ME 5385 Metal Additive Manufacturing Final Report

Comparison of properties and performance of topologically optimized additively manufactured components.

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References, Methods	Results	Introduction, Conclusion	Methods	Discussion

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1. Introduction

Topological optimization (TO) has recently made significant advancements due to the increasing viability of metal additive manufacturing (MAM) as a manufacturing technique [1-3]. Previously, TO was limited by conventional manufacturing processes which could not fabricate designs which were too organic with non-traditional shapes. This would require a manual step between TO and fabrication to normalize the structure and create machinable features from the TO model [4,5]. However, this step eliminated much of the weight reduction and stiffness advantages which the TO model possessed.

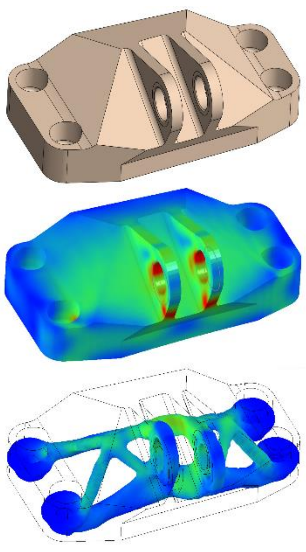

Figure 1. A bracket redesigned using density-based topology optimization.

Recent advancements in MAM have enabled the generation of complex, optimized structures which would be impossible to fabricate with conventional techniques [6]. Layer by layer fabrication techniques such as laser powder bed fusion (L-PBF) enable fabrication of non-solid internal structures and features which can be exploited to create topologically optimized designs with improved mechanical performance at a fraction of the weight of non-optimized parts. Optimization of internal structure can be tailored to focused improvements on stiffness, strength, weight, or manufacturing cost depending on application. Conventional finite element analysis (FEA) software such as ANSYS are able to quickly optimize a given design based on optimization variable and loading constraints, greatly reducing the number of iterations previously needed in human designs [7-9].

Although MAM is able to fabricate TO structures with much less constraint on part geometry, there are new challenges present in the process that pose current limitations to use of such parts in critical applications [1,2]. One main limitation is the absence of TO software that is optimized for AM construction. Although some progress has been made in this regard, significant pre-fabrication processing is still needed to manually ensure successful fabrication and removal of support structure. Additionally, while less limited by geometry, MAM components, including TO components, generally possess characteristics such as high surface roughness (Ra), porosity, and residual stress which must be dealt with in post-processing to improve fatigue life [10].

In our investigation, we will analyze the effects of TO in AM on weight reduction and mechanical performance. Specifically, we will design and fabricate optimized and standard specimens for a bending test and compare their performance correlated with their mass.

2. Methods

2.1. CAD modelling for mechanical testing

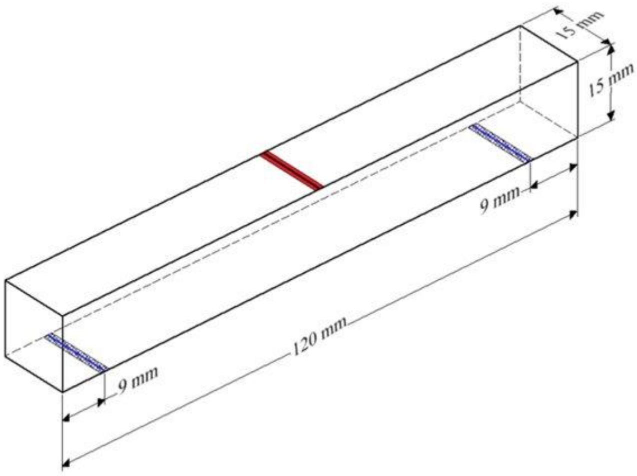

Figure 2. Analytical drawing of 3-point bending test sample without topological optimization.

Demonstration of the capabilities of topology optimization were analyzed using a rectangular beam in a three-point bending test. The beam was constructed in SOLIDWORKS CAD software and was printed solid with 100% infill using an Ultimaker S3 3D printer. PLA was selected for material due to availability and accessibility of material properties. All samples were printed on the same printer in the same orientation using identical process parameters to ensure comparability.

Table 1. Important print parameters

Parameter	Value	Units
Material	PLA	
Nozzle Temperature	200	ºC
Bed Temperature	60	ºC
Bed Surface	Glass	
Print Speed	70	mm/s
Infill Density and Orientation	100%, Horizontal	
Infill Pattern	Zig Zag	
Layer Height	0.15	mm

2.2. Density-based topology optimization for weight reduction

The original beam design was imported into ANSYS topology optimization software. The

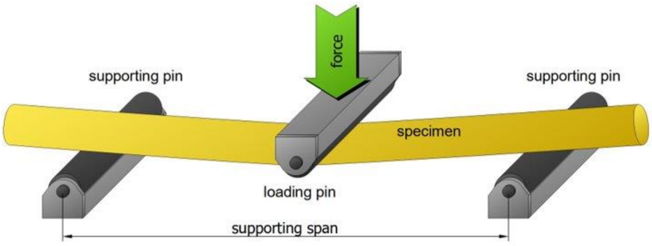

Figure 3. 3-point bend test setup with supports and load location specified.

model was constrained as shown in Figure 2 and the software was instructed to reduce weight while maintaining performance of the component in the specific test shown. The optimized model was reviewed to ensure printability. The optimized model were printed in the same conditions as the original specimen.

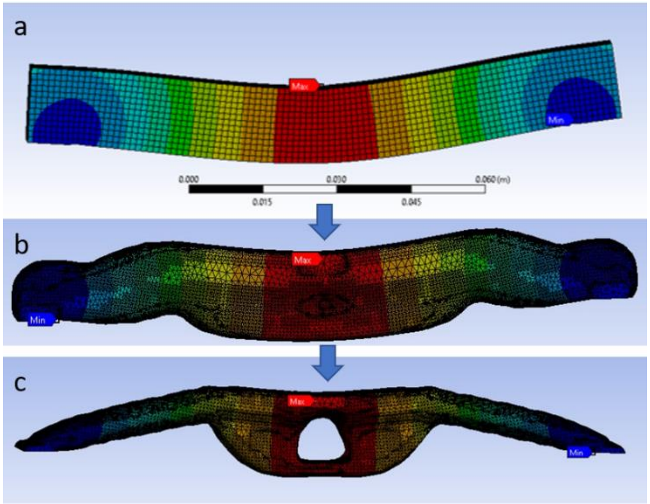

Figure 4. ANSYS TO Process with loading on (a) original specimen, (b) 25% weight reduction specimen and ; (c) 70% weight reduction specimen.

2.3. Experimental comparison of as-built and optimized designs

To compare the performance of the as-built and optimized beam designs, a three point bending test was performed as shown in Figure 3. Maximum applied load was measured for each experiment and compared to the measured weight of each sample. Three identical

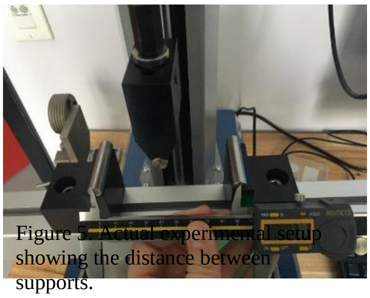

Figure 5. Actual experimental setup showing the distance between supports.

samples for each configuration were tested and the results were averaged.

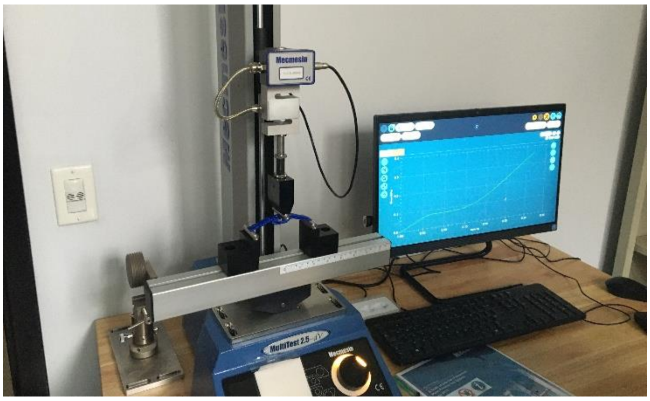

Figure 6. Example test setup with output stress versus strain graph for the TO 30% volume fraction specimen.

3. Results & Discussion

3.1. Experimental specimen testing

Before the three-point bending test, each sample was weighed to determine average weight reduction due to TO. It was found that the TO design reduced weight from 31.1 grams for the fully solid part to 22.1 and 9.1 grams for the 2 different topology optimized designs. Print time was also compared to reflect time-cost savings. Print time for the TO designs were 25% faster for the 75% volume fraction part and 55% faster for the 30% volume fraction component. Average material usage decreased according to the volume fraction with the 30% part requiring 3.4 m of filament compared to 12.0 m needed for the original specimen.

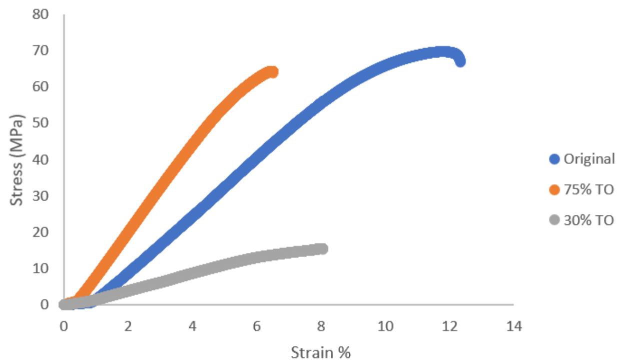

Figure 7. Engineering Stress-Strain curves for all three test samples. These graphs do not give the true stress as it was difficult to determine cross-sectional area of TO parts.

The topology optimized parts did not perform as well as expected in the 3 point bending tests. Baseline data for the control part was difficult to get because the part was too strong for the testing frame. The testing frame is designed for thin, primarily plastic specimens, and therefore has a maximum force of only 2500N. When tested to failure, the specimen broke at 2615N, with the machine failing to automatically stop at its maximum force value. Given the violent breaking of the part once it finally did break, combined with fear of damaging the machine, the lab monitor assisting with the tests ruled that no further tests could be done with the control specimens. The machine going past its rated limit, combined with only having a single data point for

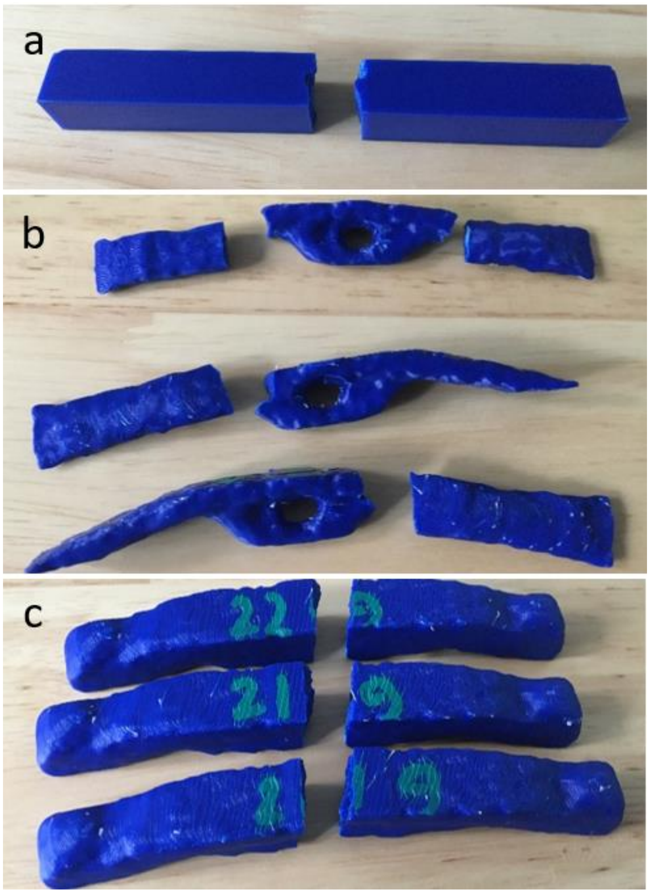

Figure 8. Fracture results for (a) Original, un-optimized specimen (b) 30% volume fraction TO specimen and (c) 75% volume fraction TO specimen.

this test, makes it difficult to entirely trust the baseline results.

After testing the baseline sample, the three 75% TO parts were tested and the three 30% TO parts were tested. Each of the parts were tested to failure with the same three-point bending setup. The 75% TO parts had an average yield strength of 1573N, while the 30% parts had an average yield strength of 430N. The 75% parts had an average maximum strain of .059, while the 30%

parts had an average strain of .09. The maximum strain of the control part was .049.

Table 2. Comparison of predicted and actual stress and deflection at 50 N.

ANSYS Simulation	Value	Units
Original Stress	5.27	MPa
Original Deflection	0.7	µm
75% Stress	15.1	MPa
75% Deflection	0.3	µm
30% Stress	11.0	MPa
30% Deflection	0.5	µm
Experimental	Value	Units
Original Stress	1.3	MPa
Original Deflection	0.4	mm
75% Stress	2.02	MPa
75% Deflection	0.5	mm
30% Stress	1.35	MPa
30% Deflection	0.4	Mm

It is of note that one of the 30% TO parts fractured into three pieces rather than the expected two pieces. The 2 exterior arms that broke off are nearly identical, each weighing 2.2 grams. This helps to show that the tests were self-consistent, as a force applied exactly in the center of the beam is the only way it would fracture so evenly. From the graphs of the tested samples, we can see they deformed primarily plasticly due to the long linear section of their stress-strain curves. This makes sense and provides some confidence in the data. However, there were some unexpected results. As is expected, the maximum stress and strain are progressively higher on each graph. Unfortunately, the properties of the topology optimized samples were not impressive.

Table 3. Strength to weight ratio.

Specimen	S/W ratio
Control	84.09
75% TO	71.30
30% TO	47.27

3.2: Comparison of ANSYS and Experimental Results

Comparison of our experimental results and our ANSYS simulation was done at the applied force of 50 N since that was the used in the simulation. Table 3 summarizes the maximum deflection and stress at this loading condition. It was found that the agreement between our simulated an experimental values was not generally good with variation between 75% and 750% in stress comparison and deflection varying by several orders of magnitude. This vast discrepancy was most likely caused by several factors including the time interval selected for the simulation and the selection of material properties which will be discussed in the following section.

3.3: Discussion

There are several possible causes for why the topology optimized parts did not perform significantly better than the regular part. One of the likely causes is the material properties used in the simulation. The simulation used material properties of solid PLA. A more accurate simulation should be run with the material properties calculated by first testing a control sample and evaluating the material properties based on that control sample. Factors like layer delamination and differences in PLA properties could play a factor in this.

Another potential source of error is the amount of force the parts were simulated with in ANSYS. When the models for the TO parts were created, they were created with only 50 N of force applied, instead of applying force till failure. This may have resulted in parts that are optimized only for 50 N of force. During the testing, force over 400 N were applied to fracture the 30% TO parts and force over 1500 N for the 75% TO part. Additionally, during simulation, a simulated time interval of one second was used which did not allow for the specimen to reach steady state through stress-relaxation which is an inherent feature of many polymers such as PLA. Future topology optimizations should make sure to failure instead of to a limited force value an allow for the proper amount of time needed to reach stead state.

The ANSYS optimization was also limited in its exploitation of the inherent advantages of AM. Due to time constraints, our team did not investigate the optimization of the internal geometry, or infill, of our samples which would have more effectively showcased the advantage of AM coupled with TO.

A further limitation of the current testing was that of the 3-point bending apparatus which had a maximum loading limit of 2500 N which was exceeded by our unaltered test specimen. This limited the number of tests we could achieve for the original specimen. In future testing, investigation of reduction of the infill percentage may allow for more complete comparison.

4. Conclusion

Our study was able to show that reduction in weight AM components with maintenance of loading requirements is possible with TO. However, more precise input, focused on material properties, and internal structure, is needed to achieve a desired performance outcome. The finding of our study can be summarized by refollowing:

- ANSYS TO was effectively able to eliminate the desired volume fraction for our designs.
- Consideration of material properties, desired performance values need to be incorporated in TO optimization.
- True stress and strain values would more effectively relate strength to weight ratios and may show that TO designs are advantageous.
- Consideration of internal structure optimization is a critical advantage of AM overlooked in this investigation.

Our team concluded that with proper analysis and comparison o true stress and strain values, TO and AM could be shown to offer significant advantage over conventional manufacturing techniques.

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