Construction of a 3-Dimensional RepRap printer and material testing of samples in addition to the production of a useable part for the SAE team

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This project involves the introduction of the Ultimaker, a new type of rapid prototyping 3-Dimensional (3-D) printer, to the university. In addition, the objectives were to conduct material testing (shear, compression and tension) on printed standard test samples. This was in order to get an idea of how the extrusion temperature and in-fill ratios affected the strengths of the printable plastics Polylactic acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). Due to a number of complications, the shear and tensile test specimens printed in ABS were not able to be printed. The main reason for this was warping of the plastic on the platform. Furthermore, the tensile rig which was custom built was not able to provide a great enough force to hold in the PLA tensile samples without damage. The results which were obtained showed that the extrusion temperature did vary the strength of the plastics significantly. Also, a trend for how the in-fill ratio affected the strengths of the plastics was ascertained. The final component of this project was to manufacture a useable part for the Society of Automotive Engineers (SAE) team on their race car. This part was an air intake and it underwent various design changes in order to accommodate the limitations of the printer.

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I. Introduction

Over the past decade, 3-D printing technologies have improved drastically. The applications for which these printers can be used for are immense and will continue to increase as the technology matures. The greatest benefit of this technology is that virtually everything on these printers is open source, such as software and design modifications which allows users to add improvements making the evolution of the system rapid.

This thesis will provide information on how the extrusion temperature and in-fill ratio affects the material properties of both ABS and PLA plastics. This will give an indication as to what stresses a printed object will be able to withstand to determine the usefulness in practical applications. Due to the anisotropic nature of the material, ASTM D635 [2], ASTM D695 [3] and ASTM D732 [4] were used to specify the characteristics of the samples for tensile, compressive and shear testing. Based on these standards, CAD models were created in order to generate `.stl` files for the printer to read and can be seen in Appendix A.

In addition to the material testing, a useable part for the SAE team would be created. By doing this it will prove the viability of the printer by physically producing items which would normally have to be sent interstate to get manufactured. This will save on time and money and allow other disciplines within the university to take advantage of the new technology.

II. Background

The specific RepRap printer being used is known as the Ultimaker. This device employs a moveable extruder head in the x-y plane and a platform which moves up and down in the z-direction. A Bowden cable connects the extruder to the head where the plastic wire is fed through to be heated above the thermoplastics’ melting temperature. [9] An image showing the completed setup of this printer can be seen in Appendix B. The Ultimaker has a build volume of 210 x 210 x 220 mm which is sufficient to accommodate the needs of the SAE team. It uses a range of plastic filaments, the most common being PLA and ABS and this particular model has one of the highest build-volume to frame ratios. [8]

Plastic objects produced by a 3-D printer have anisotropic characteristics. This is a consequence of the way the heated plastic filament is bound layer by layer, making the mechanical properties highly dependent on direction. In 2007, a study into the compressive strength of 3D-printed test cylinder specimens was conducted. The study showed that varying the build orientation, cure time and cure temperature had a significant effect on the compressive strength and other bulk material properties. [5] An additional study into the mechanical properties of ABS specimens fabricated in differing ‘raster’ layer orientations (0˚, 45˚, 90˚ and +45˚/-45˚) was also conducted. The results from this particular report substantiated that the ultimate and yield strengths were largest for the 0˚ raster orientation followed by the +45˚/-45˚, 45˚ and then 90˚ orientations. However interestingly, when conducting compression tests, it was recorded that the 45˚ raster orientation was deemed to be the weakest. [7]

III. Complications

Whilst undergoing this thesis a multitude of problems were encountered due to the fact that it is a relatively new technology and there was no prior experience with any piece of equipment similar to the Ultimaker. In this section, the difficulties will be broken down into main groups in order to help future students troubleshoot any problems they may encounter. Most of the significant issues related to the use of the ABS plastic and some of these could not be resolved without modifications.

A. Mechanical

Firstly, mechanical problems were the most common throughout the construction and the operation of the printer. Many were simple issues which could be resolved quickly once the solution was found. For example, the distance between the platform and the extruder nozzle had to be perfect. It had to be close enough so that the plastic was able to stick and not too close as to tear the heat resistant tape. This had a flow on affect which was the level of the bed. Obviously, if one corner was too low then the plastic would not stick in that section, similarly, if one corner was too high then the nozzle would scrape into the tape and possibly mark the platform. A simple adjustment could be made to perfect the distance of the nozzle and the platform by turning the z-axis motor by hand just before the print started. Alternatively, a more precise attachment could be printed which utilizes a screw to fine tune the z-axis stopper switch.
By far the most important mechanical issue was the extruder mechanism. In particular, when using the ABS filament it was discovered that the extruder bolt had less grip due to the smoothness and hardness of this particular plastic over PLA. This meant that if there was too much back pressure, the wire would not move and the bolt would just shred into the plastic. The generation of back pressure could be generated through a number of different factors. If the temperature was too low then the plastic was still too viscous and required a much greater force to push it through. A flow on affect from this was the print profile, specifically the RPM at which each layer would print at. At lower temperatures the plastic could not have a higher RPM. Furthermore, if the plastic was extruded too slowly then not enough material would be expelled to form the in-fill layers. This required very intricate tweaking in which not every combination was possible in order to print identical specimens. A more intricate issue to detect was back pressure being created from a gap between the end of the Bowden cable and the PEEK. If there was a gap here, then a pool of molten plastic would settle. This meant that for the next print the plastic could not be extruded as the pool of plastic had solidified. The solution to this was quite arduous. The heating element needed to be heated up for long enough in order to soften the plastic trapped in the PEEK. Then the heating element and PEEK had to be removed and the solidified pool removed. Lastly, in regards to back pressure, if the heating element was heated up too high for the plastic it would expand part of the wire which is located within the Bowden cable. This would ultimately cause the filament to generate too much friction and make it impossible to push through with the current extruder motor.

The extruding mechanism itself had some deficiencies also. If the screw was done up too loosely then the bolt would simply spin freely. Consequently, if the screw was done up too tight then the bolt would either shred the plastic or not allow the motor to rotate at all. If the extruder bolt shreds the plastic then either it will clog up with plastic or deform the wire so that it generates friction within the Bowden cable because of the tight tolerances. The complicated and very frustrating reality is that the tightness required will depend on the temperature, the speed and the amount of back pressure which is being generated. Constant adjustments must be made during an individual print depending on these factors.

As the Ultimaker comprises of pulleys and belts to maneuver, it is necessary to keep the belts tight. If there is too much slack then the teeth of the pulleys may slip and cause inaccuracies. Simple belt tensioner designs are readily available to print to remedy this problem. Finally, the original printer came with a standard plastic fan duct to direct the air onto the tip of the nozzle. This would allow the plastic to cool quickly and help reduce the effects of warping which is a separate issue and will be discussed further on. However, this fan duct was not an optimal design as the air flow was only directed in one direction. Various designs are available to print in either multiple parts or as a whole which direct the flow radially in. This is a much more desirable design except that the plastic duct gets too close to the nozzle and it melts after extensive use.

B. Software

Due to the fact that virtually everything related to the Ultimaker is open source, various software upgrades and changes become available to the greater community. These upgrades can noticeably change the performance of the printer. For instance, the latest update increased the smoothness of the extruder heads movement which allowed for a better, more precise print. Also, it provided a more accurate temperature control regulation. Additionally, the specific type of program used to run the Ultimaker also has a large impact on the prints. For this thesis, Netfabb was used however other programs such as ReplicatorG exist and generate a different g-code to build the object. This is particularly important as the in-fill structure along with other such factors will be different and cause inconsistent material properties.

In each program there are advanced settings which are able to fine tune a vast number of parameters such as the layer thickness, extrusion rates, support structure etc. Adjusting certain settings allows a better print to be produced as the type of plastic may alter the performance significantly. The main issue with this is that once an alteration has been made, a test print must be completed in order to identify the differences. This is very time consuming and may lead to other problems being uncovered while using the new setting.

C. General

The biggest down set of this project was the tensile rig which unfortunately did not operate as anticipated. This is because it could not provide a large enough frictional force without causing damage to the ends of the specimen. The rig was setup to clamp down on each end by tightening a set of bolts. Three different materials were used to help increase the amount of friction between the clamp and the sample. Self-amalgamating tape, scotch bright and a silicon-carbide mesh all proved to be insufficient at providing the necessary friction. Another unforeseeable setback was the variation in the thickness of the plastic wire. On one of the first rolls of plastic which was purchased, the wire was generating too much friction within the Bowden cable. It was
discovered that the actual manufactured wire had a slightly larger diameter and hence could not slide through the Bowden cable freely.

Undoubtedly the most important issue which requires a solution is the effect of warping. Both PLA and ABS prints showed evidence of warping and it could not be prevented easily if at all. At higher temperatures warping would become more predominant due to the platform remaining at room temperature. The only way to stop this from occurring would be to reduce the temperature difference between the nozzle and the platform. It may have been possible to increase the room temperature up to a higher temperature but the easiest solution would be the addition of a heated bed. Unfortunately, this is a custom part which has not been obtained by the university yet. Another factor which has an impact on warping was the shape and construction of the object being printed. Sharp corners and solid objects increased the amount of warping whereas smooth curves and hollow objects minimized it.

D. ABS

As mentioned previously, the main issues that were encountered related to the use of ABS. This is due to the higher melting temperature, hardness and smoothness of the filament. In particular this led to the extruder bolt not being able to grip the ABS as effectively as it did with PLA. However, even though virtually all of the complications affected the ABS plastic, the most important issue was warping. ABS had a much higher tendency to warp on the platform then PLA. This had no easy solution and can only be resolved by major modifications to the printer. Such alterations like the addition of a heated bed would drastically reduce the effect of warping due to the smaller temperature difference between the extruded plastic and the platform.

IV. Results

At the beginning of the year, this thesis intended on conducting shear, compression and tensile tests on two different types of plastics (PLA and ABS). However, due to an innumerable amount of problems, some of these tests were not conducted. The tensile tests were completely dropped because the rig which was specifically created for this test did not work as it was intended. Furthermore, when printing with ABS it was unknown just how problematic this could be without a heated bed. There was just too much warping in the samples to complete the shear specimens either. Therefore, the results below indicate the successful tests which have been conducted. All the detailed stress-strain graphs which have been produced to determine these results can be found in Appendix C.

All of the results which were obtained are for samples that have a 0˚ raster orientation. This means that the buildup of layers is parallel to the force applied. Furthermore, for the temperature dependent samples the in-fill ratio was kept constant and similarly for the in-fill dependent samples, the extrusion temperature was kept constant. A comparison of relevant strength values could not be obtained as they are highly dependent on the specific type of plastic and vary significantly. Moreover, as the plastic being used throughout the project was purposely designed for 3-D printers the properties vary with the way that the object is printed and as such the results are unique. This is the reason why these results are so useful and will require more extensive investigation. Pictures of the different test rigs and specimens can be located in Appendix D.

A. PLA Results

<table>
<thead>
<tr>
<th>Temperature Dependent Compression Samples</th>
<th>190˚</th>
<th>200˚</th>
<th>210˚</th>
<th>220˚</th>
<th>230˚</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Stress (MPa) Compress</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>121</td>
<td>128</td>
<td>130</td>
<td>130</td>
<td>130</td>
<td>7%</td>
<td></td>
</tr>
<tr>
<td>Compression Modulus (GPa) R^2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.53</td>
<td>2.26</td>
<td>2.41</td>
<td>2.63</td>
<td>1.83</td>
<td>42%</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 above indicates the results which were found from conducting compression tests on PLA samples printed under varying temperatures. It shows that the yield stress has only a small variation over the temperature scale but the compression modulus varies much more significantly. Graph 1 below provides a visual representation of the relationship between the yield stress and temperature. It shows that the maximum yield stress that can be obtained is 130 MPa and it reaches this at 210 degrees after which it remains constant. This is extremely useful as PLA is easier to print at around 200 degrees as there is less back pressure to compete with due to the lower viscosity.
In-fill Dependent Compression Samples

<table>
<thead>
<tr>
<th>Yield Stress (MPa)</th>
<th>2.03mm</th>
<th>4.22mm</th>
<th>6.01mm</th>
<th>8.10mm</th>
<th>10.00mm</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>27</td>
<td>18.6</td>
<td>17.4</td>
<td>13.8</td>
<td>12.5</td>
<td>54%</td>
</tr>
<tr>
<td>Compression Modulus (GPa)</td>
<td>1.08</td>
<td>0.669</td>
<td>0.635</td>
<td>0.574</td>
<td>0.417</td>
<td>61%</td>
</tr>
<tr>
<td>R²</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 2 above provides the results for the PLA compression samples which were dependent on the in-fill ratio. This ratio on the Netfabb program is determined by the spacing of the internal structure and is hence described by a distance. This table shows that both the yield stress and compression modulus are highly dependent on this internal structure. This is not a surprising result because as the spacing gets greater than the amount of required material is less. Graph 2 below shows that as the object becomes semi-solid with an internal structure than the yield stress drastically drops. At about a 2mm spacing, the stress levels off which is a result of the outer shell providing the majority of the strength.

PLA Temperature Dependent Compression Samples

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Yield Stress (MPa)</th>
<th>Shear Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>190 °</td>
<td>5.22</td>
<td>102</td>
</tr>
<tr>
<td>200 °</td>
<td>7.27</td>
<td>150</td>
</tr>
<tr>
<td>210 °</td>
<td>6.80</td>
<td>136</td>
</tr>
<tr>
<td>220 °</td>
<td>8.45</td>
<td>187</td>
</tr>
<tr>
<td>230 °</td>
<td>7.58</td>
<td>108</td>
</tr>
<tr>
<td>Variation</td>
<td>38%</td>
<td>45%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Yield Stress (GPa)</th>
<th>Shear Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>190 °</td>
<td>0.97</td>
<td>0.94</td>
</tr>
<tr>
<td>200 °</td>
<td>0.55</td>
<td>0.87</td>
</tr>
<tr>
<td>210 °</td>
<td>0.94</td>
<td>0.87</td>
</tr>
<tr>
<td>220 °</td>
<td>0.87</td>
<td>0.95</td>
</tr>
<tr>
<td>230 °</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The results which are shown above in Table 3 indicate that temperature has a greater effect on the shear properties in comparison to the compression samples. Graph 3 below indicates that the shear yield stress varies up and down due to the temperature. However, these results may not give the best representation of the relationship as some of the samples had slight warping which may have affected the graph. A greater number of samples will be required in order to properly determine the true relationship. As stated previously, only an estimated relationship was meant to be discovered while observing the variation in strengths from the varying print conditions.

Table 4 above represents the results that were obtained from the shear testing of the PLA in-fill dependent samples. It can be seen by Graph 4 below that it correlates with the in-fill dependent compression samples which showed a drastic drop in the strength at 2mm spacing. Unfortunately the shear modulus was unable to be obtained as the laser extensometer that was used was set to a setting which did not provide sensitive enough results.

B. ABS Results

The tensile and shear specimens were not possible to be printed due to the complications discussed earlier. There was not enough surface area contacting the platform to make it stick without warping considerably. Also, due to the extrusion bolt, there was insufficient grip to push the wire through to get a sufficient amount of in-fill. When attempting to change the print profile, if the speed was too low then there was not enough material to create the honeycomb structure inside. If it was too fast then the bolt would just tear the plastic wire.
Table 5 above shows the results for the ABS temperature dependent compression samples. It can be seen that the yield stress has a higher variation compared with PLA. Another important fact to note is that the strength seemed to go up and down with a maximum at 255°C which is represented in Graph 5 below. However, this may be due to the smaller temperature intervals and the inaccuracies with the temperature regulation on the Ultimaker which could vary by 5°C.

The final results which were obtained are the ABS in-fill dependent compression samples. Table 6 above shows that the results correspond with the PLA in-fill dependent samples. The sample with 10mm spacing was unable to be printed as there was not enough in-fill to complete the sample. However, extrapolating from Graph 6 below it can be seen that the last sample was unnecessary to obtain the trend.
C. SAE Printed Part

A crucial part of this project was to show the viability of the printer by fabricating a usable part for the SAE team. The part which was chosen to be printed was an air intake for the SAE car which a fellow thesis student, Peter Prendergast was working on. This was an adequate test of the capability of the printer as this particular part was fairly complex and had a relatively long build time of approximately 20 hours. Also, the use for this part meant that there would not be any external stresses as it is not a structural component and the estimated operating temperature was less than 60°C.

In order to accomplish this goal, the original design had to undergo multiple variations in order to accommodate the limitations of the printer. The first design which was provided by Peter had an overhang in which the printer could not print neatly without a support structure. Due to a lack of understanding of how the printer operated Peter did not realise that this design could not work straightforwardly. After discussion it was decided to add a solid support structure to the design instead of using the default support which the Ultimaker provides. This is because the default support structure would add unnecessary material to areas which did not require any additional support. After attempting to print this design, it was found that the solid column support gets broken off before it could reach the overhang. This was because there was slight warping which made the nozzle hit the column which was slightly raised higher and broke it off.

This led to the decision of incorporating the support structure permanently into the design of the part. To properly ascertain the viability of this option, a scaled model was printed to see if any complications would arise. Once it was verified that the new design was possible, the full scale air intake was ready to be printed. However, unforeseeably due to the extreme print time, it took an innumerable amount of attempts to get close to finishing the part. The main complication which affected the print was the extruder bolt getting continually clogged and losing grip which was explained earlier. In the end, the part was printed on a different Ultimaker which had a modified extruder bolt that did not clog up. Pictures of the final product and the evolutionary designs can be found in Appendix E.

V. Conclusions

The overall outcome of this project was to determine whether or not the extrusion temperature and in-fill ratio had an effect on the strength of printed objects. It was found that the PLA temperature dependent compression samples had a variation of 7% and the shear samples had a variation of 38%. For the PLA in-fill ratio compression samples there was a 54% variation and an 85% variation for the shear samples. Furthermore, the ABS temperature dependent samples showed a variation of 15% and there was a variation of 42% for the in-fill dependent compression sample.

The importance of the results which were obtained was that it showed the extrusion temperature did have a noticeable effect on the strength of the samples. Additionally, it provided a trend as to specifically how much the strength decreased with varying in-fill ratios. In conjunction with the results was the identification of various issues which were encountered. Some solutions to these problems have been discussed and via the list of recommendations below, the main issues of warping and the extruder can be rectified by future students through modifications. Furthermore, the viability of the usefulness of the printer was demonstrated through the manufacturing of the air intake for the SAE team.
VI. Recommendations

From the research and personal experiences which have been acquired throughout this project there are a number of elements which could be improved or added to complete and evolve the research. These are outlined below:

- **Heated bed:** One of the most important issues which needs to be addressed is warping. The effect of warping not only disfigures the object but it has the possibility of bowing so much that it peels off and the print cannot be completed. A solution to this problem would be the use of a heated bed. It will decrease the temperature gap between the extruder nozzle and the plate which will reduce the amount the plastic has to cool down by and less shrinkage will occur.

- **Modified extruder bolt:** Designing and manufacturing a new extruder bolt will solve the problem of the plastic getting stuck during long prints. It will minimise the amount of plastic which gets shredded from the filament causing it to clog up lose grip. In addition, it may be possible to have a new bolt to generate a greater friction initially in order to provide a greater pushing force to overcome back pressures.

- **Upgraded extruder motor:** With the addition of a more powerful extruder motor, the Ultimaker will be able to exert a greater force on the plastic wire. This will simply be able to overcome a greater back pressure up until the limit of the Bowden cable popping out.

- **Upgraded Bowden cable:** Although the issues with the Bowden cable resulted from the deformation of the plastic wire, it may be possible to find a replacement which reduces the amount of friction. Also, it may make a difference if the diameter of the cable was slightly larger to enable a lower tolerance of the diameter of the plastic to let deformed plastic to slide through unrestricted.

- **Modified tensile testing:** A few options may be available in order to complete the tensile tests. The first option would be to use an adhesive to hold the samples in the current testing rig. This would however become very time consuming as the adhesive would have to be dissolved after each use. Another option may be to redesign the samples so that either a greater surface area is available to generate greater friction or that the sample ends are able to withstand a greater clamping force. Finally, the last option would be to redesign the entire tensile rig to solve the issues that has been discovered.

Acknowledgements

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References