

DEFINING A FAILURE SURFACE FOR FFF PARTS USING A NOVEL FAILURE CRITERION

Gerardo A. Mazzei Capote

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Approval

The following thesis, **Defining a failure surface for FFF parts using a novel failure criterion**, developed at the **University of Wisconsin-Madison** has been approved by:

Signature

Date

Professor Tim A. Osswald
Department of Mechanical Engineering
College of Engineering
University of Wisconsin-Madison

Abstract

Yada Yada Yada

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Table of Contents

Front Matter	i
Abstract	i
Acknowledgments	ii
Nomenclature	v
List of Figures	vi
List of Tables	vii
Introduction	1
1 Background	3
1.1 Additive Manufacturing	3
1.1.1 Advantages, Disadvantages and Success Stories	4
1.2 Fused Filament Fabrication	6
1.2.1 The FFF process	7
1.2.2 Mechanical Properties of FFF parts	9
1.3 Failure Criteria	10
2 A Novel Failure Criterion	12
2.1 The Gol'denblat-Kopnov Model	12
2.2 The Osswald-Osswald Criterion	15
3 Experimental Methods	19
3.1 Material	19
3.2 Sample Preparation	20
3.2.1 Printing Equipment	20
3.2.2 Tensile Specimens	22
3.2.3 Compressive Specimens	23
3.2.4 Torsion and Combined Loading Specimens	24
3.3 Mechanical Testing	26
3.3.1 Tension and Compression tests	26
3.3.2 Torsion and Combined loading tests	26

Symbols and Acronyms

Acronyms

- μ CT Micro Computer Tomography
 ABS Acrylonitrile Butadiene Styrene
 AM Additive Manufacturing
 CAD Computer Aided Design
 EF Extrusion Factor
 FDM Fused Deposition ModelingTM
 FFF Fused Filament Fabrication
 GKC Gol'denblat-Kopnov Criterion
 OOC Osswald-Osswald Criterion
 RP Rapid Prototyping
 SLA Stereolithography
 SLS Selective Laser Sintering

Symbols

$\dot{\epsilon}$	Engineering Strain rate	min^{-1}
$\dot{\gamma}$	Shear Strain rate	min^{-1}
ϵ	Engineering Strain	
γ	Shear Strain	
μ^{1112}	OOC parameter- slope at pure shear failure in the $\sigma_{11} - \tau_{12}$ plane	—
μ^{2212}	OOC parameter- slope at pure shear failure in the $\sigma_{22} - \tau_{12}$ plane	—

σ	Axial stress	MPa
σ_{11}	Axial stress in the 1-1 direction	MPa
σ_{22}	Axial stress in the 2-2 direction	MPa
σ_{33}	Axial stress in the 3-3 direction	MPa
τ	Shear stress	MPa
τ_{12}	Shear stress in the 1-2 plane	MPa
τ_{13}	Shear stress in the 1-3 plane	MPa
τ_{23}	Shear stress in the 2-3 plane	MPa
S	Shear strength in the 1-2 plane	MPa
S_{45n}	Negative shear strength for 45° specimen	MPa
S_{45p}	Positive shear strength for 45° specimen	MPa
X_c	Compressive strength in the 1-1 direction	MPa
X_t	Tensile strength in the 1-1 direction	MPa
Y_c	Compressive strength in the 2-2 direction	MPa
Y_t	Tensile strength in the 2-2 direction	MPa

List of Figures

1.1	Process flow of AM	3
1.2	Shoes with AM midsoles	6
1.3	The basic FFF machine configuration	7
1.4	Model, toolpath and final part in the FFF process	8
1.5	Typical FFF part mesostructure and its origin	8
1.6	Results from Koch <i>et al.</i> [6]	10
1.7	Comparison of different Failure criteria. [23]	11
2.1	Different load directions in an anisotropic material	13
2.2	GKC failure surface developed using data from the WWFE-1 [21]	15
2.3	μ^{2212} parameter in the $\tau_{12} - \sigma_{22}$ plane	16
2.4	λ^{ijjj} parameters in a generic $\sigma_{ii} - \sigma_{jj}$ stress plane	17
2.5	Comparison of GKC and OOC failure envelopes [21]	18
2.6	Failure surface for SLS developed through the OOC [25]	18
3.1	Extrusion line setup	20
3.2	Printing equipment	21
3.3	Print process in <i>Otto</i>	21
3.4	ASTM D-638 Type I coupon	23
3.5	Toolpath considerations for the tensile coupons	23
3.6	Compression specimen geometry	24
3.7	Representation of compression samples	24
3.8	S_{45} Torsion specimen geometry	25
3.9	S_{45} Representation of the 45° specimen	25
3.10	Mechanical testing setup	27
3.11	Stress and strain caused by torque on a tubular geometry [25]	27
3.12	Machine setup for combined loading scenarios	28

List of Tables

1.1	Advantages and Disadvantages of Additive Manufacturing	5
2.1	Nomenclature of the GKC parameters	14
2.2	Tensorial components of the GKC	14
2.3	Interaction components attainable through the OOC	17
3.1	Mechanical tests required for the OOC	20
3.2	Constant printing parameters	22

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* (FDMTM), 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. Recent studies performed by Koch *et al.* [6] and Rankouhi *et al.* [7] 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. However, literature related to preventing failure through design 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 commonly used failure criteria that make it difficult to develop an accurate failure surface.

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 1. Chapter 2 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.

1 Background

1.1 Additive Manufacturing

Additive Manufacturing (AM) technologies had their beginnings in the decade of the 1980s. During this time, various independently developed patents were filed across the globe, describing a process that would construct an object by selectively adding layers of material -as opposed to removing excess matter or deforming mass to obtain a desired shape. This represents the core definition of AM: any technology where the final geometry of the manufactured object is obtained through controlled addition of material qualifies as an Additive Manufacturing technique [1].

Advancements in the fields of computing, *Computer Aided Design* (CAD), and controllers, among other technological developments, were necessary to translate the patents into working prototypes, with some eventually becoming the foundations of commercially successful companies -such as 3D Systems in 1986 and Stratasys in 1989 [1, 8, 9]. The basic process of AM has remained largely unchanged from its first iteration in the late 80s: First, a computer model of the object is made using CAD software and exported under the *.stl* file format. Afterwards, the part geometry is stratified, or “sliced”, and translated into machine instructions using a specialized software called *slicing engine*. An AM machine then follows said instructions, commonly referred to as the *toolpath*, to build the object in layers. Finally, the part is available to the user. Depending on either the requirements of the part, or the specifics of the AM technique used, some post-processing may be required [1]. A visual representation of the process is shown in Figure 1.1.

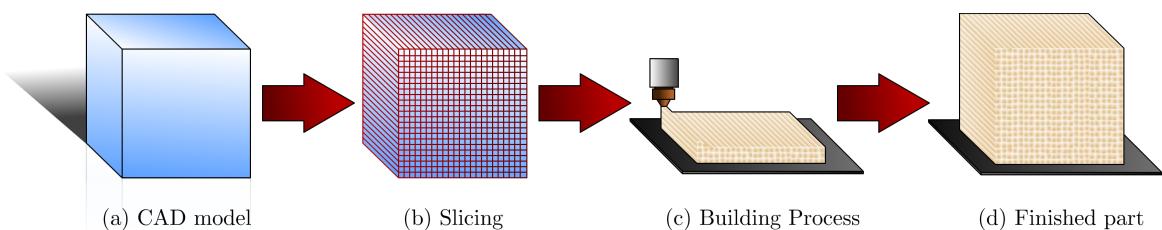


Figure 1.1: Process flow of AM

While all AM technologies operate on the same basic process flow described above, the specifics of each AM technique vary substantially, ranging from processes that use paper and binder, all the way through metal-based, laser tracing technologies. Since this is a rapidly evolving field, no general consensus exists for classifying the multiple AM processes available as of the time of this writing. However, the classification system proposed under the ASTM/ISO 52900 standard [10], has been somewhat accepted by the field and divides AM technologies as follows:

1. **Binder Jetting:** AM techniques where a binding agent is used to selectively promote cohesion in powder materials -generally gypsum, sand or metallic powders [10, 11].
2. **Directed Energy Deposition:** AM processes where a focused thermal energy source (i.e. laser, electron beam, plasma arc) is used to fuse materials as they are being deposited in the build volume. Materials are almost exclusively metals [10, 11].
3. **Material Extrusion:** In this type of AM technology, material is dispensed through a nozzle or orifice. Fused Filament Fabrication belongs to this classification. Materials are almost exclusively thermoplastics [10, 11].
4. **Material Jetting:** AM techniques where build material is deposited selectively in droplets. Materials are usually wax or thermoplastics, but there are examples of metal-based, material jetting techniques [10, 11].
5. **Powder Bed Fusion:** AM processes where portions of a powder bed are selectively fused through application of thermal energy. *Selective Laser Sintering* (SLS) belongs to this category. Materials are usually thermoplastic polymers or metals [10, 11].
6. **Sheet Lamination:** In this type of AM technology, the final part is formed by bonding sheets of material -usually paper or composites [10, 11].
7. **Vat Photopolymerization:** In this AM process, a liquid photopolymer is selectively cured by a light source. *Stereolithography* (SLA), arguably the first AM technology, belongs to this category. Due to the nature of this technique, the only materials used are photopolymers [10, 11].

1.1.1 Advantages, Disadvantages and Success Stories

Since AM processes allow a relatively direct conversion of a CAD model into a constructed object, they were originally exclusively used for prototype development. For this reason, they were initially classified as “*Rapid Prototyping*” (RP) technologies. This terminology is still used today, however, it is being superseded by *Additive Manufacturing* since its potential to become a proper fabrication technique exists [1]. While

being capable of quickly jumping from part design to manufacturing is a great advantage, AM has its own set of drawbacks. Table 1.1 summarizes the most noteworthy set of advantages and disadvantages typical of most AM technologies.

Table 1.1: Advantages and Disadvantages of Additive Manufacturing

Advantages	Disadvantages
Faster product development cycles [1]	Part quality highly dependent on process parameters [1]
No additional tools needed for part fabrication[1]	Stratified build generally results in anisotropic parts [1, 2]
Cost effective for small batches of parts [12, 13, 14]	Costly for production of more than hundreds of parts [12, 13, 14]

Out of all the described advantages and disadvantages, the high anisotropy of AM parts is responsible for the slow embrace of AM in highly demanding engineering fields -such as the aerospace and automotive industries. The highly anisotropic mechanical behavior makes it extremely difficult to predict part failure, therefore, it cannot be implemented in engineering applications where catastrophic failure is to be avoided at all costs. Even so, success stories of implementation of AM in industrial environments are abundant. Below is a number of relatively recent examples:

- **Volkswagen Autoeuropa:** This automotive assembly plant implemented the use of FFF machines to manufacture tools, jigs and fixtures used in their assembly line. They now produce 93% of the tools that were historically externally sourced, and have reportedly cut their tool development time and costs by 95% and 91% respectively [5].
- **General Electric:** GE is currently producing a complex fuel nozzle injector for the LEAP jet engine, using powder based, metal AM. The complex geometry of this component could not be manufactured by any other manufacturing technique. The production plant in Alabama is expected to have 50 AM machines producing 35,000 fuel nozzle injectors annually by 2020 [15].
- **Adidas and New Balance:** Both shoe companies have developed separate approaches to constructing highly optimized, 3D printed midsoles for high performance running sneakers. New Balance makes use of SLS technology to build the intricate geometry of their “*Zante Generate*” sneaker, using powdered TPU elastomer as the parent material. The designed honeycomb structure of the midsole, combined with the flexible material used, is supposed to improve the comfort and support brought by the shoe [16]. Adidas on the other hand chose to develop the “*AlphaEDGE 4D LTD*” running shoe using the CLIP technology by Carbon3D. While the cell geometry in the midsole is also supposed to bring performance and comfort improvements, the final ambition of Adidas is to perfect the technology to a point where a customer can simply go to a shoe store, have their feet

scanned, and receive a fully customized shoe with a 3D printed midsole that fits their particular needs [17, 18]. In both cases, the geometry of the midsole can only be produced by AM. The intricate structures in the midsoles can be seen in Figure 1.2.



Figure 1.2: Shoes with AM midsoles

Note that in the cases presented, the main reason behind the usage of AM was either reduction of expenses associated with producing small batches of parts, or the capability of reproducing a unique and complex geometry. This is a trend that is observed in most of the literature describing implementation of AM into industrial scenarios.

While the advantages and disadvantages described here cover the field of AM as a whole, each technique comes with its own set of pros and cons that may make it the preferred method to reproduce a particular product or geometry. This work, however, focuses solely on FFF. The specifics of this process are described in detail in Section 1.2.

1.2 Fused Filament Fabrication

Fused Filament Fabrication (FFF) is an AM technology where the final geometry of the part is obtained through controlled extrusion of a liquid, self-hardening material—usually a thermoplastic polymer in molten state [1]. Originally developed by Stratasys in the 1980s under the still trademarked *Fused Deposition Modeling* (FDMTM) moniker, it has recently become one of the most widely used AM techniques due to the advent of low-cost, desktop FFF machines in the early 2010s caused by the expiration of key patents from Stratasys [1, 2].

1.2.1 The FFF process

At its core, the typical FFF machine consists of a heated build surface commonly referred to as a *build plate*, a specialized tool known as a *printhead*, and the fabrication material -supplied in the form of spools of thermoplastic polymer filament. The printhead is itself composed of a heating element, a nozzle, and some form of driving mechanism that pushes the filament downward. As the thermoplastic material is moved through the heated chamber, polymer melt is formed and extruded through the opening at the tip of the nozzle, producing a *bead*. The molten polymer can then be deposited upon the build plate, where controlled movements of the printhead and the fabrication surface gradually construct the final geometry of the part in a layer-by-layer build approach [1]. The typical setup of an FFF machine can be seen in Figure 1.3. In this example, the printhead moves in the *x-y* plane, while the build plate moves in the *z* direction.



Figure 1.3: The basic FFF machine configuration

Like all AM technologies, the FFF process starts in a computer with a CAD model converted to the *.stl* file format. The geometry is then translated to machine instructions through a *slicing engine*, where the user inputs a plethora of process parameters that include nozzle and build plate temperatures, print speed, layer thickness, and build orientation. Finally the *toolpath* is executed by the FFF printer, building the object in a layer-by-layer basis – sometimes referred to as *2.5D* printing [1, 4]. Figure 1.4 shows an abridged version of the process. The *z* axis indicates the intended build direction. Note how some of the finer details in the original CAD file are lost in the printed part – due in part to the layer height and build orientation selected.



Figure 1.4: Model, toolpath and final part in the FFF process

The process is capable of producing complex geometries that would be otherwise hard to reproduce through other polymer processing techniques, such as injection molding. However, it is bound by the disadvantages described in Section 1.1.1, as well its own unique set of drawbacks. Namely:

- The circular orifice in the nozzle makes FFF incapable of reproducing sharp corners, limits the size of the smallest reproducible feature, and causes the final part to be filled with voids –originating in the junction of round beads. These problems can be seen in Figure 1.5: On the left, a comparison of a 90° corner planned in the toolpath and the final geometry of the printed bead is shown. Note the rounded nature of the turn. On the right, a cross section of an FFF part obtained through *Micro Computer Tomography* (μ CT) shows the voids that form during the printing process.

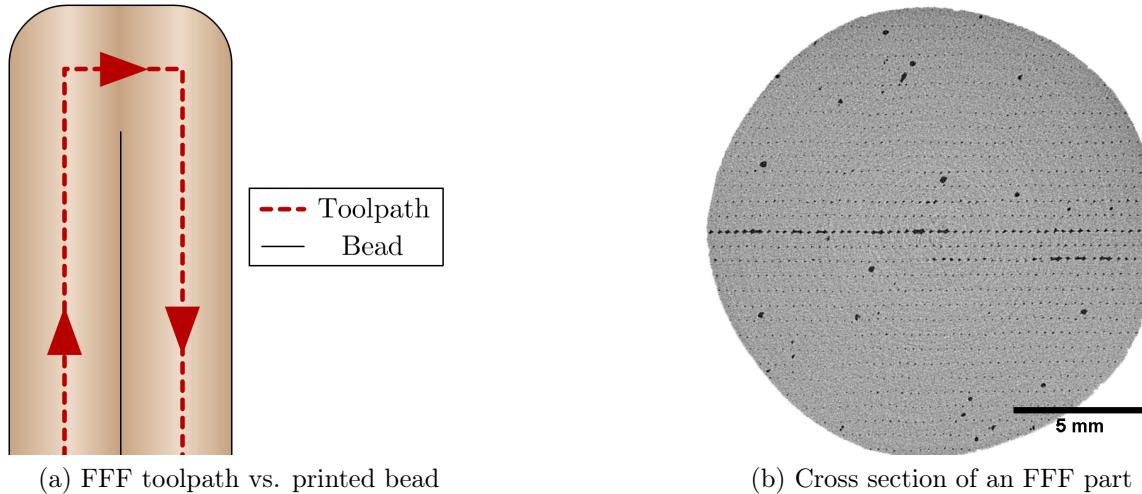


Figure 1.5: Typical FFF part mesostructure and its origin

- The junction of adjacent beads behaves akin to a polymeric weld, and has inferior mechanical properties than the bulk material [2]. This, coupled with the aforementioned voids which can act as stress concentrators, causes FFF parts

to behave in extremely anisotropic manner with diminished mechanical performance when compared to analogous parts obtained through traditional polymer processing technologies – such as injection molding [2].

This last disadvantage is responsible for the slow embrace of FFF as a proper manufacturing technique: the high anisotropy of FFF parts imply that predicting part failure becomes extremely difficult and thus, proper part design that guarantees safe operation of the object under important loads is hard to achieve. For this reason, efforts to characterize the mechanical behavior of FFF parts have existed since as early as the 1990s. Recent examples are presented in Section 1.2.2.

1.2.2 Mechanical Properties of FFF parts

Efforts have been made to characterize the mechanical anisotropy of FFF parts. However, due to the lack of testing standards and problems during toolpath planning, most studies focus solely in the tensile mechanical performance of FFF coupons.

Recent studies performed by Koch *et al.* [6] and Rankouhi *et al.* [7] indicate that the final tensile properties of FFF coupons are particularly sensitive to bead orientation and proper mass output through the nozzle. Other process parameters, such as the layer thickness, have varying degrees of impact upon the final tensile strength of the part. In both studies, tensile coupons were printed with bead orientations of 0° , 45° and 90° in the x - y plane. Results showed that in all the experimental conditions selected, a 0° orientation always behaved closer to the bulk material, whereas a 90° sample always had significantly lower tensile strengths. The 45° samples sat between both extremes. It is important to note that in both studies, toolpath manipulation was necessary to avoid premature failure of the coupons due to stress concentrators originating in void formation due to the elliptical nature of the beads. Figure 1.6 shows some of the results by Koch *et al.* The geometry corresponds to an ASTM Type I Tensile coupon. Injection molded results are denoted *IM* for comparison. Note that the 90° orientation had a tensile strength that was 25% inferior to the IM counterpart, and 20% worse than the 0° oriented FFF coupon. This is a prevalent trend in the consulted bibliography.

Literature for other types of mechanical testing of FFF parts is relatively scarce when compared to tension experiments. Research indicates that the compressive strength of FFF parts tends to be higher than the tensile strength, as well as being less sensitive to process parameters —the bead orientation in particular seems to have a significantly diminished impact upon the compressive strength when compared to its effect upon tensile tests [19, 20]. Shear strength results are virtually non-existent.

Figure 1.6: Results from Koch *et al.* [6]

1.3 Failure Criteria

The increased use of advanced materials in industry has brought upon a necessity to properly characterize their strengths and failure modes. Composites in particular are commonly used in highly demanding engineering fields given that they excel in mechanical properties. However, due to their nature, their behavior is extremely anisotropic. For this reason, it has been of great interest to develop a proper way to model the behavior of anisotropic materials under mechanical stresses as a way to predict part failure – a practice from here on referred to as developing a *failure criterion*.

Early attempts to properly predict failure of anisotropic materials go as far back as 1948 with the Hill model [21]. Further developments led to a plethora of failure criteria, such as the Tsai-Hill, Malmeister, Tsai-Wu, Gol'denblat-Kopnov, Puck, and Cuntze to name a few [21, 22]. A wide variety of criteria exists because a model will rarely capture the complete failure behavior of an anisotropic material. To illustrate this point, refer to Figure 1.7, reproduced from work by Sun *et al.* [23] where a composite glass fiber and epoxy laminate was loaded biaxially, in a direction that was either parallel (σ_{11}), perpendicular (σ_{22}) to the fiber, or a combination of both. Positive stresses indicate tensile load, while negative values point to compressive forces. The data, represented by the white squares, does not agree with any of the used models in the fourth quadrant of the graph. This type of behavior is common throughout the literature: Puck's model is great at predicting shear strengthening effects, but doesn't perform well when dealing with combined axial loading scenarios; the Gol'denblat-Kopnov model by contrast is great at predicting axial stress interactions, but falls short when dealing with shear strengthening effects caused by combined shear-axial loadings. These trends point to the limitations of each model: in order to either facilitate calculations, or due to the difficulty of performing combined loading tests, interaction effects are neglected either

by mathematical choice, or indirectly through the inner workings of the failure criterion [21].

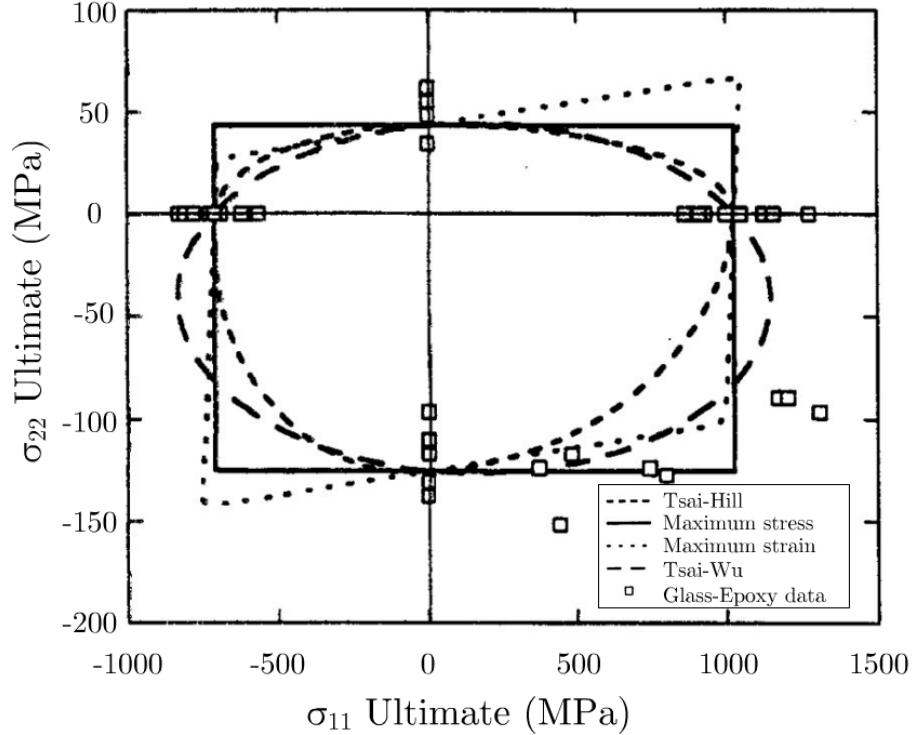


Figure 1.7: Comparison of different Failure criteria. [23]

Properly mapping a failure surface through a criterion proves to be an invaluable tool for design, since it allows engineers to assess if a part will perform safely under its intended loading conditions. Such tool could in theory help overcome the main shortcoming of FFF since a properly tailored failure envelope would allow proper part design considerations. However, since no present criterion completely captures the behavior of anisotropic materials, a novel technique is needed. Chapter 2 describes in detail a novel approach, based on the Gol'denblat-Kopnov model, that includes interaction effects to properly describe the failure behavior of anisotropic parts.

2 A Novel Failure Criterion

The Osswald² criterion

As described during Section 1.3 of Chapter 1, currently available failure criteria fail to completely integrate interaction effects into the modeled failure behavior of anisotropic materials. In 2017, Paul and Tim Osswald proposed a model that attempts to overcome these limitations [21]. This recent failure criterion has the following characteristics:

- **Tensor based and purely mathematical:** as opposed to phenomenological or mechanistic models such as the Puck or Cuntze failure criteria.
- **Based on the Gol'denblat-Kopnov model.**
- **Includes stress interactions that other models neglect.**

Originally titled “A Strength Tensor Based Failure Criterion with Stress Interactions”, it will be referred in this work as the Osswald-Osswald Criterion (OOC). This chapter will describe the Gol'denblat-Kopnov model upon which the OOC is based, followed by a proper description of how this novel model implements stress interactions.

2.1 The Gol'denblat-Kopnov Model

The Gol'denblat-Kopnov Criterion (GKC) describes a mathematical function that depends on the stress state of an anisotropic material. Should the computation of this expression exceed a threshold, part failure is to be expected. To that end, a scalar function that depends on stress tensors that completely characterize the state of the material was developed [24]. This function is shown in Equation 2.1, where stresses are denoted σ , and the subindices i,j,k,l denote a particular load direction.

$$f = (F_{ij}\sigma_{ij})^\alpha + (F_{ijkl}\sigma_{ij}\sigma_{kl})^\beta + (F_{ijklmn}\sigma_{ij}\sigma_{kl}\sigma_{mn})^\gamma + \dots \quad (2.1)$$

The terms F_{ij} , F_{ijkl} and F_{ijklmn} represent second, fourth and sixth order tensors respectively. These terms of the equation depend on engineering strength parameters, such as the ultimate tensile and compressive strengths of the material in a particular load direction [21]. Due to the complexity associated with using higher order tensors, Gol'denblat and Kopnov limited their approach to using only the second and fourth order terms. Thus Equation 2.1 is reduced to:

$$f = (F_{ij}\sigma_{ij})^\alpha + (F_{ijkl}\sigma_{ij}\sigma_{kl})^\beta \quad (2.2)$$

In order to attain a linear criterion scalar function, the exponents α and β were assigned values of 1 and 1/2 respectively. Finally, in plain stress scenarios, the GKC becomes:

$$\begin{aligned} f = F_{11}\sigma_{11} + F_{22}\sigma_{22} + F_{12}\tau_{12} + & (F_{1111}\sigma_{11}^2 + F_{2222}\sigma_{22}^2 + F_{1212}\tau_{12}^2 \\ & + 2F_{1122}\sigma_{11}\sigma_{22} + 2F_{1112}\sigma_{11}\tau_{12} + 2F_{2212}\sigma_{22}\tau_{12})^{1/2} \end{aligned} \quad (2.3)$$

Note that in Equation 2.3 σ and τ denote normal and shear stresses respectively. Figure 2.1 depicts an anisotropic material and all the possible loading directions for reference.



Figure 2.1: Different load directions in an anisotropic material

Per Gol'denblat and Kopnov's design, should the computation of f in Equation 2.3 be greater or equal to 1, part failure is to be expected. However, to simplify calculations, they deliberately assumed the interaction terms F_{1112} and F_{2212} to be zero. This is an important consideration that will come into play when describing the OOC.

Most of the terms in the GKC are obtained through mechanical testing of coupons under pure uniaxial loads in the 1 or 2 direction, or pure shear in the 1-2 plane [21]. In these scenarios, f will be equal to 1 at failure, and the stress state will be known to the user, allowing some of the unknown tensorial parameters to be easily calculated. Using F_{11} and F_{1111} as examples, the process would be as follows:

1. The tensile and compressive strength in the 1-1 direction would be obtained through mechanical testing. These values are named X_t and X_c respectively.
2. Under these failure conditions, Equation 2.3 is reduced to the following system of equations:

$$\begin{cases} +1 = F_{11}X_t + (F_{1111}X_t^2)^{1/2} \\ +1 = -F_{11}X_c + (F_{1111}X_c^2)^{1/2} \end{cases}$$

3. F_{11} and F_{1111} can be obtained, yielding $F_{11} = \frac{1}{2}(\frac{1}{X_t} - \frac{1}{X_c})$ and $F_{1111} = \frac{1}{4}(\frac{1}{X_t} + \frac{1}{X_c})^2$.

The only exception to this procedure would be the F_{1122} component, which requires measuring the positive and negative shear strengths of a coupon with reinforcement oriented in 45° . These parameters are named S_{45p} and S_{45n} respectively. Table 2.1 summarizes the nomenclature used for the strength parameters required to completely populate the failure function of the GKC. Table 2.2 summarizes all the tensorial component calculations.

Table 2.1: Nomenclature of the GKC parameters

Parameter	Description
X_t	Tensile strength in the 1-1 direction
X_c	Compressive strength in the 1-1 direction
Y_t	Tensile strength in the 2-2 direction
Y_c	Compressive strength in the 2-2 direction
S_{45p}	Positive shear strength for 45° specimen
S_{45n}	Negative shear strength for 45° specimen
S	Shear strength in the 1-2 plane

Table 2.2: Tensorial components of the GKC

Component	Formula
F_{11}	$\frac{1}{2}(\frac{1}{X_t} - \frac{1}{X_c})$
F_{1111}	$\frac{1}{4}(\frac{1}{X_t} + \frac{1}{X_c})^2$
F_{22}	$\frac{1}{2}(\frac{1}{Y_t} - \frac{1}{Y_c})$
F_{2222}	$\frac{1}{4}(\frac{1}{Y_t} + \frac{1}{Y_c})^2$
F_{12}	0
F_{1212}	$\frac{1}{S^2}$
F_{1122}	$\frac{1}{8}[(\frac{1}{X_t} + \frac{1}{X_c})^2 + (\frac{1}{Y_t} + \frac{1}{Y_c})^2 - (\frac{1}{S_{45p}} + \frac{1}{S_{45n}})^2]$

2.2 The Osswald-Osswald Criterion

One of the assumptions made in the GKC is that the components F_{1112} and F_{2212} in Equation 2.3 are null. While this simplifies the model, it essentially neglects any interactions between axial loads and shear stresses, namely, the σ_{11} - τ_{12} and σ_{22} - τ_{12} interactions. Practically, this causes the failure surface developed through the GKC to under predict shear strengthening effects exhibited by anisotropic materials loaded in combined axial and shear conditions. Figure 2.2 shows a comparison between experimental data obtained from the first World Wide Failure Exercise (WWFE-I) and the GKC envelope developed for this material. In this example, a unidirectional glass reinforced epoxy composite was tested in multiple loading conditions in the σ_{22} and τ_{12} stress plane. White circles indicate average values for pure uniaxial or shear scenarios. Note how on the first quadrant, the model follows the data closely. However, in the second quadrant, the criterion is relatively conservative, failing to capture the strengthening that occurs when loading the material in compression and shear.

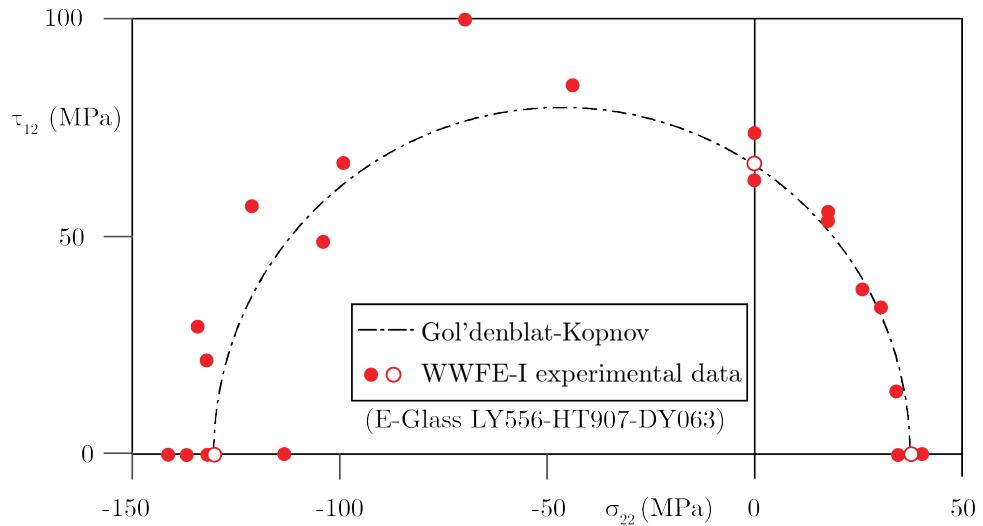


Figure 2.2: GKC failure surface developed using data from the WWFE-1 [21]

The Osswald-Osswald Criterion (OOC) attempts to overcome these limitations by building upon the GKC. For the OOC, the interaction effects are captured through the use of the slopes of the failure surface at any of the points where the engineering strength is known within a particular stress plane [21]. In this failure scenario, the stress state of the coupon is known and easy to implement into Equation 2.3, where $f = 1$. The resulting expression can then be derived with respect to one of the stresses, allowing for the interaction components to be calculated. This is better illustrated through an example. Assuming the component of interest is F_{2212} , the procedure to calculate it through the OOC would be as follows:

1. Obtain all the tensorial components possible through the GKC.
2. Using the $\sigma_{22}-\tau_{12}$ stress plane, derive Equation 2.3 as a function of σ_{22} in the scenario of failure under pure shear ($f = 1$). This yields the expression:

$$0 = F_{22} + [F_{1212}S(\frac{d\tau_{12}}{d\sigma_{22}}) + F_{2212}S] \quad (2.4)$$

where $\frac{d\tau_{12}}{d\sigma_{22}}$ is the slope of the graph at failure under shear. This term is named μ^{2212} in the OOC and can be obtained by performing combined loading tests. Refer to Figure 2.3 for a visual representation.

3. Rearranging Equation 2.4 to solve for the unknown F_{2212} gives the following expression:

$$F_{2212} = -\frac{F_{22}}{S} - F_{1212}\mu^{2212} \quad (2.5)$$

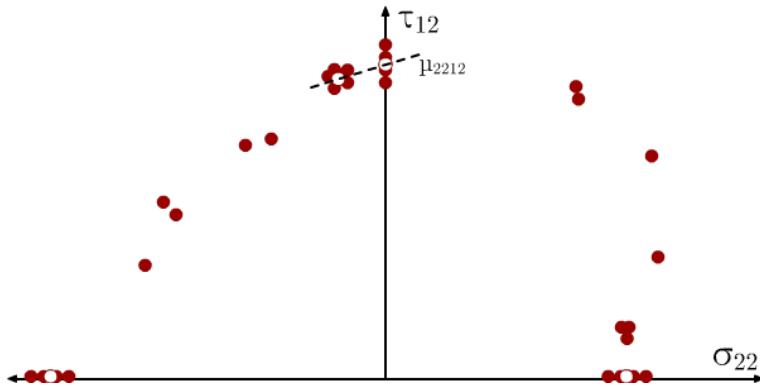


Figure 2.3: μ^{2212} parameter in the τ_{12} - σ_{22} plane

A similar procedure can be followed for any $\sigma_{ii}-\tau_{ij}$ interaction, or even any $\sigma_{ii}-\sigma_{jj}$ components. For this last scenario, the user has four potential choices of slopes to determine the tensorial component of interest. In the OOC, any slope obtained from a $\sigma_{ii}-\sigma_{jj}$ stress plane is named λ^{iijj} , as opposed to μ^{iiji} for slopes in a $\sigma_{ii}-\tau_{ij}$ reference. A schematic of all possible λ^{iijj} is shown in Figure 2.4, while Table 2.3 summarizes all the possible interaction factors available through the OOC, where τ_{ij}^u denotes ultimate shear strength in a particular shear plane.

Figure 2.4: λ^{iijj} parameters in a generic σ_{ii} - σ_{jj} stress plane

Table 2.3: Interaction components attainable through the OOC

Component	Formula
F_{iiji}	$-\frac{F_{ii}}{\tau_{ij}^u} - F_{ijij}\mu^{iiji}$
F_{iiji} through λ_1^{iijj}	$-\frac{(F_{ii} + F_{jj}\lambda_1^{iijj})F_{iiji}^{1/2} + F_{iiji}}{\lambda_1^{iijj}}$
F_{iiji} through λ_2^{iijj}	$-(F_{ii} + F_{jj}\lambda_2^{iijj})F_{jiji}^{1/2} - F_{jiji}\lambda_2^{iijj}$
F_{iiji} through λ_3^{iijj}	$\frac{(F_{ii} + F_{jj}\lambda_3^{iijj})F_{iiji}^{1/2} - F_{iiji}}{\lambda_3^{iijj}}$
F_{iiji} through λ_4^{iijj}	$(F_{ii} + F_{jj}\lambda_4^{iijj})F_{jiji}^{1/2} - F_{jiji}\lambda_4^{iijj}$

Applying the OOC to the data shown in Figure 2.2 demonstrates how the failure surface developed through this new criterion better reflects the failure behavior than its GKC counterpart. A comparison between the two can be seen in Figure 2.5. Note how the OOC envelope captures the shear strengthening effect that the GKC under-predicts.

The OOC offers a way of capturing in a more accurate manner the different failure modes of parts produced through AM technologies. As an example, the model has been

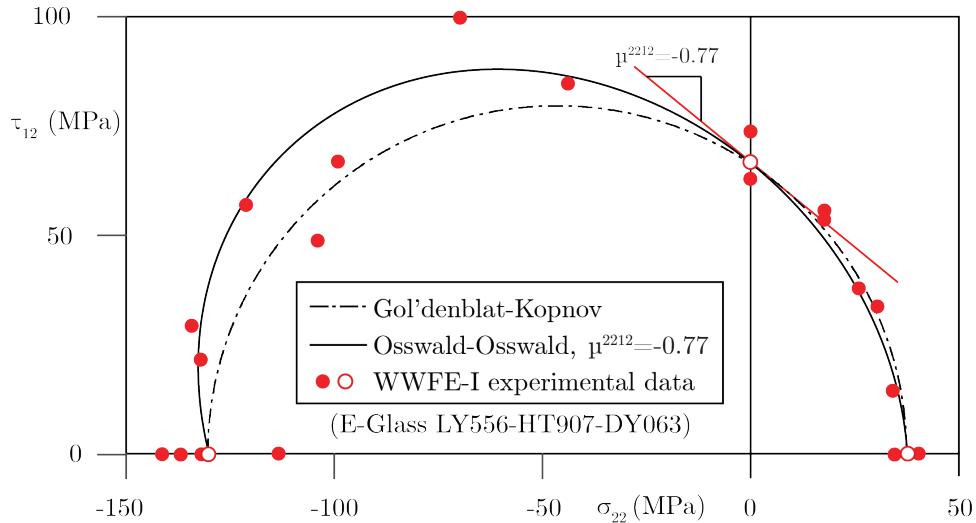


Figure 2.5: Comparison of GKC and OOC failure envelopes [21]

successfully implemented by Obst *et al.* in 2018 for SLS manufactured parts produced with PA12 [25, 26]. Their results show how the model was able to capture the τ_{12} - σ_{22} and σ_{11} - σ_{22} interactions. The failure surface obtained is shown in Figure 2.6.

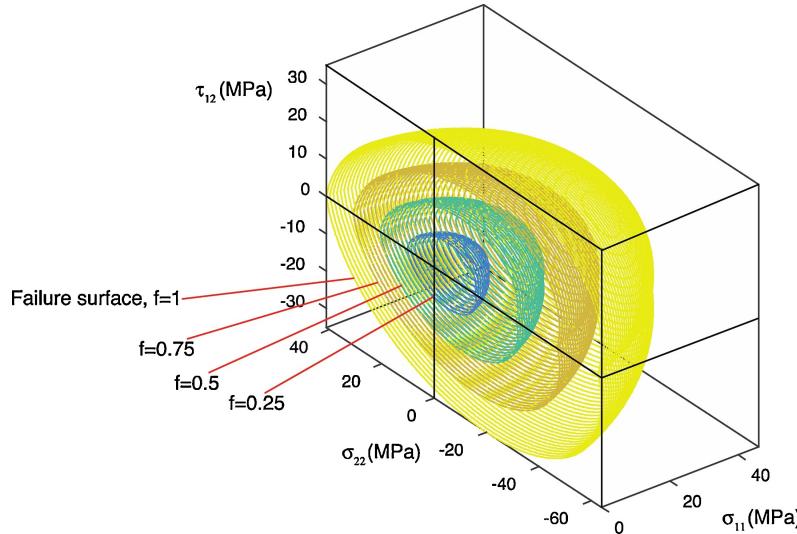


Figure 2.6: Failure surface for SLS developed through the OOC [25]

This work will apply the OOC to FFF, in the hopes that it becomes a tool for safely designing parts intended to be manufactured through this process. Chapter 3 will detail the material and experimental methods used to achieve this goal.

3 Experimental Methods

3.1 Material

The first step of the experimental work involved development of a custom thermoplastic filament for the FFF process. The reasoning behind this decision was two-fold. First, the use of an off the shelf, commercial thermoplastic filament generally does not guarantee that two different spools were produced under the same processing conditions—or even using the same parent material. Secondly, the results from Koch *et al.* [6] show that fluctuations in the filament diameter have an impact in the mechanical properties of FFF parts due to improper volumetric output at the nozzle.

The CyclocacTM MG94 material produced by SABIC was chosen for this work. This is an Acrylonitrile Butadiene Styrene (ABS) based material traditionally used for injection molding thin walled parts, as well as extrusion of FFF filament. With a reported Melt Flow Index of 11.7 g/10 min, it is an ideal material for both the FFF and extrusion processes. The MG94 was extruded in a setup that consisted of a single screw extruder (Extrudex EDN 45X30D, Germany) with 45 mm screw diameter and L/D ratio of 30D. The hot melt was extruded at 205 °C through a circular die with a 5.8 mm diameter, and then guided through a pre-skinner into a vacuum-assisted, heated water bath (Conair, USA) to cool the extrudate whilst minimizing void formation. The solidified filament was then passed through a 3-axis laser micrometer (LaserLinc, USA) and a belt puller (Conair, USA) configured in a control loop. The dimensions of the filament were controlled by automatically adjusting the speed of the puller if the readings from the micrometer were out of specification—in this case a diameter of 2.85 mm with a tolerance of ± 0.02 mm. Finally, the product was wound onto spools using a filament winder. A schematic of the extrusion setup can be seen in Figure 3.1. Prior to any usage in a printer, the filament was dried in a silo (Novatec, USA) at 82 °C for 3 hours.



Figure 3.1: Extrusion line setup

3.2 Sample Preparation

As explained in Chapter 2, the OOC requires mechanical tests to obtain the multiple tensorial components of the mathematical function that describes part failure. Table 3.1 summarizes the tests required.

Table 3.1: Mechanical tests required for the OOC

Mechanical Test	OOC parameters obtained
Tensile	X_t, Y_t
Compressive	X_c, Y_c
Torsion	S, S_{45p}, S_{45n}
Combined loading	μ^{1112}, μ^{2212}

Given that at the moment of this writing AM testing standards are still in development, custom specimen geometries had to be created in order to test certain loading conditions. Additionally, some bead orientations required are difficult or impossible to reproduce through 2.5-D FFF. Therefore, the use of a customized robotic, off-axis FFF printer was necessary. This section will detail the coupon geometries used to perform all the mechanical tests described in Table 3.1, as well as the printing equipment, and toolpath considerations necessary to properly arrange the printed beads in the desired orientation for each condition.

3.2.1 Printing Equipment

Specimens were produced using either a commercially available desktop FFF printer (Lulzbot TAZ5, USA), or a customized 6-axis robotic printing solution whenever the bead orientation was hard to achieve using a 2.5-D machine. The robotic printer, developed in the Polymer Engineering Center and nicknamed *Otto* [4], was based on a 6-axis robot (ABB IRB-120, Switzerland) and fitted with a stationary printhead mounted on an aluminum frame, chosen to be the same extruder from the traditional printer (LulzBot TAZ Single Extruder Tool Head v2, 0.5 mm nozzle, USA) to minimize machine influence on the results. The printing equipment can be seen in Figure 3.2.

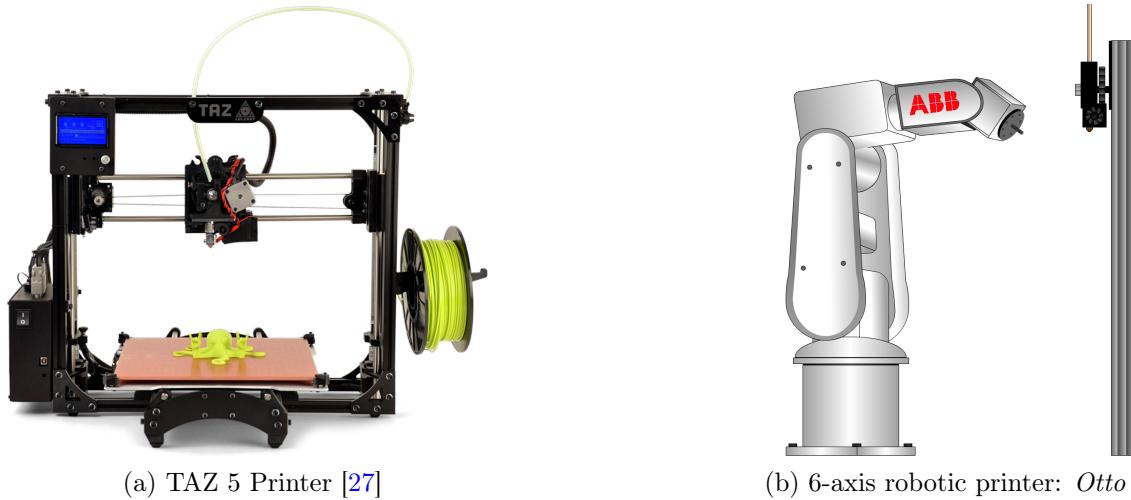


Figure 3.2: Printing equipment

The 6-axis robotic printer's layout is optimized to produce objects of cylindrical nature. A specialized base plate is attached to the sixth axis of the robot, where a threaded rod allows the attachment of disposable plastic cylinders that acts as a build surface. A cylindrical core can then be built by *Otto*, upon which beads in any orientation can be deposited after the robot reorients its joints. Refer to Figure 3.3 for a representation of the process. The left side shows the core being produced atop the disposable build surface, followed by the right hand side, where beads are being laid upon the core in a 45° angle.

Figure 3.3: Print process in *Otto*

Since printing parameters in FFF are known to impact in varying degrees the mechanical performance of objects manufactured through this technology, a conscious effort was made to keep as many processing parameters as possible constant. Table 3.2 summarizes these values.

Table 3.2: Constant printing parameters

Printing Parameter	Value
Nozzle temperature	220°C
Bed temperature ^a	100°C
Printing Speed	2000 $\frac{mm}{min}$
Layer height	0.2 mm
Path width	0.5 mm
Extrusion Factor	1

Extrusion Factor (EF) refers to a ratio of the area occupied by the cross section of a bead (A_{bead}) divided by the product of the bead width (W_{bead}) with the layer height (H_{layer}). This factor is used to calculate the length of filament (L_{fil}) necessary to produce a bead of known length (L_{bead}) as shown in Equations 3.1 and 3.2. The cross sectional area of the filament (A_{fil}) is known through the filament diameter used by the printer.

$$EF = \frac{A_{bead}}{W_{bead} \times H_{layer}} \quad (3.1)$$

$$\frac{L_{fil}}{L_{bead}} \times A_{fil} = EF \times W_{bead} \times H_{layer} \quad (3.2)$$

3.2.2 Tensile Specimens

Tensile coupons were manufactured on the TAZ5, with bead orientations of 0° and 90° with respect to the load direction in order to test X_t and Y_t respectively. The chosen geometry was the ASTM D-638 Type I coupon [28] which can be seen in Figure 3.4. The toolpath required to produce these samples was developed through *SciSlice*, a customized slicing engine created in the Polymer Engineering Center that allows layer-by-layer and part-by-part controls of crucial process parameters —such as the bead orientation—making it ideal for research in the field of FFF [29].

^aApplicable only to prints performed on the traditional FFF printer.

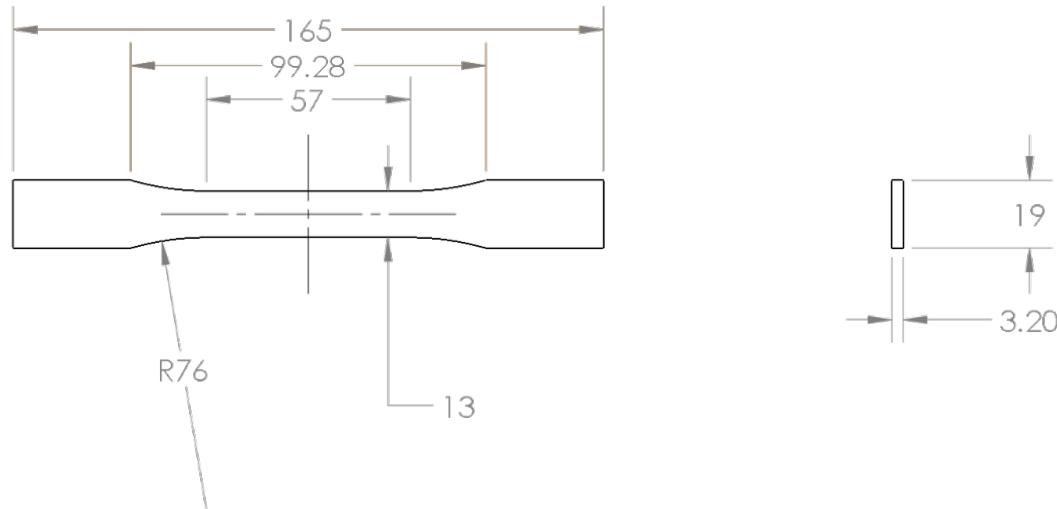


Figure 3.4: ASTM D-638 Type I coupon

In order to minimize stress concentrators due to printing discontinuities, the 0° specimens were printed using 13 perimeters, also known as *shells*. This produced a continuous toolpath with beads oriented in the loading direction at the neck section of the specimen. No shells were added to the 90° samples. Refer to Figure 3.5 for a visual representation of the coupons.

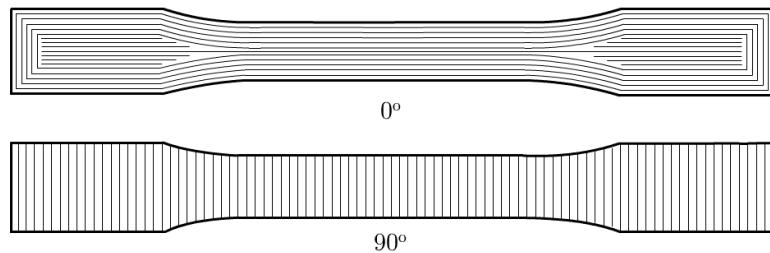


Figure 3.5: Toolpath considerations for the tensile coupons

3.2.3 Compressive Specimens

Compressive samples were designed with a tubular cross section. This geometry was chosen to mitigate hydrostatic stresses that could artificially increase the compressive strength of the sample if it were made as a completely solid object. Additionally, the cylindrical geometry allowed production of the 0° samples in *Otto*. The geometry can be seen in Figure 3.6.

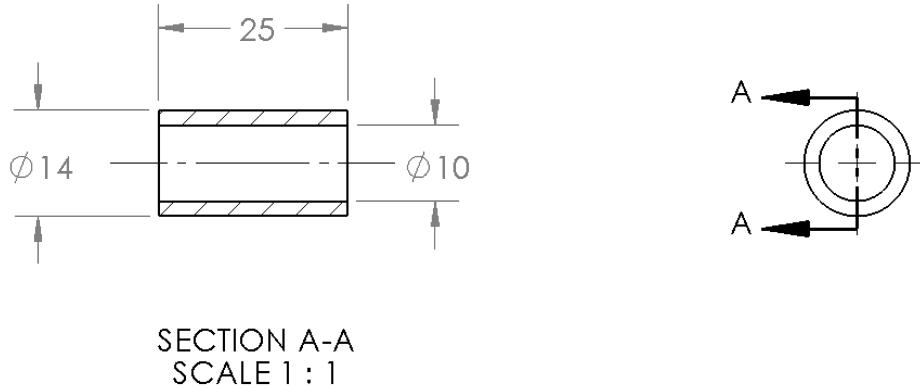


Figure 3.6: Compression specimen geometry

Compression samples with a bead orientation of 90° with respect to the loading direction were produced using the TAZ5 and *SciSlice*. The coupons with a bead orientation of 0° with respect to the loading direction were made using *Otto* and a customized *Python* script that converted process parameters into instructions for the robotic arm through ABB's *RAPID* toolpathing language. A visual representation of the specimens can be seen in Figure 3.7.

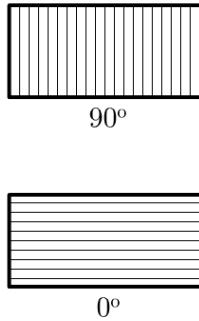


Figure 3.7: Representation of compression samples

3.2.4 Torsion and Combined Loading Specimens

The geometry of the torsion specimens was loosely based in the EN ISO 3167, Type A specimens used by Obst *et al.* [25]. The cross sectional area of the testing area was chosen to be the same as for the compression specimens. This geometry was chosen since its tubular arrangement allows easy integration with the 6-axis robotic printer, as well as offering axisymmetry and reduction of the risk of artificially increasing the strength of the sample due to yielding restrictions associated with using a completely

solid coupon [25]. However, due to toolpathing complications, more than one torsion geometry was necessary. Each one is described in detail below.

45° torsion samples

To test the $\sigma_{11}-\sigma_{22}$ interaction, a torsion sample with beads oriented in 45° was necessary. The geometry, which can be seen in Figure 3.8, consists of a specimen of cylindrical nature, with a filleted, widening change in cross sectional area that culminates in a gripping section. In this portion, three flat surfaces are added to ensure proper contact with the grips of the torsion machine.

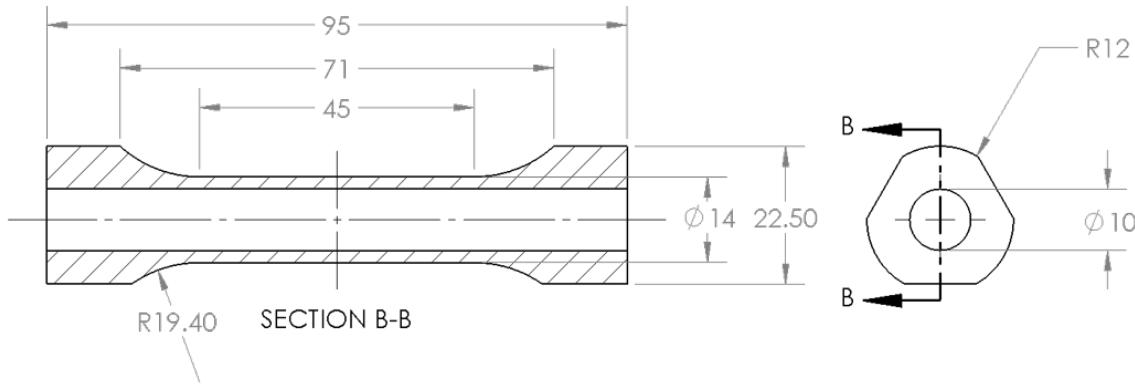


Figure 3.8: S_{45} Torsion specimen geometry

The manufacturing of this type of specimen through *Otto* involved laying 10 layers of beads in a 45° angle atop a cylindrical core of 10 mm in diameter and 95 mm in height. Finally, the gripping section is added using beads in alternating ±45° orientations, culminating in a wider area with a diameter of 24 mm. The flat areas had to be machined in post processing by producing cuts of 1.5 mm in depth in the grips, separated by 120°. A visual representation of the finished sample can be seen in Figure 3.9. Note that the disposable build surface (visible on the left side of the figure) becomes a part of the coupon without impacting the gage section of the sample. All toolpath was generated using a customized *Python* script that converted process parameters into instructions for the robotic arm.

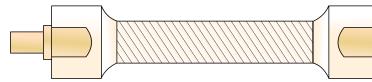


Figure 3.9: S_{45} Representation of the 45° specimen

0° and 90° torsion samples

For the 0° and 90° bead orientations, a specimen redesign was necessary due to tool-pathing problems. Specifically, the length of the 45° torsion specimens proved problematic to print using 0° and 90° orientations, each for different reasons. In the case of the 0° orientation, the long and unidirectional travel distance of each bead introduced considerable tool pressure on the core, causing bowing. This was significant enough to cause poor adhesion of the beads towards the end of the specimen. By contrast, the 90° samples caused the sixth axis of the robot to heat up considerably and to almost completely maximize its range.

The modified torsion sample was redesigned to have the same cross sectional area as the original 45° torsion samples, but shorter length. An optimal distance was devised through multiple print trials where the length of the specimen was varied between 95 and 50 mm. The final chosen geometry is shown below in Figure ???.

3.3 Mechanical Testing

3.3.1 Tension and Compression tests

Tensile and compressive tests were performed with an Instron 5967 Dual Column Universal testing machine, using a 30 kN load cell. All data acquisition was handled through the accompanying Instron Bluehill 3 software. A movement speed of 5 mm/min was used to deform the tensile specimens, while a testing speed of 2.5 mm/min was used in the compression samples. These testing speeds, combined with the sample dimensions, ensured a strain rate of 0.1 min⁻¹ across both specimen types.

The tensile specimens were tested using clamp grips and an extensometer. To protect the samples from excessive gripping force, emery cloth tabs were used, as described by Mazzei Capote *et al* [2]. Figure 3.10 shows a photograph of the setup.

3.3.2 Torsion and Combined loading tests

All torsion tests were performed using an ADMET eXpert 9618 torsion machine fitted with an MTEST Quattro controller and software suite. The machine sits on a rail system that allows the sample to deform freely during testing. The equipment has two adjustable jaws, with three contact surfaces that holds the sample in place, as shown in Figure 3.10. Of the two jaws, one rotates as controlled by a servomotor, while the other is fixed in terms of angular movement.

A conscious effort was made to maintain the same strain rate of 0.1 min⁻¹ used for the tensile and compression tests. The approach used was the same described by Obst *et al.* [25]. The initial assumption is that the shear strain rate ($\dot{\gamma}$) is twice the engineering strain rate ($\dot{\epsilon}$), as shown in Equation 3.3.

$$\dot{\gamma} = 2 \times \dot{\epsilon} \quad (3.3)$$

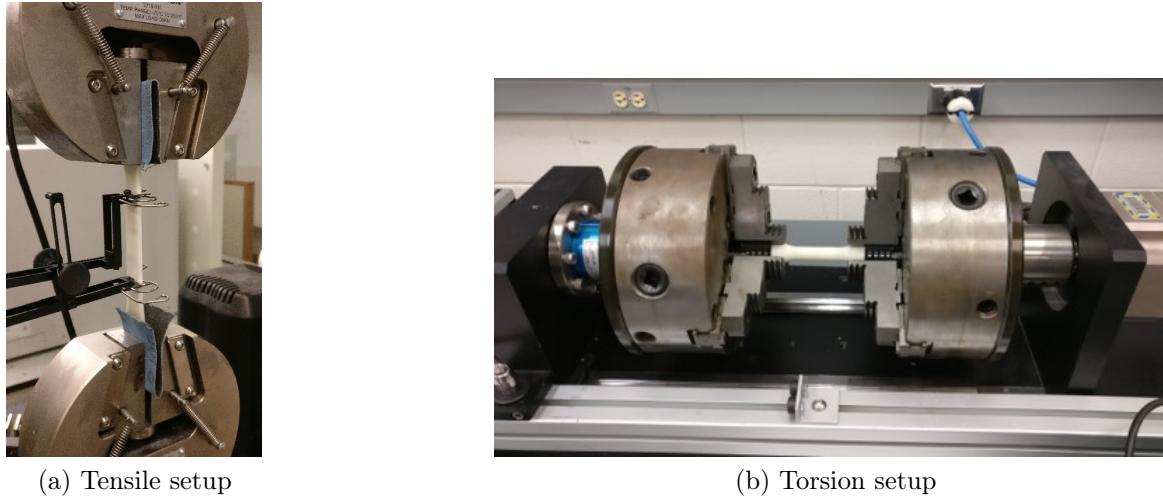


Figure 3.10: Mechanical testing setup

Figure 3.11 represents a tubular element of outer radius ρ and length L , subjected to a torque T . Using this image as reference, one can see that if point B is fixed in space —as is the case of the stationary jaw of the torsion machine used throughout this work—point A will deform to position A'. The angle of twist Φ can then be approximated using the arc length AA' as $AA' = \rho \times \Phi$ for small values of shear strain γ . It can also be seen in Figure 3.11 that the relationship $AA' = L \times \gamma$ also exists. From this, Equation 3.4 can be obtained.

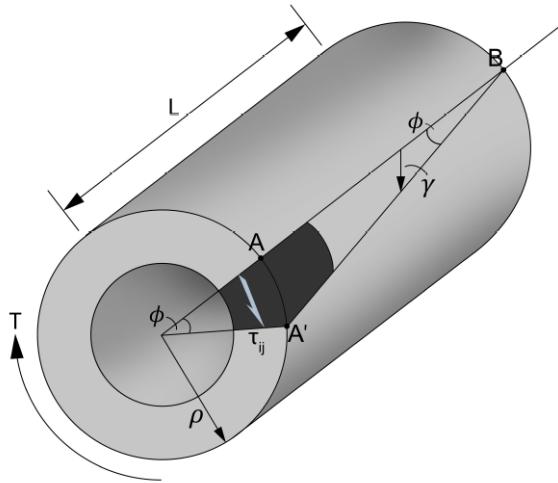


Figure 3.11: Stress and strain caused by torque on a tubular geometry [25]

$$L \times \gamma = \rho \times \Phi \quad (3.4)$$

Finally, after rearranging and deriving with respect to time, Equation 3.5 is obtained.

$$\dot{\Phi} = \frac{L \times \dot{\gamma}}{\rho} \quad (3.5)$$

For this work, $\dot{\gamma}$ is known to be $2 \times 0.1 \text{ min}^{-1} = 0.2 \text{ min}^{-1}$, as dictated by Equation 3.3 and the testing conditions chosen for the tensile and compressive tests. In the case of the 45° specimens, preliminary tests performed in positive torsion showed an average outer radius of 6.91 mm and a mean length of failure propagation of 54 mm. Using these values in Equation 3.5 yields a rotational speed of 1.56 rad/min, or $89.4^\circ/\text{min}$. Following a similar procedure for the 0° and 90° samples, the angular speed of the torsion test was calculated to be ???.

In the case of combined loading scenarios, the setup was fitted with a pulley system that allowed a weight to pull the sample in a nominal direction, while the torsion machine applied shear stresses. Refer to Figure 3.12 for a visual representation of the compressive and tensile force setup of the torsion machine.

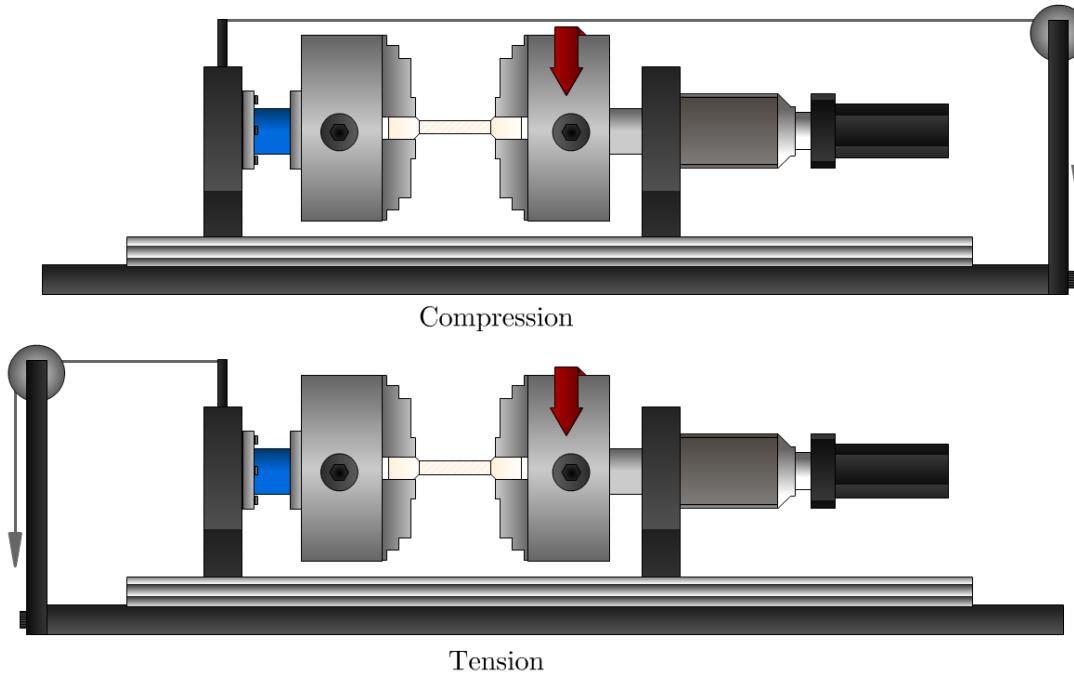


Figure 3.12: Machine setup for combined loading scenarios

The shear stress from the torsion tests was obtained through Equation 3.6, where τ_{ij} , R , T , and J_z represent the shear stress in the ij plane, the outer radius of the sample, the Torque applied, and the second moment of area respectively.

$$\tau_{ij} = \frac{T \times R}{J_z} \quad (3.6)$$

For this case, the second moment of area is defined as described in Equation 3.7, where r represents the inner radius of the tubular specimen.

$$J_z = \frac{\pi \times (R^4 - r^4)}{2} \quad (3.7)$$

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