theta = 0°$ displayed inter-laminar fracture and had a load/displacement response consistent with brittle behavior (Fig. 1.2a). Horizontally printed samples with $\theta = 90°$ displayed cross-laminar fracture and had a load/displacement response consistent with ductile behavior (Fig. 1.2a). Obliquely printed samples with $\theta = 75°$ displayed mixed cross- and inter-laminar fracture, resulting in mixed ductile and brittle crack propagation (Fig. 1.2a). Since fracture behavior was inconsistent across sample types, differing methods of fracture analysis were required to determine the samples' fracture toughness. Analysis methods are reserved for further reading in Hart et al. [1]. Results of the fracture toughness analysis reveal that the critical elastic-plastic strain energy release rates for inter-laminar and cross-laminar fracture were 256 ± 84 J/m^2 and 2260 J/m^2, respectively, demonstrating that significantly more energy is required to propagate a crack across the laminae than between them.

This study confirms that the low strength of weld-lines between or among laminae, relative to within a deposited polymer trace, limits the toughness of the overall part. However, the likelihood of catastrophic failure due to fracture in an AM structure can be reduced by considering anticipated stress fields when designing laminae orientations. Naturally orthotropic materials such as wood, bone, and nacre, have all adapted to capitalize on the increased toughness afforded by flaw/laminae alignment to impart global toughness in spite of constituents which may be individually brittle [2–7]. We believe that there exists considerable opportunity to engineer higher performance AM parts by exploiting these design principles to create tailored fracture and failure behaviors.

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J. Wang et al. (eds.), *Mechanics of Additive and Advanced Manufacturing, Volume 9*,
Conference Proceedings of the Society for Experimental Mechanics Series, DOI 10.1007/978-3-319-62834-9_1

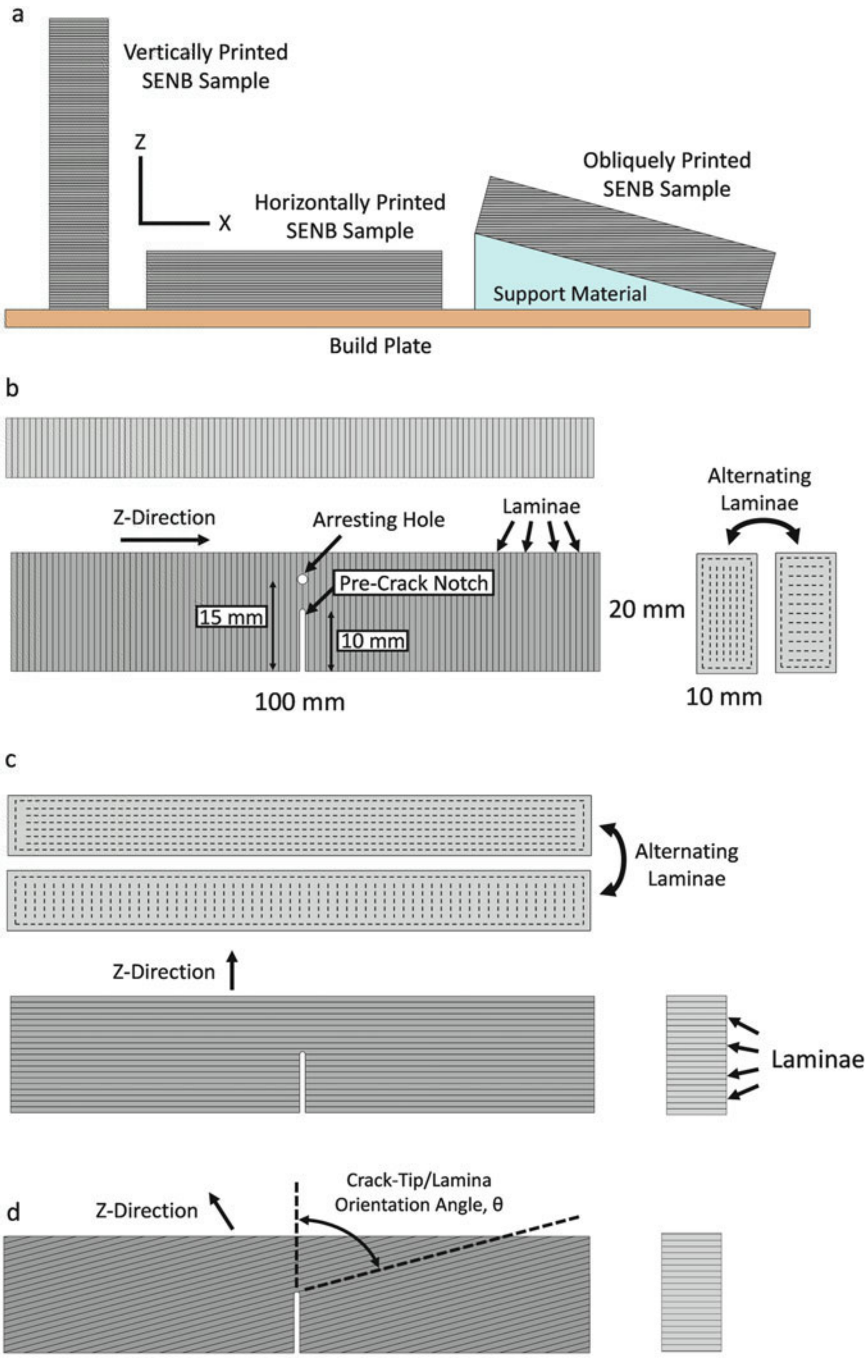

Fig. 1.1 Illustrations of SENB fracture specimens. (**a**) Orientation of vertically, horizontally, and obliquely printed SENB specimens with respect to the build plate. (**b**) Dimensions of a vertically printed SENB sample after removal from the build plate, preparation of the pre-crack, and machining of the arresting hole. Here the laminae run parallel to the pre-crack, facilitating inter-laminar fracture. (**c**) Illustration of a horizontally printed SENB sample after removal from the build plate and preparation of the pre-crack. Here the laminae run perpendicular to the pre-crack, facilitating cross-laminar fracture. (**d**) Illustration of an obliquely printed SENB sample after removal from the build plate and preparation of the pre-crack. Laminae are oriented at an angle of θ with respect to the pre-crack notch. Laminae, pre-crack notches, and raster lines are not to scale. *Dashed lines* indicate position and orientation of weld-lines (not to scale) between deposition traces within each laminae. Image adopted from Hart et al. [1]

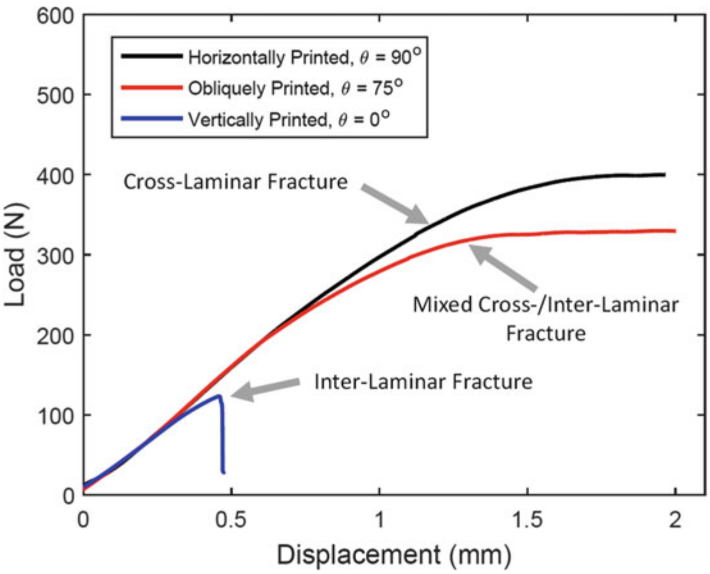

Fig. 1.2 Load vs. displacement curves for SENB specimens with crack-tip/lamina orientation angles of $\theta = 0°$, $\theta = 75°$, and $\theta = 90°$. Vertically printed SENB specimens with $\theta = 0°$ exhibit brittle, inter-laminar fracture. Horizontally printed SENB specimens with $\theta = 90°$ exhibit ductile, cross-laminar fracture. Obliquely printed SENB specimens with $\theta = 75°$ exhibit mixed cross-/inter-laminar fracture behavior. Image adopted from Hart et al. [1]

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Chapter 2
Complex Modulus Variation by Manipulation of Mechanical Test Method and Print Direction

Megan L. Liu, Katherine K. Reichl, and Daniel J. Inman

Abstract 3D printing technologies have made creating prototypes with complex geometries relatively simple thus it has become an increasingly popular method for creating prototypes in a research setting. Therefore, it is crucial to understand the properties of the materials being used. This paper examines the effects of printing direction and testing method type on the complex modulus of viscoelastic materials printed using the Objet Connex 3D Printer from Stratasys. Because of its ability to print multiple materials in a single print job, this printer is a popular choice to create models. Throughout these tests the sample material will be kept constant to isolate the effects of print direction and test performed. DM 8430 is produced by mixing VeroWhitePlus™ and TangoPlus™ in a specific ratio. Since the 3D printer threads and smooths the sample uniaxially, the print direction of the sample can be manipulated by changing the orientation at which the sample is placed on the printer. Two different print directions, that are perpendicular with respect to each other, will be examined. The two test methods that will be used to determine the complex modulus are the Dynamic Mechanical Analysis (DMA) test, which examines the tensile behavior of the material, and the vibrating beam test, which examines the bending behavior. The goal is to gain greater insight into the uncertainty in the complex modulus that results from changing the test and printing direction used to determine this value. This will be done by performing a total of four tests. For each testing method, DMA and vibrating beam, the complex modulus will be found for two samples of different print direction, vertical and horizontal. These results will permit a greater understanding of the amount of variability produced by print direction.

Keywords Additive manufacturing • Complex modulus • Viscoelastic • Passive damping • Dynamic modulus analysis

2.1 Introduction

Additive manufacturing has become increasing popular across almost all engineering fields. The field of interest to the authors is in applications for metastructures to be used for vibration suppression [1, 2]. The specific printer of interest is the Objet Connex printer which is capable of printing rubber-like materials. These materials exhibit viscoelastic properties which is of particular interest for vibration suppression [3]. The purpose of this paper is towards the determination of the viscoelastic properties of the printed materials.

The Object Connex printer uses PolyJet printing technology which works like an inkjet printer. The parts are made by depositing many small dots of material and then curing the resin resulting in an end material that appears homogenous. Because of the digital natural of this method, these materials are referred to as digital materials (DM). This method allows the printer to easily mix two different base materials in various ratios to create a gradient of material with various hardness levels [4]. This method also allows for parts made in a single print with both rigid and viscoelastic materials.

Using this technique and the many base materials available, the Object Connex printer has the capability to create many materials but for this paper the focus will be on the digital materials created using the two base materials, VeroWhitePlus™ and TangoPlus™. VeroWhitePlus™ is a rigid opaque material and TangoPlus™ is a rubber-like transparent material [5]. Using these two base materials, ten different digital materials can be created [6]. The material studied here is DM 8430 which is the third stiffest material. In the field of active composites and origami, H. Jerry Qi has done extensive work using the Objet Connex 3D printer and his papers provide many details the actual mechanisms the 3D printer utilizes [7].

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J. Wang et al. (eds.), *Mechanics of Additive and Advanced Manufacturing, Volume 9*,
Conference Proceedings of the Society for Experimental Mechanics Series, DOI 10.1007/978-3-319-62834-9_2