Determining the Effect on Yield Strength of Acrylonitrile Butadiene Styrene through the inclusion of Chopped Carbon Fibre.

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Additive Manufacturing (AM) technology offers significant opportunities to industry, having the capability to rapidly manufacture components of complex geometries. Acrylonitrile Butadiene Styrene (ABS) is a common thermopolymer used in the AM process of Fusion Deposition Modelling. There is a significant interest in increasing the strength of AM parts. One way of doing this is to modify the material composition of the plastics currently used in manufacture. Using chopped Carbon Fibre (CF) within the matrix of ABS is one way which is being investigated to improve the mechanical properties of ABS components. This project identifies that the inclusion of chopped CF particles within ABS reduces the yield stress of the material. However, additional testing needs to be conducted to ensure that all test data can be validated and verified against existing results.

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1 SBLT, School of Engineering & Information Technology. ZEIT4500.
Nomenclature

3D = Three-Dimensional
ABS = Acrylonitrile Butadiene Styrene
AM = Additive Manufacturing
CAD = Computer Aided Design
CF = Carbon Fibre
FDM = Fusion Deposition Modelling
STL = Stereolithography
TS = Tensile Strength
YS = Yield Strength

I. Introduction

ABS is a common thermopolymer used in the AM process of FDM, otherwise known as 3D printing. The desire to improve some material properties of ABS exists within the market. One of these properties is the YS. Currently, methods for improving the strength of ABS require complicated printing techniques such as lamination with other products, or design of parts to allow for additional materials to be added within a component. CF is a common form of reinforcement used in a variety of materials including many composites and plastics. However, this regularly comes on the form of continuous fibres throughout the material. This report aims to identify whether chopped CF filaments can improve the material properties of ABS from FDM. It will do this by conducting testing of CF-ABS components and ABS components to determine if a significant difference in the material properties exists in either.

II. Project Scope

The project scope entails determining the difference between ABS and CF-ABS. this is broken into 3 separate tasks. Task 1 is determining the YS of filament through tensile testing. Task 2 is to determine the tensile strength of printed components in accordance with reference 1. Task 3 is to analyse the results from the experiments to obtain a meaningful conclusion. In addition to this, the project also offers suggestions for future work which could be conducted within this area. The project does not discuss in depth other material properties of the tested materials other than YS.

III. Project Aim

The aim of this project is to assess whether chopped CF reinforcement increases the yield stress of ABS plastic, in addition to observing any other material characteristics from testing. The project does this by assessing the mechanical behaviour of each material against existing data for the material. In addition to this, it will analyse the effect the printing process has on the strength of each material.

Figure 1 - Project Flow
IV. Literature Review

A. Background

AM was first conceptualised by J.E. Blanther in 1892 when he created a layered approach to form topographical maps [2]. This first concept outlined impressing topographical contours onto a series of plates. The stacking of these plates would allow for a 3D surface to be created. This initial use of layered objects to create a larger item is the first patented idea to suggest that layered stacking of objects could be utilised to create larger whole items.

The other important concept which lead towards creating AM technology was the photo sculpture created by François Willème in 1860. This sculpture was created to prove that an exact 3D replica of an object could be created by taking multiple photos of it from various angles as shown in Figure 2. To do this, Willème placed a subject in a circular room and mounted 24 cameras at equal distances throughout the room. These cameras took a simultaneous image of the subject allowing an artist to create a 3D sculpture of the subject.

Both initial ideas have allowed for the modern process of AM to exist. The layered approach allows for parts to be created in increments, and the 3D imaging allows digital images of desired parts to be converted into real objects.

B. Additive Manufacturing Process

The total AM process is comprised of 8 basic steps, which each contribute towards the manufacture of a complete part [3]:

1. CAD: parts are created within a digital format. In this condition, any desired geometries can be created.

2. STL convert: STL was created to allows the conversion of geometric surfaces into a triangular mesh which can be interpreted by the AM device [4]. This step is critical to allow AM methods to be created with the desired accuracy of the digital model.

3. File transfer to machine: the file is converted to a format the AM machine can interpret to allow it to create the part.

4. Machine Setup: the machine setup is a crucial part of the AM process as it

Figure 1 - Blanther’ Layered Approach [2]  Figure 2 - Willème’s Sculpture [2]
determines the accuracy and cost of the component to be produced.

5. Build: the building of the component is the step which takes the most time. Although for most AM machines this entire section is fully automated.

6. Removal: once the part has been completed, it must be removed from its foundations. Depending on the type of AM machine used, this process can either be quite simple or complex.

7. Postprocessing: this process is highly dependent on the required quality of the chosen part. For plastic parts, postprocessing requirements are often minimal.

8. Application: the final step of the AM process is to place the parts into use. They might still require additional treatment such as lubrication or a surface such as paint to be applied dependant on their application.

FDM fits within this process, as a method to rapidly manufacture components of complex geometry from extruded materials.

C. Fusion Deposition Modelling

The FDM process builds components in a series of layers similar to Blanther’s approach to layering topological maps. The FDM process uses a filament in an extrusion process to create layers of consistent thickness in the required geometry. The material becomes bonded to the layer, instantly hardening allowing for more material to be added on top of it, in another layer [5]. Figure 3 shows how a typical FDM system is setup to allow for material deposition.

Within this, the feed rate, layer thickness and print temperature can all be configured to print a part of desired resolution using different materials. The feed rate and print temperature need to be precisely controlled to ensure that they conform to the required parameters as determined by the material type. If the print temperature is too low it can lead to a lack of bonding between layers. Contrariwise, if the print is too hot, it might boil causing defects within the final product. The feed rate within the printer must be kept at a constant rate to ensure that the amount of material deposited in each layer is consistent. A low feed rate will result in a starved filament reducing layer thickness and can cause the filament to break. A high feed rate can cause bending between the feed rollers and heating element, which can induce stress within the filament. As shown in figure 4, the feed rate for different layer thicknesses and materials needs to be carefully selected ensuring that the filament does not experience any unnecessary stress.

D. Uses of Additives within Additive Manufacturing

AM processes have the capacity to utilise a series of additives including metals, ceramics and fibres. These can be included as laminates, unidirectional or random fibres, weaves and as particles. The use of additives within AM is done to improve certain material properties such as tensile stress, elasticity, conductivity and thermal resistance [5]. A lot of research on continuous fibres within AM processes has already been conducted. Typically, continuous fibres are used to improve the tensile stress in a material. Less research has been conducted in the field of chopped fibre reinforcement. However chopped fibres have the potential to reduce the difficulty of manufacture for AM components. The ability to include chopped fibres within the material and treat the material as homogenous allows for components to be manufactured in standard methods such as FDM without an extra allocation for post processing.

E. Material Properties of ABS

The material properties of ABS need to be identified to ensure that obtained results can be correlated with existing data. ABS has a YS between 18.5-51 MPa [6]. With the YS of ABS listed as 36.4MPa for the standard chosen for experimental procedure [1]. The wide change in strength comes from a variety of factors including small changes in the chemical composition and manufacture process. ABS is manufactured by emulsion which
combines styrene and acrylonitrile monomers to a container containing polybutadiene. This creates small rubber like particles typically of size 0.05-1 µm in diameter [7]. These particles are then compressed at high temperatures of 180°C into 2mm isotropic sheets. The manufacture of ABS plastic is based on this process which already has the possibility to include defects within the material. This is why ABS has such a wide range of strengths depending on how it was manufactured. The addition of CF particles to create CF-ABS is conducted after the ABS plastic has already been developed. The inclusion of CF into an already unpredictable material creates additional possibility for the inclusion of defects. This means the strength of CF-ABS could exhibit over a wider band than ABS components. Therefore it is recommended in future manufacture of CF-ABS components that the mixture is made in one process to limit the chance of defects within the material. It is also possible to produce ABS from a process known as continuous mass polymerisation. This process creates particles with higher strength in their internal structure. However, it is rare so difficult to find manufacturers who utilise this method for large scale production.

Since testing is being conducted in accordance with reference 1, the expected yield stress for chosen ABS is anticipated at 36.4MPa. The value of tensile yield stress for CF-ABS is not quoted in any references the author was able to locate. In addition to this, the author was unable to find any literature for the bond strength between ABS and CF, meaning any results to be obtained from experimental procedure can not be verified against existing data.

V. Experimental Procedure

A. Filament Testing
The filament supplied by the manufactured for ABS and CF-ABS is supplied at 1.75mm diameter. The cross sectional area of the entire length of filament was consistent on measurement. To determine if the addition of CF within ABS has any effect on its material properties, the filament can be tested. To conduct this testing filament is loaded into a Shimadzu tension test machine capable of determining the required force to cause catastrophic failure of the samples. The machine is calibrated and compliant with International Standards and ASTM standards. ABS and CF-ABS samples were tested at a rate of 5mm/minute, with a gauge length of 100mm to determine if a significant difference in TS occurred in either sample. It should be noted that the change in cross sectional area of the filament will affect the results of the TS stress of each type of material. However, the purpose of the tests is to determine a difference between the material types, not the exact data for each material. Since both materials are being tested under the same conditions, the reduction in cross sectional area of the filament at the jaws is unideal. However, the results produced still help in giving a comparison

It should be noted that the filament is not naturally straight, which causes it to exhibit some pre-stress upon straightening. The required stress to straighten the samples is also negligible when compared to their YS, thus making the straightening of the samples have a small impact on the overall YS.

B. Printed Component Testing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Diameter</td>
<td>0.4mm</td>
</tr>
<tr>
<td>Extrusion Width</td>
<td>0.4mm</td>
</tr>
<tr>
<td>Layer Height</td>
<td>0.1mm</td>
</tr>
<tr>
<td>Print Speed</td>
<td>50mm/s</td>
</tr>
<tr>
<td>Temperature</td>
<td>255°C</td>
</tr>
</tbody>
</table>

Final Project Report 2018, UNSW Canberra at ADFA
To validate the results from filament testing, components were printed from both ABS and CF-ABS materials. These components were printed at two different orientations, alternating layers perpendicularly within the print between 0° and 90° degrees and ±45°. The change in layer orientation is used to test the failure mode of the sample. Composite laminate theory is used to compare how the print direction affects the strength of components. There are three modes of failure for which composites can fail [8]:

Mode 1: refers to failure parallel to the printing direction, in either the CF or ABS.
Mode 2: refers to shear failure of the matrix resulting from large shear stress acting across the fibres. Within FDM parts, this is considered as failure between the fibres.
Mode 3: refers to failure perpendicular to the printing direction, in either CF or ABS.

Within the design of the components the 0°-90° samples are used to test failure mode 1 and 3, while the ±45° sample is used to check for shear failure. All samples were printed flat on the bed of the 3D printer, meaning that no supports were required within the printing process. The geometry of the samples to be tested was created to be type 1B specimens in accordance with reference 1. The only modification to the sample geometry was to add extra length to the tabs to ensure no slippage in testing. The alternation of the layers was required, as the printing process is unable to create unidirectional materials. The layers need to orientate perpendicularly to ensure that they the plastic bonds properly between the layers. This prevents weakness in any one direction. In addition to this, the change in orientation could be used to determine if any significant difference in fibre orientation occurred due to the printing process. As the fibre geometry is unknown, this was unable to be examined in the current test procedure. However, this could be conducted in future work.

The exact geometry of the components is shown in figure XX, this is designed to ensure that all samples break within the gauge length of 60mm through the thin section of the material. Although all samples are desired to be printed at the exact same geometry factors such as thermal shrinkage and inaccuracy of printing causes the parts to all be slightly different. Therefore, each component must have its gauge width and thickness measured accurately prior to testing to ensure that accurate tensile stress values are calculated for each.

**Figure 7 - Design Geometry of Printed Component**

<table>
<thead>
<tr>
<th>Sample</th>
<th>YS CF-ABS [MPa]</th>
<th>YS ABS [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.6</td>
<td>39.0</td>
</tr>
<tr>
<td>2</td>
<td>27.6</td>
<td>40.7</td>
</tr>
<tr>
<td>3</td>
<td>29.6</td>
<td>40.0</td>
</tr>
<tr>
<td>4</td>
<td>28.5</td>
<td>40.0</td>
</tr>
<tr>
<td>5</td>
<td>28.4</td>
<td>39.8</td>
</tr>
<tr>
<td>6</td>
<td>28.1</td>
<td>40.0</td>
</tr>
<tr>
<td>Average</td>
<td>28.6</td>
<td>39.9</td>
</tr>
<tr>
<td>Variance</td>
<td>0.57</td>
<td>0.37</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.75</td>
<td>0.61</td>
</tr>
</tbody>
</table>

**Table 2 - Filament Yield Stress Results**

**VI. Analysis of Results**

A. Filament Yield Stress

From the filament testing, it is clear to observe an average reduction in YS of CF-ABS filament compared to ABS filament. This reduction in strength is approximately 28.6%. The initial evidence suggests that the addition of CF into an ABS matrix causes a reduction in its YS. However, the standard deviation of 0.18MPa found in 6 other laboratories [1] suggests that the samples tested do not meet the required standard when combined with other researchers.

As shown in figure 5, the black CF-ABS sample has experienced more plastic deformation than the blue ABS. Initial estimates suggest that the CF-ABS sample are more ductile than the ABS samples due to a higher level of deformation upon completion of tension testing. This result is consistent among all the tested samples of filament. Further analysis of the comparison of ductility between the two test samples will be evaluated in the analysis of the printed components.

**Figure 8 - Deformed Filament After Tension Testing**
B. Yield Stress of Printed Samples

The stress over strain curves shown in figures 9-13 depict the recorded data for the samples run under tensile testing to failure. It can be observed from the data that the ABS samples obtain higher values for YS than the CF-ABS samples. This is made more observable in figure 13 which plots the strongest sample from each test group.

The data collected from the printed sample testing yields similar results as the filament testing. The YS of the components printed in each material is lower than the filament. This suggests that the printed components may have some voids or other defects from the printing process. The inclusion of defects within FDM components is common and is difficult to avoid [5]. Although the stress levels similar to the filament is ideal, the reduction in strength of the CF-ABS parts is still observed. For the 0-90° orientation, an average reduction in strength of 21.1% is observed. For the ±45° orientation samples, an average reduction in strength of 12.9% is observed.

The company responsible for manufacture of the filament was attempted to be contacted on multiple occasions without result. From previous work with the product, it is advised the CF particles have an approximate aspect ratio of 1, meaning they exhibit no overall benefit in any one direction. This means that the testing modes of failure are currently unbeneficial, as the low aspect ratio means the fibres do not exhibit an increase in tensile strength in any direction. From this, the potential to increase the YS of ABS relies on the bond strength between the ABS and CF to be higher than ABS to ABS. The author is unable to find any research being conducted in this field. Other matrices such as epoxy resin, utilising chopped particles exhibit lower bond strength between CF particles and the matrix whilst at high viscosities [9]. As ABS has a high viscosity, the company responsible for manufacture may not have considered using a proper mixing procedure for the ABS within the chopped CF.

Figure 9 - 0°-90° ABS

Figure 10 - ±45° ABS

Figure 11 - 0°-90° CF-ABS

Figure 12 - ±45° CF-ABS

Figure 10 - Comparison between Strongest Samples from each Test Group
This could be a large factor which affects the change in strength from ABS to the CF-ABS samples. The use of a proper mixing procedure and modifying the CF geometry could be considered as future work on the topic.

From the results of the printed component tensile testing it can be observed that all the ABS samples achieved higher YS values when compared to the CF-ABS parts. In addition to this, all ABS samples experienced higher levels of plastic deformation when compared with the CF-ABS components. This suggests in contradiction to the filament testing that ABS is more ductile than CF-ABS. The reason the CF-ABS samples appear to have experience higher plastic deformation in filament testing is since the ABS sampled failed before their yield stress.

### VII. Conclusion

From data collected within this research, it is concluded that the inclusion of chopped CF particles within ABS plastic results in a reduction of between 13-29% tensile strength. More research needs to be conducted to determine the exact reasoning for this. However, an initial estimation is that the bonding between the CF particles and ABS results in a weaker material. The failure of the CF-ABS components is expected to occur at the fracture between CF particles and ABS plastic itself. This report has built a foundation for the comparison of strength between CF-ABS components and ABS. More work could be done to analyse the fracture mechanics of the components and research into the bond strength between CF and ABS.

### VIII. Recommendations

It is recommended that further work be conducted within this field of work. Further work can be conducted in analysing the fractured surface of the tested components. It should be noted that using techniques such as Scanning Electron Microscopy is difficult on this product as ABS is made mostly from carbon and analysing via a standard microscope is difficult due to the changes in height across the fracture surface of the material. Additional work can also be conducted by modifying the weight percentage and geometry of fibres within the ABS matrix. This experimentation could lead to the potential where CF added into ABS can improve the strength of components. Also, some experimental procedures which measure the hardness and flexural strength of the components could be used to indicate conditions in where this material might excel. As a reduction in YS might lead to some additional benefits such as extra hardness or toughness. This extra research would be able to confirm the results found from experimental procedure within this project, and potentially validate claims that bond strength between ABS and CF is the reason for the reduction in YS for CF-ABS components when compared with standard ABS. In addition to this, the variation of CF parameters within the ABS could be optimised to generate a material balanced between cost and strength.

### Acknowledgements

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### References


