A Preliminary Study of Using Plastic Molds in Injection Molding

THESIS

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By

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Abstract

Two critical aspects of 3D printed tooling are studied in this thesis: tool survivability and mechanical properties of the molded parts in reference to the ones molded on metal molds.

Understanding tool survivability is a critical requirement for implementing 3D printed tooling in industry. The tool must be able to withstand the heat and pressures during the injection molding process. Tool survivability was analyzed in this thesis experimentally and with simulations. Two ribs of different aspect ratios were printed on a tool insert and used in a mold assembly. The aspect ratio was changed by doubling the rib thickness while maintaining the same height. The ribs were tested individually under varied flow rates. Experimental results showed that the thinner rib failed after the first shot. The thicker rib did not fail after the first shot; instead, it failed after several shots possibly due to the increase in temperature with consecutive moldings. It was found that the thicker rib did not fail when the mold open time was set to four minutes. This allowed the temperature on the rib surface to not exceed the heat deflection temperature for the mold material. Simulation was used to evaluate the net force on the rib surface during the filling stage due to the pressure difference and its effect on the Von Mises stress at the base of the rib. It was found that if the Von Mises stress obtained from an FEA simulation was larger than
the yield strength of the Digital ABS tool material, it is predicted to fail at the first shot; If the Von Mises stress was not larger, the rib was predicted not to fail on the first shot.

It was found that mechanical properties for parts molded in plastic 3D printed molds were similar to the ones molded in metal molds with the exception of ductility. Parts molded in plastic molds in general have a much lower ductility than the ones molded in metal molds. The effect of mold and melt temperature, filling speed and material residence time in the injection barrel on ductility was evaluated, for both, a semi crystalline and an amorphous material. Finally, the effect of mold surface finish on ductility was studied.

Results found that the significant parameters affecting ductility were mold and melt temperature, crystallinity and injection speed. By adjusting the above mentioned process parameters the ductility of parts molded in a plastic tool could be increased to similar values to the ones molded in metal molds for amorphous materials. For semi-crystalline materials, the ductility can be increased but it can not be made similar to the ductility of parts molded in metal molds.
Acknowledgments

Thank you to Dr. Castro and Dr. Mulyana for their mentoring and encouragement throughout my college career. Thank you to Ben Hoffman for his passion and expertise that drove this project from the beginning. Lastly, thank you to my family for their love and support.
Vita

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Fields of Study

Major Field: Industrial and Systems Engineering
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Chapter 1: Introduction

Historical Background

Injection molding is the most common process used for manufacturing plastic parts. The startup costs are high for obtaining injection-molded parts due to the high cost of designing and machining mass production (MP) tooling (Groover, 1996). Sometimes it is necessary to have a physical part for test verifications before final MP tooling is ready. When this situation arises, there are multiple options available to obtain a part before making the decision to machine a tool. In most cases the options that are available to manufacture a part ahead of MP tooling will not match all the material, mechanical properties, or surface quality requirements. Another challenge arises when the design is changed and there is a tool that costs tens of thousands of dollars and took months to arrive that is now obsolete. (Vincent Rodet, 2003). An alternative to machining a metal tool for prototype or low volume applications is to utilize 3D printing technologies to manufacture a tool for injection molding (T. Tábi, 2016).

Using 3D printed plastic tooling for injection molding is an attractive approach if parts are needed with the same final material and with similar mechanical properties as final MP parts from conventional tooling. 3D printed plastic tooling could help improve the flexibility of a part manufacturer by providing parts similar to the MP parts during the earliest stages of design. This flexibility allows for the increased modification and
implementation of design concepts when using plastic 3D printed applications for prototype tools instead of conventional tooling (Pedro Gonçalves Martinho, 2009).

Fluid-based additive manufacturing (AM) technologies have been used to manufacture successful tools for injection molding including stereolithography (SLA) and PolyJet technologies (T. Tábi, 2016). The advantages of using a UV-curable 3D Printing technology is the high thermal resistance and surface quality of the printed plastic mold without excessive post processing (Stratasys, 2008).

There are challenges that arise when using plastic 3D printed tools for injection molding. Clearly, 3D printed plastic tools are not as strong as machined metal tools. The survivability of plastic 3D printed tools under the heat and pressure of the injection molding process has been considered (Neri Volpato, 2016) (Gabriel Antonio Mendible, 2017) (József Gábor Kovács, 2015). Research suggests that epoxy based plastic 3D printed tools are stable under molding conditions and can produce parts with similar physical attributes as the ones in metal molds (Neri Volpato, 2016). The molding process needs to be modified to mold good parts due to the lower thermal conductivity of the 3D printed plastic tools. Specifically, the cooling time had to be increased for the part to solidify and eject as it would from a metal tool (Gabriel Antonio Mendible, 2017). Mold failure has been found to occur when using plastic 3D printed tools for injection molding due to ejection forces. To increase tool survivability, research suggests minimizing the ejection forces by modifying the draft angles, surface finish and undercut interferences (Gabriel Antonio Mendible, 2017). Another study has recommended increasing the cycle time while molding with plastic 3D printed tools due to the poor thermal conductivity (József Gábor
Kovács, 2015). The cycle time may be decreased in the future by improving the thermal conductivity of the 3D printed plastic tooling material.

Before implementation, a thorough understanding of the new technology is required to justify the time and cost modification when compared to the current process. For prototype and low volume applications, studies have shown that 3D printed plastic tooling is an attractive option when the goals are to cut costs and save time (Gabriel Antonio Mendible, 2017) (T. Tábi, 2016) (Rajitha Aluru, 2001). For short runs, plastic 3D printed tooling saves money due to the lower cost of 3D printed molds with respect to metal molds.

There are positives and negatives to every new technology. Identifying them is critical in deciding if it is worth it to adopt a new technology. Simulation is a great tool to save even more time and money by identifying issues that may arise during molding. Multiple studies have been completed considering how to simulate injection molding into 3D printed plastic tooling inserts (József Gábor Kovács, 2015) (Rajitha Aluru, 2001). Extensive research has been conducted on the morphology, thermal and mechanical properties of parts molded from 3D printed plastic tooling (Pedro Gonçalves Martinho, 2009) (R.A. Harris, 2004) (T. Tábi, 2016) (J. I. Segal, 2001). The thermal history of parts molded in plastic 3D printed tooling are different due to the slower cooling rate when compared to conventional tooling. The slower cooling rate causes a difference in crystallinity for parts molded in plastic versus metal molds, which will cause differences in mechanical properties (T. Tábi, 2016) (Gabriel Antonio Mendible, 2017) (Neri Volpato, 2016) (Pedro Gonçalves Martinho, 2009) (J. I. Segal, 2001) (R.A. Harris, 2004). Preliminary studies have been performed on the change in mechanical properties of parts molded from a
Stratasys PolyJet mold by Tábi et. al. in 2015. The results indicated that there was a significant reduction in strain at break when molding with a semi-crystalline material in a 90°C steel tool compared to a lower recommended tool temperature of 23°C. A higher tool temperature caused a decrease in the mechanical properties of parts molded in the steel tool. A higher crystallinity was also measured in parts from a PolyJet mold compared to parts from a 23°C steel mold. This thesis will look into the effect of slow cooling rate and crystallinity on mechanical properties, but with an emphasis on how to vary the processing conditions to improve the mechanical properties of the parts from a plastic tool.

Motivation and Research Objectives

The motivation for implementing 3D printed plastic tooling in industry comes from the desire to save time and money when manufacturing prototype and low production volume parts. If there is a faster and more economical way to deliver a new product to the customer, then industry will be interested in the new technology. However, there is not enough evidence in the literature to verify that parts molded in plastic tools will have the similar properties as parts molded in metal molds. This thesis will compare tensile properties of parts molded in 3D printed plastic tools versus parts molded with a steel tool. Work will be performed on how to modify the molding parameters so that mechanical properties will get closer to those from parts molded with the steel tooling. The motivation for this thesis is to support the implementation of this 3D printed tooling technology for prototype and low volume applications.
Digital ABS by Stratasys printed on an Objet1000 Plus 3D printer was used for all 3D printed plastic tooling inserts in this thesis due to support from our research collaboration with a local manufacturer. The Objet1000 Plus 3D printer, which uses Stratasys PolyJet technology, is capable to deposit a thin layer of photopolymers from print heads onto the work space. Each layer has a thickness of only 30 micons and solidifies when exposed to UV light (Stratasys, 2008). Digital ABS was chosen by other researchers to use as a 3D printed tooling material due to its accuracy and versatility (József Gábor Kovács, 2015) (T. Tábi, 2016).

This thesis looks at two aspects of 3D printed plastic tooling: mold survivability and the mechanical properties of the molded parts. Mold survivability is studied using inserts printed out of Stratasys Digital ABS. Two 3D printed inserts are printed with different rib aspect ratios. Simulations and experiments are used to analyze rib integrity under different tool temperatures and injection rates. Next, mechanical properties of tensile bars injection molded from a Stratasys Digital ABS insert are compared to tensile bars from conventional steel tooling. What was found is that most mechanical properties are similar except for ductility. Parts molded in the plastic tool were found to be much less ductile than parts molded in a conventional steel mold. Our research seems to indicate that the factor most significantly effecting ductility is the much lower cooling rate of the plastic mold. The main goal of this work is to find the processing conditions needed when molding in a plastic mold, to increase and if possible to match the ductility of parts molded in metal molds.
Organization of this Thesis

Chapter 1 reviews the current state of plastic tooling and how it is being studied and implemented. Chapter 2 discusses plastic tool survivability based on previous work done in our research group. Simulations and experiments are used to study the survivability of a rib under different process parameters. Chapter 3 discusses the mechanical properties from parts molded in plastic tools. Since most mechanical properties are similar to that of parts molded in conventional metal molds except for ductility, the discussion focuses on the process parameters affecting ductility. Processing conditions are varied in an attempt to understand the reason behind the lower ductility of the parts molded in plastic tools. Special emphasis is put on processing changes that could increase the ductility of parts molded on plastic tools, to values close to the ductility of parts molded in conventional metal molds. Chapter 4 summarizes this work and suggests a path forward for future studies. Finally, in the Appendix, other mechanical properties where no major differences were found are summarized.
Chapter 2: Mold Survivability

Introduction

This chapter is based upon previous work completed by a former graduate student, Eric Grunden. Eric graduated from Ohio State with a Master’s degree in Industrial Engineering in May 2016. Eric’s thesis named Examination of Rapid Prototype Tooling used simulation and experiments to examine the impact of flow rate and the mold open time on tool rib aspect ratios. Chapter 2 will review the results of Eric’s thesis comparing the lifetime of two rib aspect ratios under varied injection rates.

Setup and Materials

The tooling geometry used for the mold survivability experiment is two mirrored Ohio shapes shown in Figure 1. The pockets inside this mold base allow for customization with different inserts.
The mold survivability experiments consisted of inserts with ribs of two different height-to-width ratios. The height-to-width ratios used were 10:1 and 5:1. Both ribs had the same height of 3.75 mm, but the 10:1 rib was 0.375 mm thick and the 5:1 rib was 0.75 mm (twice as thick). The rib inserts were tested by molding using different injection rates to determine the critical rib failure point.

The molding material used was thermoplastic polyolefin (TPO) Sequal 1490 from Solvay Engineered Polymers. All the mold survivability experiments were conducted on a Sumitomo 50-ton injection-molding machine.

Simulation and Loading Analysis

To validate the experiments, the software Moldex3D was run using the same molding parameters used during experiments. Pressure data at the ribs were obtained using
sensor nodes during the filling phase. Sensor nodes record values at specific points along the cavity during the simulated molding process. The placement of sensor nodes used in the simulations is shown in Figure 2.

![Moldex3D Simulation Showing the Sensor Nodes Placed Around the Rib](image)

Figure 2: Moldex3D Simulation Showing the Sensor Nodes Placed Around the Rib

From the predicted pressures from two opposing sensor nodes on the front and back face of the rib during the filling stage, the net force acting on the rib was calculated. The predicted pressure from two opposing sensor nodes (SN3 & SN5) during filling is shown in Figure 3. Note that SN3 is on the front face of the rib and it measures higher pressures than SN5 located on the back face.
Applying this net force to the rib, and using the FEM package Abaqus, the Von Misses stresses were calculated at the base of the rib, as shown in Figure 4.
Table 1 shows the Von Mises stresses predicted at the base of the rib during filling. If the Von Mises exceeds the yield strength of Digital ABS (52 MPa), then it is predicted that the plastic tool rib will fail during filling for the first shot. The simulation assumes that all experiments are being completed at room temperature. The experimental results are shown in Table 1. Values in bold indicate predicted failure of the rib during the first shot.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Flow Rate ($cm^3/s$)</th>
<th>Pressure Difference (MPa)</th>
<th>Von Mises value</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:1 Rib</td>
<td>66.15</td>
<td>0.34</td>
<td>51.6 - Fail</td>
</tr>
<tr>
<td></td>
<td>15.04</td>
<td>0.35</td>
<td>53.1 - Fail</td>
</tr>
<tr>
<td></td>
<td>6.15</td>
<td>0.50</td>
<td>63.7 - Fail</td>
</tr>
<tr>
<td>5:1 Rib</td>
<td>54.88</td>
<td>0.68</td>
<td>29.69</td>
</tr>
<tr>
<td></td>
<td>40.16</td>
<td>0.55</td>
<td>24.02</td>
</tr>
<tr>
<td></td>
<td>18.29</td>
<td>0.70</td>
<td>30.56</td>
</tr>
<tr>
<td></td>
<td>6.59</td>
<td>1.05</td>
<td>45.85</td>
</tr>
</tbody>
</table>

Table 1: Predicted Von Mises Stresses at the Base of the Ribs for different filling rates.
The 10:1 rib was predicted to fail for all cases. The simulated stress at the base of the 5:1 rib does not exceed the yield strength of Digital ABS, so the 5:1 rib is not predicted to fail during the first shot. The 5:1 rib is predicted to only experience elastic deformation during the first shot due to injection pressures. This prediction does not consider fatigue failure as well as the increase in temperature with consecutive moldings.

Testing

Effect of Flow Rate

Table 2 shows the experimental results from molding with the two different rib inserts under varied flow rates. The last shot that ultimately broke the rib was not included in the count of number of good shots produced.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Packing Pressure (MPa)</th>
<th>Cooling Time (s)</th>
<th>Flow Rate (cm³/s)</th>
<th>Insert Temp (°C)</th>
<th>Metal Temp (°C)</th>
<th># Good Shots</th>
<th>Simulation Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:1 Rib</td>
<td>8.35</td>
<td>70</td>
<td>66.15</td>
<td>76</td>
<td>29.6</td>
<td>0</td>
<td>51.6- Fail</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15.04</td>
<td>65</td>
<td>27</td>
<td>0</td>
<td>53.1- Fail</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.15</td>
<td>69</td>
<td>28</td>
<td>0</td>
<td>63.7- Fail</td>
</tr>
<tr>
<td>5:1 Rib</td>
<td>8.35</td>
<td>70</td>
<td>54.88</td>
<td>83.4</td>
<td>31.7</td>
<td>9</td>
<td>29.69- Pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40.16</td>
<td>81</td>
<td>30.5</td>
<td>10</td>
<td>24.02- Pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>18.29</td>
<td>80</td>
<td>30.9</td>
<td>14</td>
<td>30.56- Pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.59</td>
<td>78</td>
<td>28.6</td>
<td>4</td>
<td>45.85- Pass</td>
</tr>
</tbody>
</table>

Table 2: Experimental Results for the Two Rib Configurations

The 10:1 rib as previously discussed failed experimentally during the first shot for all flow rates tried (66.15, 15.04 and 6.15 cm³/second). The 5:1 rib did not fail during the first shot like the 10:1 rib. The 5:1 rib however does fail after a certain number of shots. This is most likely due to the temperature increase of the plastic insert during continued
molding. The temperature of the insert at the time of failure is recorded to be above 58 °C which is the lower limit of the HDT of Digital ABS given by Stratasys (Stratasys, 2017). Therefore, the 5:1 rib most likely failed due to the increase in temperature.

Effect of Temperature

An additional experiment was done to examine the effect of temperature on the survivability of the 5:1 rib. This was completed by molding on a Digital ABS insert for 10 shots, then leaving the mold open and allowing the insert to open air convection cool. The surface temperature of the insert was recorded every minute while the mold was open and the insert was cooling. The cooling rate is shown in Figure 5.
A longer cycle time is necessary for the AM insert due to the lower thermal conductivity, therefore slower cooling rate of Digital ABS compared to a traditional metal mold. The mold open phase time was increased in the next experiment to allow the insert to cool down between runs longer than in the previous experiments. Previous experiments only had a mold open time of 50 seconds. Based on the mold open cooling time result shown in Figure 5, a longer mold open time was determined to be 4.5 minutes (270 seconds). This allowed for the insert temperature to drop below 58 °C before the start of the next shot. During this experiment, the holding pressure and cooling time remained the
same as previous experiments: 8.25 MPa and 70 seconds, respectively. The flow rate tested was 6.59 cm³/second.

Table 3 displays how increasing the mold open time more than doubles the number of good shots that can be produced by the 5:1 AM insert. The 5:1 rib did not break with the longer mold open time. With a longer mold open phase time, at least 40 shots could be molded without the 5:1 rib being damaged.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Packing Pressure (MPa)</th>
<th>Cooling Time (s)</th>
<th>Flow Rate (cm³/s)</th>
<th>Insert Temp (°C)</th>
<th>Metal Temp (°C)</th>
<th># Good Shots</th>
<th>Simulation Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:1</td>
<td>8.35</td>
<td>70</td>
<td>6.59</td>
<td>77.3</td>
<td>35</td>
<td>40+</td>
<td>45.85- Pass</td>
</tr>
</tbody>
</table>

Table 3: Experimental Results for Molding with a Longer Mold Open Time

The AM insert surface temperature was taken before the mold was shut at the start of each shot. The purpose of this second temperature reading is to verify that the AM insert temperature is dropping below 58 °C before another molding cycle. The temperature of the 3D printed insert throughout the extended cycle time experiment is shown in Figure 6. While the surface temperature of the insert is above 58°C after part ejection, the temperature before molding is always allowed to drop below 58°C. This could be a safe temperature to mold on to ensure that mold survivability is increased.
The temperature patterns seem to show that although the AM insert becomes increasingly hotter for each shot, a longer mold open time could allow for the AM insert to survive and still create successful parts compared to a traditional tool. Specifically, if the insert can maintain a temperature below the HDT range of the AM insert material at the start of each shot, then the tooling should survive the next molding cycle.

Figure 6: Measured Surface Temperatures During Longer Mold Open Time Experiment
Conclusions

This work can be used to help understand how to design a plastic tool to survive the processing conditions of injection molding. Using plastic tooling can help save time and money when producing low volume parts. By applying the current understanding of mold survivability, an increase in cycle time will help keep the plastic tool temperature under the material deflection temperature and extend the mold life.
Chapter 3: Molded Part Mechanical Properties

Introduction

A critical aspect for using additive manufactured (AM) tooling for injection molding is to evaluate the similarity in mechanical properties of the parts obtained from the plastic 3D printed mold to parts molded out of a steel mold. This is especially important for safety critical parts or parts that need to be mechanically tested before mass production tooling is manufactured.

A plastic AM mold of two tensile bars was printed in Digital ABS on a Stratasys Objet1000 Plus 3D Printer. The mold was attached to a Sumitomo 180-ton injection molding machine to mold tensile bars to be tested for mechanical properties. Two materials were used: polypropylene and polystyrene. Polypropylene was used to study a semi-crystalline material in a 3D printed tool and polystyrene was used to study an amorphous material. Preliminary results indicate that when comparing parts molded in the plastic tool versus the metal tool, most mechanical properties are close, the anomaly being ductility. Thus, Chapter 3 is focused on exploring the effects of processing parameters, mold parameters and different materials on ductility. Other mechanical properties including Young’s Modulus and Tensile Strength are shown in Appendix A.

Experiments in this thesis are in line with available research that the decrease in elongation is assumed to be caused by the different cooling rate of samples molded in the Digital ABS mold due to the much lower thermal conductivity of the plastic printed tool (József Gábor Kovács, 2015) (T. Tábi, 2016). The slow cooling rate promotes an increase
in crystallinity in semi-crystalline materials (T. Parenteau, 2012) (M. Elmajdoubi, 2003) (Aaron Law, 2008) (T. Tábi, 2016). Mendible et. al. discusses how a slower cooling rate can promote crystal growth of the polymer, which increases shrinkage because of the high density of the crystalline phase (Gabriel Antonio Mendible, 2017). Additionally, an increase in mold temperature can generate differences in the frozen layer during the filling phase (Dongman Choi, 2002). The frozen layer is affected by the cooling rate. These variables and their effect on ductility were explored further during this research through experiments that compared tensile bars produced with printed plastic tools and tensile bars molded with a steel tool.

The purpose of using a steel tool during this research is to understand how changing the process parameters during molding affects the final part’s mechanical properties. This will help us understand what are the main causes of the decrease in ductility when molding with the Digital ABS tool.

In summary, the main objective of this research was to find the process parameters that would increase the ductility of the samples molded in the plastic tool to values similar to those molded in metal molds. The parameters that are causing the decrease in ductility in the plastic tool need to be identified and their effect on ductility quantified.

**Experimental Setup**

**Tooling**

There were two mold bases used during the injection mold trials. The first mold base was for the steel ASTM family tool. The base is a steel Master Unit Due (MUD) 12/16
UF 321 made by DME. The cavity includes a tensile bar, thick flex, thin flex, and an impact testing specimen. There are cooling channels in this base. The part molded from this tool is shown in Figure 7. Figure 8 shows the cavity of the steel ASTM tool installed in the injection molding machine.

Figure 7: Part Produced from Steel ASTM Family Mold

Figure 8: Steel ASTM Family Mold in Injection Molding Machine
The second mold base is the same U-Frame MUD used in the experiments discussed in Chapter 2. No cooling channels are available in this mold base assembly. There is a rectangular pocket in the mold base assembly that is used to insert the 3D printed plastic tool. The 3D printed plastic tool is made from Digital ABS printed on a Stratasys Objet1000 Plus 3D printer. The tensile bars molded from the Digital ABS insert are shown in Figure 9. The printed Digital ABS insert for the tensile bars is shown in Figure 10. Figure 11 shows the cavity of the Digital ABS insert and its mold base installed in the injection molding machine.

![Part Produced from Digital ABS Mold Insert](image)

Figure 9: Part Produced from Digital ABS Mold Insert
Figure 10: Digital ABS Printed Insert

Figure 11: Digital ABS Insert in Injection Molding Machine

Equipment

The injection molding was done using a Sumitomo SG180M-HP C560 injection molding machine. The machine is shown below in Figure 12. This machine has a maximum clamping force of 180 tons, a maximum injection speed of 13.8 in/sec., and a maximum
injection pressure of 39,740 psi in the nozzle. The footprint dimensions of this press are 202 x 54 x 79 inches.

Figure 12: Sumitomo 180-ton Injection Molding Machine

The tensile properties of the molded specimens were measured on an INSTRON 5569 Dual Column Table-Top Load Frame. This machine has a 50kN load capacity, a maximum speed of 500 mm/min, and a minimum speed of 0.005 mm/min. The machine is shown below in Figure 13. The molded tensile specimens were pulled at a rate of 50 mm/minute. The ASTM standard requires 5 samples to be taken and averaged to find the tensile properties of a given batch. During the following experiments, a minimum of five, but often more tensile bars were molded, so those bars were also tested and included in the data. Since it was desired to reach a strain of at least 200% (a specification goal given by a
local manufacturer), the tensile bars were pulled without an extensometer. When using the extensometer, the test needs to be stopped when strain reaches 100%.

Figure 13: INSTRON 5569 Tensile Testing Machine

A TA Q20 Differential Scanning Calorimeter (DSC) was used to measure the crystallinity of the molded polypropylene and polystyrene samples. The Q20 has a temperature range from ambient to 720°C and is accurate to within +/- 0.1°C. Aluminum TZERO Lids and Pans were used. The Q20 DSC equipment is shown in Figure 14.
An OV-12 Vacuum Oven was used to anneal molded polypropylene samples prior to tensile testing in one experiment. The oven is shown below in Figure 15. The OV-12 has a temperature range from ambient to 250°C with an accuracy of +/- 2°C
Figure 15: OV-12 Vacuum Oven

Roughness was measured to compare the surface quality of tensile bars molded in the metal tool to the ones molded in the plastic tool. The surface roughness was measured with a Mitutoyo Surftest SJ-500/P, SV-2100 profilometer shown in Figure 16.
A Computer Numerical Control (CNC) Bridgeport Mill was used in two experiments to determine if post processing the 3D printed mold helps increase the ductility of the molded tensile bars. The mill is shown in Figure 17. In another experiment using the same CNC mill, the edges of the molded tensile bars were machined as shown in Figure 18.
Figure 17: CNC Bridgeport Mill used to Post Process the Digital ABS Mold and Tensile Specimens

Figure 18: Milling the Edges of a Molded Tensile Bar
A Quanta Scanning Electron Microscope (SEM) was used to inspect polypropylene samples taken from the edge of an un-pulled tensile bar from each mold (steel and Digital ABS). The location of the sample from both the steel and Digital ABS mold is shown in Figure 19. Sample preparation included cleaning with acetone and blowing dry with compressed gas. Due to poor conductivity, the samples were gold coated to eliminate the charge effect. The samples were mounted to a fixture to be viewed with the Quanta SEM.

Figure 19: Schematic Representation of the Section of the Tensile Bar Where the Electron Microscope Image Was Taken

Swiss Precision Instruments (SPI) Digital Calipers were used to measure the molded tensile bars before tensile tests. The calipers are shown in Figure 20.
Mold surface temperatures were measured with a K-type Omega HH800A thermocouple probe shown in Figure 21.
Materials

Polypropylene and high impact polystyrene were used for the injection molding experiments. The polypropylene is made by Advanced Composites with a melt index of 31.0 g/10min at 230°C, 2.16 kgf. The polystyrene used was made by Styrolutio and has a melt index of 3.0 g/10min at 230°C, 2.16 kgf.

Testing

Experiments were carried out to identify the conditions causing the parts molded in the plastic tools to be less ductile than the steel tool samples. The experiments explored six different aspects: (1) melt and injection temperatures, (2) material crystallinity, (3) filling speed (4) surface finish, (5) mold stability and (6) polymer melt residence time in the barrel.

Effect of Mold and Injection Temperatures

The thermal conductivity (TC) of a Digital ABS tool is 71 times lower than the TC of a traditional metal tool. The TC of Digital ABS was measured to be 0.28 $W\ (mK)^{-1}$, and the TC of a traditional P20 steel tool is 20-25 $W\ (mK)^{-1}$ (T. Tábi, 2016). This extremely large difference in TC will cause differences in the thermal history of the molded parts in the Digital ABS mold, despite using the same injection molding processing conditions than in a steel tool.

During the injection phase, the outside layer of the polymer melt comes into contact with the mold surface. In a traditional metal tool, the outer layer will instantaneously drop in temperature when it meets the cool mold, but the core will remain hot. The surface layers
are now under compressive stresses, and the inner layers are still hot and behave as a fluid (A. Guevara-Morales, 2014). When molding with a Digital ABS mold, it is assumed that the surface layers will not be under the same compressive stresses due to a lack of instantaneous temperature drop. Instead, there will be a more uniform and much slower cooling rate through the cross section of the molded part. The through thickness morphology of molded parts with epoxy resin molds was analyzed compared to the through thickness of steel molds by Martinho et. al. The through thickness results showed a more uniform morphology and β-form spherulites that are associated with slower cooling (Pedro Gonçalves Martinho, 2009). The steel mold’s specimens through thickness morphology results showed a layered structure across the thickness including a spherulitic core, two intermediate crystalline and oriented layers, and two highly oriented skin layers (Pedro Gonçalves Martinho, 2009).

Two experiments were run for this thesis to explore the effect of different mold and injection temperatures on tensile strain at break. Experiment 1 looks at molding with the steel ASTM tool varying only the initial mold temperature using ethylene glycol coolant running through the cooling lines to control the mold temperature during the molding cycle. Experiment 2 looks at molding with the Digital ABS tool and comparing the ductility of the sample from shot 1 compared to shots 2-12 where the mold temperature had increased due to previous shots.

Experiment 1

The steel ASTM tool was used to mold 10 tensile specimens at the recommended steel tool temperature of 45°C and 10 specimens at an elevated tool temperature of 80°C.
The molding material used was Polypropylene. The molding process conditions are shown below in Table 4.

<table>
<thead>
<tr>
<th>Melt Temperature (°C)</th>
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</thead>
<tbody>
<tr>
<td>Tool Temperature (°C)</td>
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<tr>
<td>Mold Open Time (s)</td>
<td>10</td>
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<tr>
<td>Injection Time (s)</td>
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</tr>
<tr>
<td>Packing Pressure (psi)</td>
<td>300</td>
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<tr>
<td>Packing Time (s)</td>
<td>25</td>
</tr>
<tr>
<td>Cooling Time (s)</td>
<td>30</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polypropylene</td>
</tr>
</tbody>
</table>

Table 4: Molding Parameters used for Experiment 1

After molding, the 10 tensile bar specimens from each molding condition were tested on the INSTRON machine pulled at 50 mm/min. A pull rate of 50 mm/min instead of the ASTM recommended values was used, as recommended by a local manufacturer. The strain to break (ductility) results are shown below in Figure 22.
A two sample t-test was run at 95% confidence level comparing the strain at break results from the two different mold temperatures. The p-value was 0.0194. According to these results, a tool temperature of 80°C significantly decreased the strain at break in samples from 243% to 150%. This could help explain the decrease in elongation results from the plastic tool samples, as tool temperature and therefore the thermal history of the molded parts is most likely a significant factor. The Digital ABS tool used in this thesis cannot be thermally controlled like the steel tool due to a lack of cooling lines. The Digital ABS mold heats up quickly due to its low TC and will stay warm if it is not allowed to cool completely between shots.
Experiment 2

Polypropylene was used to mold 12 shots into the Digital ABS tool. The injection molding parameters used are listed below in Table 5. Note that the mold open time was extended from 10 seconds, used previously with the steel tool in Experiment 1, to 240 seconds. Additionally, the packing pressure was decreased from 300 psi to 175 psi to help prolong the life of the tool. The packing pressures listed in the tables in this thesis are the machine pressures, not the real packing pressure values in the cavity. A previous experiment was done to determine the pressure in the cavity of the steel tool recorded by internal sensors. The pressure in the cavity is about 3415 psi when the machine setting is at 175 psi. The cooling time was increased to 50 seconds to allow the molded part to completely solidify before ejecting.

<table>
<thead>
<tr>
<th>Melt Temperature (°C)</th>
<th>212</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Open Time (s)</td>
<td>240</td>
</tr>
<tr>
<td>Injection Time (s)</td>
<td>1</td>
</tr>
<tr>
<td>Packing Pressure (psi)</td>
<td>175</td>
</tr>
<tr>
<td>Packing Time (s)</td>
<td>30</td>
</tr>
<tr>
<td>Cooling Time (s)</td>
<td>50</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polypropylene</td>
</tr>
</tbody>
</table>

Table 5: Molding Parameters used for Experiment 2

After molding, the 12 tensile bars were tensile tested. The results are shown below in Figure 23.
The mold temperature at shot 1 was recorded to be similar to the initial steel mold temperature around 27°C. Shots 2-12 had an initial mold temperature of 45°C after waiting for 240 seconds between shots. Results show that shot one from the Digital ABS tool has a much larger strain at break value compared to shots 2-12. Shot 1 has a strain at break of 105% compared to shots 2-12 which have an average strain at break of 23%. This result could be due to the cooler initial mold for shot 1.

An additional experiment was done with the Digital ABS tool to determine how repeatable the results from experiment 2 are. The processing parameters used to mold the polypropylene tensile bars from the Digital ABS tool were the same as described above in
Table 5. It should be noted that a different Digital ABS tool was used for this experiment.

The strain at break results are shown below in Figure 24.

![Polypropylene- Digital ABS Tool- Strain at Break Comparing Shot 1 to Shots 2-8](image)

Figure 24: Digital ABS Tool Strain at Break Comparing Shot 1 to Shots 2-8

Again, results indicate that the first shot has increased ductility compared to shots 2-8 in the Digital ABS tool. Comparing the strain values from Shot 1 (105% and 95%), there is slight variation between the two different experiments. Although these experiments were run with the same processing conditions, the difference could be due to possible slight differences in the Digital ABS tools used. It is recommended that this result be examined further in future studies.
Effect of Crystallinity

As stated above, the thermal conductivity of the Digital ABS tool is much lower than that of a steel tool. The lower TC causes a slower removal of heat from the part to the mold (T. Tábi, 2016). This causes the molded part to have a slower cooling rate which will cause larger spherulite diameters and higher crystallinity in the molded parts. These factors all impact the molded part mechanical properties, more specifically, it has been found that necking will occur earlier in tensile specimens (T. Parenteau, 2012).

The slower crystallization of syndiotactic polypropylene was compared to isotactic polypropylene by Choi et. al. Syndiotactic polypropylene showed no crystallization during the filling stage and then a significant stress relaxation after the filling stage. This caused lower orientation in the core zone of the tensile specimens (Dongman Choi, 2002). This could be similar to what is happening when injection molding with polypropylene in the Digital ABS tool. The slow cooling occurring in the plastic mold could cause slower crystallization during the filling phase.

The effect of different cooling rates on the morphology of polypropylene was studied by Elmajdoubi et. al. The results showed that an increase in the cooling rate led to smaller, less perfect spherulites (M. Elmajdoubi, 2003). Another study by Tábi et. al. researched the average spherulite diameter sizes in PLA samples molded in a Digital ABS tool compared to a 23°C steel tool. The results showed that the average crystallite sizes of samples from the Digital ABS mold were 45-50 nm where the steel crystallite sizes were 3-4 nm (T. Tábi, 2016). The larger spherulites were due to a slow cooling rate because crystallization takes place only above the glass transition temperature. When molding in a
Digital ABS mold it was found that, the part will stay above the glass transition temperature of the polymer melt for 66 seconds compared to only 15 seconds in a 23°C steel mold (T. Tábi, 2016).

Harris et. al., found that an increase in crystallinity of just 2% had a significant effect on the shrinkage of polypropylene (R.A. Harris, 2004). The crystallinity of nylon (PA66) was measured with DSC after being molded into a 3D printed Stereolithography mold. The DSC results showed an exotherm prior to the heat of fusion due to recrystallization (R.A. Harris, 2004). This exotherm is caused by incomplete crystallization when molding with a semi-crystalline material in a traditional steel tool. Additionally, an increase of crystallinity was found to increase the stiffness in molded parts (R.A. Harris, 2004) (M. Elmajdoubi, 2003).

In this thesis, three experiments were completed to observe the effect of crystallinity on the ductility of samples molded in the Digital ABS tool. Experiment 3 explores the difference between the ductility of semi-crystalline and amorphous specimens molded in the Digital ABS tool. Experiment 4 considers the crystallinity of polypropylene samples molded in the steel tool vs. Digital ABS tool. Experiment 5 looks at the effect of annealing polypropylene samples in an oven at 100°C after molding and how that impacts ductility compared to samples that were not annealed.

Experiment 3

Polystyrene is an amorphous material. Polystyrene was chosen to determine if an increase in crystallinity was the main reason causing the Digital ABS tool specimens to be
less ductile. A total of 18 samples were molded in the Digital ABS tool and 11 samples in the steel tool. The molding conditions used are shown in Table 6.

<table>
<thead>
<tr>
<th></th>
<th>Steel Tool</th>
<th>Digital ABS Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Temperature (°C)</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Mold Open Time (s)</td>
<td>10</td>
<td>240</td>
</tr>
<tr>
<td>Injection Time (s)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Packing Pressure (psi)</td>
<td>175</td>
<td>175</td>
</tr>
<tr>
<td>Packing Time (s)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Cooling Time (s)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polystyrene</td>
<td>Polystyrene</td>
</tr>
</tbody>
</table>

Table 6: Molding Parameters used for Experiment 3

After molding, the samples from both molds were tensile tested on the INSTRON machine. The average strain at break results from the tensile tests are shown below in Figure 25.
Figure 25: Polystyrene Average Strain at Break Varying Tool Material

Results show that molding with an amorphous material in a Digital ABS tool still gives parts with lower ductility. Compared to the results from molding with polypropylene in the Digital ABS tool, there is less of a decrease in ductility found when molding with polystyrene. With polystyrene there is a decrease of 66% from the steel tool to the Digital ABS tool. With polypropylene there is a decrease of 86%.

Experiment 4

The crystallinity of five polypropylene samples molded in the Digital ABS tool were measured and compared to the crystallinity of five samples molded in the steel tool.
The processing parameters used for this study are shown below in Table 7. The crystallinity results obtained from the DSC experiments are shown in Table 8.

<table>
<thead>
<tr>
<th>Melt Temperature (°C)</th>
<th>Steel Tool</th>
<th>Digital ABS Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>214</td>
<td>214</td>
</tr>
<tr>
<td>Mold Open Time (s)</td>
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<tr>
<td>Injection Time (s)</td>
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<tr>
<td>Packing Pressure (psi)</td>
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<td>175</td>
</tr>
<tr>
<td>Packing Time (s)</td>
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</tr>
<tr>
<td>Cooling Time (s)</td>
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<td>30</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polypropylene</td>
<td>Polypropylene</td>
</tr>
</tbody>
</table>

Table 7: Molding Parameters used for Experiment 4

<table>
<thead>
<tr>
<th>Mold Material</th>
<th>Average Percent Crystallinity (%)</th>
<th>Standard Deviation (n=5)</th>
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</thead>
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<tr>
<td>Digital ABS</td>
<td>28.4</td>
<td>3.11</td>
</tr>
<tr>
<td>Steel</td>
<td>24.7</td>
<td>2.26</td>
</tr>
</tbody>
</table>

Table 8: Polypropylene Crystallinity Results in Digital ABS Tool vs. Steel Tool

The polypropylene samples from the Digital ABS tool have higher average percent crystallinity than samples from the steel tool. A two-sample t-test was conducted at 95% confidence comparing the average crystallinity from the Digital ABS tool vs. the Steel tool. The p-value is 0.067. This p-value indicates that the plastic and steel samples are almost statistically different. This could be due to the lower TC of Digital ABS causing a slower cooling rate of the molded parts.

Another interesting result obtained from the DSC experiments is the presence of an exotherm in the steel molded part’s DSC experiments. This exotherm could signify that there is a development of further crystallinity occurring due to the heating during the DSC
test (R.A. Harris, 2004). The DSC experiments on the parts molded from the Digital ABS tool do not have this exotherm present. Figure 26 shows the exotherm present during DSC tests on a sample from the steel tool. Figure 27 shows the lack of an exotherm by a smooth curve when performing DSC on a sample from the Digital ABS tool.

Figure 26: DSC Analysis on a Polypropylene Sample Molded from the Steel Tool

Figure 27: DSC Analysis on a Polypropylene Sample Molded from the Digital ABS Tool
Experiment 5

An experiment was conducted analyzing the effect of annealing 10 polypropylene samples from the steel mold in an oven at 100°C. After the annealing process, the samples were tensile tested and strain at break results were compared to 10 tensile bars that were not annealed. The annealed samples were allowed to equilibrate with the ambient for 24 hours after molding, then annealed at 100°C for 4 hours. These samples were tensile tested 48 hours after annealing. The non-annealed samples were tensile tested 48 hours after molding. The injection molding processing parameters used to mold the two sets of 10 bars are shown in Table 9. The elongation to break results are compared in Figure 28.

<table>
<thead>
<tr>
<th>Melt Temperature (°C)</th>
<th>212</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Open Time (s)</td>
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<tr>
<td>Injection Time (s)</td>
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<td>Packing Pressure (psi)</td>
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<td>20</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polypropylene</td>
</tr>
</tbody>
</table>

Table 9: Molding Parameters used for Experiment 5
Figure 28: Steel Tool Strain at Break Results Comparing Not Annealed vs. Annealed Specimens

Results seem to show that annealing the semi-crystalline polypropylene tensile bars changes the ductility of the molded parts. For this experiment, only ductility was measured after annealing. Similar results were found in the literature; When annealed at 160°C, a higher crystallinity and thicker crystalline lamellae were measured. This also caused necking to occur earlier in the molded tensile bars (T. Parenteau, 2012). Another study found that when the molded parts were thermally aged at 140°C for 12 days, there was a significant increase in crystallinity compared to the control group that was not thermally aged (Aaron Law, 2008).
Effect of Filling Speed

Using different mold materials can cause differences in the flow induced stresses during the filling phase of the injection molding process. The heat transfer in the plastic mold is slower and thus can cause the molded part’s microstructure to have a more uniform through-thickness morphology. A different morphology can lead to differences in mechanical properties of molded parts.

During the filling stage using polypropylene in a traditional metal tool, 3 layers of different morphology have been identified: a spherulitic core and two highly oriented skin layers. A more uniform through-thickness can be viewed when using a tool with lower thermal conductivity (Pedro Gonçalves Martinho, 2009). The absence of this intermediate shear zone and crystalline layer suggests that there are different residual stresses in the parts due to the flow induced stresses. Different flow thermal histories experienced by the polymer melt can lead to enhanced crystallization and different types of flow-induced crystallization (A. Guevara-Morales, 2014). As mentioned before, a difference in crystallinity can lead to changes in part properties.

The effect of filling speed of the molded part on strain to break was explored in this thesis through three experiments. Experiment 6 explores the effect of molding with polystyrene, an amorphous material, in the Digital ABS tool at a slower injection speed and lower melt temperature. Experiment 7 looks at molding with polypropylene in the Digital ABS tool at a slower injection speed and a lower melt temperature. Experiment 8
utilizes a supercritical CO₂ cooling spray on the plastic mold to decrease the plastic mold temperature to 9°C before each shot.

**Experiment 6**

Experiment 3 indicated that when molding with an amorphous material in the Digital ABS tool, the ductility decreased, however not as much as for polypropylene, a semi-crystalline material. Experiment 6 explores the result of changing the processing parameters in the Digital ABS tool to increase the ductility of the polystyrene tensile bars to match the steel tool. Melt temperature and injection time were modified in attempt to increase the strain at break. The melt temperature was decreased from 240°C to 214°C and the injection time was slowed from 1 second to 4 seconds. The purpose of these changes was to increase the cooling during filling in the plastic tool cavity to promote the formation of frozen layer in the polystyrene tensile bars. The molding parameters used for Experiment 6 are show below in Table 10.

<table>
<thead>
<tr>
<th>Melt Temperature (°C)</th>
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<th>240</th>
<th>214</th>
</tr>
</thead>
<tbody>
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<td>Mold Temperature (°C)</td>
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<td>Mold Open Time (m)</td>
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<td>Injection Time (s)</td>
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<td>Packing Pressure (psi)</td>
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<td>Packing Time (s)</td>
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<td>Cooling Time (s)</td>
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<tr>
<td>Mold Material</td>
<td>Digital ABS-Recommended</td>
<td>Steel-Recommended</td>
<td>Digital ABS-214°C, 4s</td>
</tr>
</tbody>
</table>

Table 10: Molding Parameters used for Experiment 6
The resulting strain to break values are compared to the values from Experiment 4. The results are shown below in Figure 29 (n=18, 11, 10 respectively).

![Polystyrene Average Strain at Break Varying Tool Material](Image)

**Figure 29: Polystyrene Average Strain at Break Varying Tool Material**

By lowering the melt temperature from 240°C to 214°C and slowing down the injection speed from 1 second to 4 seconds when molding with polystyrene in the Digital ABS tool, ductility was increased from 88% to 267%. The strain at break value matches the results obtained when molding with polystyrene in the steel tool. These results could help determine what molding conditions to use when molding with a plastic mold.
Experiment 7

Polypropylene was used to mold with in the Digital ABS and steel tool. Melt temperature and injection speed were varied and the strain at break results were obtained and compared. The molding parameters used when molding in the Digital ABS and steel tool are shown below in Table 11.

<table>
<thead>
<tr>
<th></th>
<th>Steel Tool</th>
<th>Digital ABS Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Temperature (°C)</td>
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<td>182 / 212</td>
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</tr>
<tr>
<td>Injection Time (s)</td>
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<td>0.3 / 4</td>
</tr>
<tr>
<td>Packing Pressure (psi)</td>
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<td>175</td>
</tr>
<tr>
<td>Packing Time (s)</td>
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<tr>
<td>Molding Material</td>
<td>Polypropylene</td>
<td>Polypropylene</td>
</tr>
</tbody>
</table>

Table 11: Molding Parameters used for Experiment 7

Figure 30 shows the results from molding with polypropylene in the steel tool varying only injection speed (n=10 for both groups). The melt temperature was held constant at the recommended 212°C.
The trend shows that molding with a 0.3 second injection speed causes the strain at break result to decrease compared to an injection speed of 1 second. A similar trend is found when molding in the Digital ABS tool. Figure 31 shows the results of molding with polypropylene in the Digital ABS tool varying melt temperature and injection speed (n=10 for all four groups).
The results suggest that a decreased melt temperature and slower injection speed in the Digital ABS tool helped increase the strain at break in the molded parts. A two-sample t-test at a 95% confidence level confirms that the modified conditions of 182°C melt temperature and 4 second are significantly different than the recommended conditions of 212°C and 1 second. The p-value from the t-test comparing these two molding conditions was <0.0001 confirming that they are statistically different.

Figure 32 below compares the Digital ABS average strain to break results to the average values from the steel tool.
The recommended molding parameters used for polypropylene in the Digital ABS and Steel tool are a melt temperature of 212°C and an injection speed of 1 second. By lowering the melt temperature and slowing the injection speed, the average strain at break value was increased to 135%. The average steel mold elongation results for the same molding parameters were 267% as shown above in Figure 32.

Although the strain at break results were improved for polypropylene in the Digital ABS tool, they did not improve as much as polystyrene. When molding with the lower melt temperature and slow injection speed with polystyrene, the strain at break results matched the results from the steel tool.
The results from Experiment 7 agree with the findings from the literature review. Molding with a lower melt temperature could help keep the tool temperature lower during the injection phase, which can result in a frozen layer more similar to the steel mold. For polystyrene, an amorphous material, changing these two factors alone resulted in not only an increase in strain at break, but a value that matched the value obtained from the steel mold samples. For polypropylene, a semi-crystalline material, the strain increased considerably compared to the previous molding conditions (37% to 135%), but still did not reach the value obtained from the steel mold of 267%.

**Experiment 8**

Experiment 8 was conducted to test the effect of spraying a cooling fluid on the Digital ABS tool to cool it down rapidly between shots. The cooling fluid used was supercritical CO₂. The next shot was made immediately after the cooling fluid was sprayed on the Digital ABS mold. The mold temperature was measured to drop to 9°C. The temperature of the mold after the supercritical CO₂ sprayed on the tool is shown in Figure 33. The molding parameters used for Experiment 8 are shown in Table 12.
Figure 33: Temperature of Digital ABS Insert after supercritical CO$_2$ is Sprayed

<table>
<thead>
<tr>
<th></th>
<th>Steel Tool- Recommended</th>
<th>Digital ABS Tool- Modified Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Temperature ($^\circ$C)</td>
<td>212</td>
<td>182</td>
</tr>
<tr>
<td>Mold Open Time (s)</td>
<td>10</td>
<td>240</td>
</tr>
<tr>
<td>Injection Time (s)</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Packing Pressure (psi)</td>
<td>175</td>
<td>175</td>
</tr>
<tr>
<td>Packing Time (s)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Cooling Time (s)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polypropylene</td>
<td>Polypropylene</td>
</tr>
</tbody>
</table>

Table 12: Molding Parameters used for Experiment 8
The strain at break results from molding with polypropylene in the plastic mold with an initial mold temperature around 9°C due to the supercritical \( \text{CO}_2 \) is shown below in Figure 34.

![Graph showing strain at break varying melt temp and mold material](image)

**Figure 34: Plastic Tool Strain at Break Varying Melt Temp, Injection Speed and Supercritical \( \text{CO}_2 \)**

Preliminary results show that cooling the surface of the mold increases the ductility of the samples.

**Effect of Surface Finish**

One of the reasons the Digital ABS mold was chosen as a mold material for this thesis is its surface quality. Digital ABS tooling has been chosen by other researchers due
to its surface quality and its resistance to high temperatures and pressures (Neri Volpato, 2016) (Gabriel Antonio Mendible, 2017) (T. Tábi, 2016) (József Gábor Kovács, 2015). It is recommended to align the print line orientation in the direction of polymer flow through the cavity (Neri Volpato, 2016). Another advantage of Digital ABS for tooling applications is that little to no post-processing is required. Compared to steel tooling however, Digital ABS tooling generates parts with significantly increased roughness. For this reason, surface finish was considered when attempting to identify the variables causing a decrease in ductility of Digital ABS molded parts. The issue is, are the surface imperfections large enough so that they cause stress concentrations that would decrease ductility.

Three experiments were carried out analyzing the effect of surface finish and mold integrity on the molded part’s strain at break. In Experiment 9, the edges of the Digital ABS cavity were machined and that mold was used to mold tensile bars. In Experiment 10, the edges of the molded tensile bars themselves were machined and the strain at break value was measured and compared to non-machined tensile bars. Experiment 11 explored the effect of print line orientation of the Digital ABS mold and surface finish.

**Experiment 9**

The edges of the Digital ABS tool cavity were machined to smooth out the print lines that are present due to the printing process. The print lines on the edge of the cavity show up in detail on the molded tensile bars.

The edges of the Digital ABS mold were machined on a Bridgeport CNC machine. The parameters used during molding for Experiment 8 are shown below in Table 13.
The tensile bars were tensile tested on the INSTRON tensile testing machine and the strain at break values were recorded. The results were compared to tensile bars molded in a Digital ABS mold without the cavity edges machined. The results are shown below in Figure 35.

![Polypropylene- Digital ABS Tool- Strain at Break Varying Cavity Surface Finish](image)

**Figure 35: Strain at Break Results Varying Digital ABS Cavity Surface Finish**
Results indicate that the tensile bars molded in the machined cavity did not have an increase in ductility. This could mean that the print lines on the Digital ABS mold are not affecting the mechanical properties of the molded tensile bars.

As a result of Experiment 9, an additional study was completed to look into more detail of the surface finish of the tensile bars from each mold. Polypropylene was used to mold in the machined cavity Digital ABS mold and the metal mold. Samples of the tensile bars were prepared and analyzed with a Scanning Electron Microscope (SEM). The location of the sample taken from both bars is shown in Figure 36.

![Figure 36: The Edge of the Tensile Bar Where the Samples Were Taken for the Electron Microscope Experiments](image)

The purpose of this experiment was to compare the surface quality of tensile bars molded from different tools. Figure 37 shows a photo of the sample molded from the machined Digital ABS mold. Figure 38 shows the photo of the sample from the steel mold.
Figure 37: SEM Photo of Polypropylene Molded in the Machined Cavity Digital ABS Mold

Figure 38: SEM Photo of Polypropylene Molded in the Steel Mold
The surface roughness can be compared and it is clear that the sample molded from the machined plastic mold has more surface defects than the sample from the steel mold.

**Experiment 10**

The SEM pictures from the above experiment hinted that the surface finish is different from the tensile bars from different tools. Experiment 10 was conducted to make the surface finish of the two bars similar before performing tensile tests. Tensile bars were molded in both the steel mold and the plastic mold. Next, the edges of the tensile bars were machined and the surface roughness was measured. The tensile bars were tested and the strain at break values were recorded. The molding parameters used are shown in Table 14. The mold temperature was kept at 45°C.

<table>
<thead>
<tr>
<th></th>
<th>Steel Tool</th>
<th>Digital ABS Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Temperature (°C)</td>
<td>212</td>
<td>212</td>
</tr>
<tr>
<td>Mold Open Time (s)</td>
<td>10</td>
<td>240</td>
</tr>
<tr>
<td>Injection Time (s)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Packing Pressure (psi)</td>
<td>175</td>
<td>175</td>
</tr>
<tr>
<td>Packing Time (s)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Cooling Time (s)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polypropylene</td>
<td>Polypropylene</td>
</tr>
</tbody>
</table>

Table 14: Molding Parameters used for Experiment 10

14 tensile bars were molded from the steel tool and 14 from the Digital ABS tool. The edges of seven tensile bars from each group were machined. The surface roughness values and the strain at break of the four groups were measured and recorded. The results are shown below in Table 15.
Machining the tensile bars from the steel mold caused the surface roughness to increase from 0.98 um to 7.49 um. The increase in surface roughness did not cause the strain at break result to decrease. A two-sample t-test at a 95% confidence level gave a p-value of 0.0516 indicating that there is not statistical difference between 252.8% strain and 287.9% strain. Although this p-value is close to 0.05, it is determined that 252.8% strain did not decrease the strain to the value obtained from the plastic molds, so the surface finish is not a significant parameter causing a decrease in ductility.

Machining the tensile bars from the Digital ABS mold caused the surface roughness to decrease slightly from 4.91 um to 3.23 um. Again, a two-sample t-test was performed at a 95% confidence level comparing the machined and non-machined tensile bars from the Digital ABS mold. The p-value was 0.8831. This indicates there is no statistical difference and making the Digital ABS samples smoother did not cause the strain at break to significantly increase. Based on the results from Experiment 9 and 10 it can be concluded that surface finish does not play a significant role in the decrease in elongation found in samples from the Digital ABS tool.
Experiment 11

All prior experiments were conducted with a Digital ABS tool printed with print lines parallel to the direction of polymer flow during molding and the pull direction during tensile testing. Experiment 11 was conducted using a Digital ABS tool with print lines perpendicular to the polymer melt flow and the pull direction during tensile testing. The molding parameters used for Experiment 11 are shown below in Table 16.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Melt Temperature (°C)</td>
<td>212</td>
</tr>
<tr>
<td>Mold Open Time (m)</td>
<td>4</td>
</tr>
<tr>
<td>Injection Time (s)</td>
<td>1</td>
</tr>
<tr>
<td>Packing Pressure (psi)</td>
<td>175</td>
</tr>
<tr>
<td>Packing Time (s)</td>
<td>30</td>
</tr>
<tr>
<td>Cooling Time (s)</td>
<td>30</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polypropylene</td>
</tr>
</tbody>
</table>

Table 16: Molding Parameters used for Experiment 11

The tensile bars from the perpendicular Digital ABS tool were tensile tested on the INSTRON and the strain at break was compared to tensile bars molded from a Digital ABS tool with parallel print lines. The results are shown in Figure 39.
Figure 39: Digital ABS Tool Strain at Break Varying Print Line Orientation

Results indicate that the perpendicular print lines do not significantly decrease the strain at break value compared to the mold with parallel print lines. These results agree with the previous surface finish experiment results indicating that surface finish is not a significant parameter effecting the ductility of the tensile bars.

**Effect of Mold Stability**

Polypropylene was used to mold tensile bars in the steel ASTM mold and the Digital ABS mold. Tensile bars 1-30 were molded at a packing pressure of 50 psi, 31-60
at 100 psi, 61-90 at 175 psi, and 91-100 at 250 psi. The process parameters used are shown below in Table 17.

<table>
<thead>
<tr>
<th></th>
<th>Steel Tool</th>
<th>Digital ABS Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Temperature (°C)</td>
<td>213</td>
<td>213</td>
</tr>
<tr>
<td>Mold Open Time (s)</td>
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<td>240</td>
</tr>
<tr>
<td>Injection Time (s)</td>
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<td>1</td>
</tr>
<tr>
<td>Packing Pressure (psi)</td>
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<tr>
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<td>20</td>
</tr>
<tr>
<td>Cooling Time (s)</td>
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<td>50</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polypropylene</td>
<td></td>
</tr>
</tbody>
</table>

Table 17: Molding Parameters used for the Mold Stability Experiment

The normalized cross-sectional area of the tensile bars was measured with digital calipers 48 hours after molding. The data was normalized by dividing the measured area of the samples by the area of the tool cavity. The dimensions of the tensile bar cavity are 3.2mm by 13.0 mm, resulting in a cross sectional area of 41.6 mm². The average area of the 30 bars from 50, 100, and 175 psi and 10 bars from 250 psi were taken and normalized. The normalized area results are shown below in Figure 40.
Results indicate that the Digital ABS mold distorts with increased packing pressure. For the metal mold except at the larger pressure of 250 psi, the cross section remains unchanged.

Statistical analysis was performed comparing the area of tensile bars molded with the least packing pressure (50 psi) to the bars made with higher pressures (100, 175, 250 psi). The difference between means is greater when comparing the differences in dimensions from the plastic mold packing pressures to the differences found from the steel mold. These values are shown in Table 18. The steel mold is not creating tensile bars with
as much cross-sectional area differences, especially at 175 psi and 250 psi possibly due to less distortion of the mold during the molding process.

<table>
<thead>
<tr>
<th>Difference Between Means</th>
<th>Steel Mold</th>
<th>Plastic Mold</th>
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</thead>
<tbody>
<tr>
<td>50 psi vs. 100 psi</td>
<td>0.408</td>
<td>0.907</td>
</tr>
<tr>
<td>50 psi vs. 175 psi</td>
<td>0.829</td>
<td>5.623</td>
</tr>
<tr>
<td>50 psi vs. 250 psi</td>
<td>3.553</td>
<td>12.657</td>
</tr>
</tbody>
</table>

Table 18: Difference Between Cross Sectional Area of Tensile Bars

Effect of Residence Time in the Injection Barrel

Residence time refers to the time the polymer remains in the barrel of the injection-molding machine. When molding with the Digital ABS tool, the material residence time in the barrel is larger due to the larger cooling time needed. It is important to know if the extended time in barrel causes the polymer degradation. Experiment 12, investigated this issue.

*Experiment 12*

Polypropylene was used to mold in the steel ASTM mold for Experiment 12. The molding parameters used are shown in Table 19.

<table>
<thead>
<tr>
<th>Melt Temperature (°C)</th>
<th>212</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in Barrel (m)</td>
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</tr>
<tr>
<td>Injection Time (s)</td>
<td>1</td>
</tr>
<tr>
<td>Packing Pressure (psi)</td>
<td>300</td>
</tr>
<tr>
<td>Packing Time (s)</td>
<td>25</td>
</tr>
<tr>
<td>Cooling Time (s)</td>
<td>30</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polypropylene</td>
</tr>
</tbody>
</table>

Table 19: Molding Parameters used for Experiment 12
Time in barrel was split into three groups: control (1 minute), 5 and 25 minutes. This was accomplished by purging the barrel, molding the first shot (control), then waiting 5 minutes. The next shot was molded and labeled “5 minutes, #1.” After waiting another 20 minutes, the next shot was molded and labeled “25 minutes, #1.” The barrel was purged and the process was completed again for nine times.

The tensile bars were tested on the INSTRON and the strain at break values were measured. The results are shown below in Figure 41.

![Graph showing Steel Tool Average Strain at Break Varying Residence Time](image)

Figure 41: Steel Tool Average Strain at Break Varying Residence Time

A two-sample t-test analysis was run on the 5 and 25-minute residence time strain values compared to the control group. The P-results were 0.50 and 0.65 respectively. Using
a confidence level of 95%, these p-values indicate that an increase in the residence time does not significantly affect the ductility of the samples. This implies that the long mold open time necessary when molding with the Digital ABS mold does not promote material degradation.
Conclusions

In this chapter, we evaluated the effect of six plastic mold aspects on molded part ductility, namely: mold and injection temperatures, material crystallinity, filling speed, surface finish, mold stability and residence time in the injection barrel. Parts were molded in both plastic and metallic molds.

Results indicate that the slower cooling rate of parts molded with the Digital ABS tooling seems to be the major cause of the decrease in ductility of the tensile bars molded in the plastic tool. This decrease in ductility is larger for semi crystalline materials than for amorphous materials. The increase in roughness, nor the residence time in the injection barrel for the plastic mold with respect to the steel mold seem to play a role in decreasing ductility.

In summary, we can say that, parts molded in a Digital ABS 3D printed tool have lower ductility than parts molded in metal molds. This could be an issue if the parts molded in the plastic tool are to be used for applications where mechanical properties play a key role. Conditions that minimize this different were identified. In order to mold similar parts in the plastic tool to the ones molded in metal molds, the temperature history that the part undergoes in both molds needs to be similar. This effect is larger for semi crystalline materials than for amorphous materials.

Future Work

As mentioned above, the critical aspect to obtain similar mechanical properties of parts molded in plastic molds to parts molded in metal molds is to control the thermal
history that the part undergoes during molding. This could be accomplished by locating conductive layers on the surface of the plastic mold and modifying the processing conditions so that the difference in thermal histories is minimized. Cooling the plastic mold with supercritical fluid may be one way, however care needs to be taken not to damage the plastic mold. Conformal cooling may also be another approach. Since this difference is larger for semi crystalline than for amorphous materials, a study of the effect of processing conditions on part morphology is recommended. Using additives to influence the morphology of the part could be a way of influencing the part ductility.
Chapter 4: Summary and Conclusions

Two aspects of 3D printed tooling were analyzed in this thesis: tool survivability and part mechanical properties. Tool survivability was measured by analyzing the effect of different flow rates on different sized ribs. The predicted Von Mises stress at the base of the 10:1 rib were larger than the yield strength of Digital ABS, so it failed during all molding trials. For the 5:1 rib, the predicted Von Mises stresses did not exceed the yield strength, which agreed with the experimental results of the rib not breaking during the first shot. However, the 5:1 rib failed after several shots. When the temperature of the rib was kept below the material deflection temperature, it was found that the rib did not break after many moldings.

Most this thesis was focused on how molding with a 3D printed tool will affect the part’s mechanical properties compared to molding with a steel tool. It was found specifically that tensile elongation at break was significantly decreased in parts from a plastic mold. Experiments were conducted to evaluate the significant molding conditions affecting strain at break including thermal history, crystallinity, filling speed, surface finish, and residence time. In addition to completing experiments, a literature review was conducted and each section provides evidence from literature explaining how that parameter may affect the part’s properties.

The properties that were found to significantly affect elongation at break in the 3D printed tool parts were thermal history, crystallinity and filling speed. By modifying the parameters affecting these properties, an increase in elongation was found. Specifically, molding with a lower melt temperature and slower filling speed with polystyrene, an
amorphous material, was found to increase the strain at break to the value similar to the one from the steel mold.

It is recommended that additional research is performed on how to increase the elongation at break when molding with a semi-crystalline material, like polypropylene. Although the strain at break value was increased when changing the mold temperature, melt temperature and filling speed, the elongation value was still inferior than the one reached with the steel tool.
Appendix A: Mechanical Properties

Typical stress vs. strain curves are shown below in Figure 42 and Figure 43. These figures represent the decrease in strain found when molding with the Digital ABS tool compared to the Steel tool. Recommended molding conditions were used.

Figure 42: Stress/Strain of Polypropylene Varying Mold Material
The average young’s modulus and tensile strength of specimens molded in the steel tool compared to the Digital ABS tool were analyzed. The molding parameters that were used are recorded in Table 20.

<table>
<thead>
<tr>
<th>Molding Material</th>
<th>Steel Tool</th>
<th>Digital ABS Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Temperature (°C)</td>
<td>213</td>
<td>213</td>
</tr>
<tr>
<td>Mold Open Time (s)</td>
<td>10</td>
<td>240</td>
</tr>
<tr>
<td>Injection Time (s)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Packing Pressure (psi)</td>
<td>175</td>
<td>175</td>
</tr>
<tr>
<td>Packing Time (s)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Cooling Time (s)</td>
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<td>30</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polypropylene</td>
<td>Polypropylene</td>
</tr>
</tbody>
</table>

Table 20: Molding Parameters used for Polypropylene’s Young’s Modulus and UTS study (n=10, 10)
A 2-sample t-test run at 95% confidence level was conducted to compare both Ultimate Tensile Strength (MPa) and Young’s Modulus (E) for polypropylene in both tools. The p-value for UTS was 0.840. The p-value for Young’s Modulus was 0.493. Results seem to indicate that neither UTS or Young’s Modulus is significantly affected by changing the mold material when molding with polypropylene. The mechanical property results are shown below in Figure 44 and Figure 45. The difference in ductility from the same samples are also presented in Figure 46.

Figure 44: Average's Young's Modulus of Polypropylene Varying Mold Material
Figure 45: Average Tensile Strength of Polypropylene Varying Mold Material
Figure 46: Average Strain at Break Results of Polypropylene Showing Significant Difference Despite Similar E and UTS

The same analysis was performed comparing polystyrene’s Young’s Modulus and UTS in the steel mold vs. plastic mold. The molding conditions used are shown below in Table 21.
Table 21: Molding Parameters used for Polystyrene Young’s Modulus and UTS study (n=11, 18 respectively)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Steel Tool</th>
<th>Digital ABS Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Temperature (°C)</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Mold Open Time (s)</td>
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<td>240</td>
</tr>
<tr>
<td>Injection Time (s)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Packing Pressure (psi)</td>
<td>175</td>
<td>175</td>
</tr>
<tr>
<td>Packing Time (s)</td>
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<td>30</td>
</tr>
<tr>
<td>Cooling Time (s)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Molding Material</td>
<td>Polystyrene</td>
<td>Polystyrene</td>
</tr>
</tbody>
</table>

The two-sample t-test results at a 95% confidence level indicate that there is a difference in the mechanical properties when molding in difference tools. The p-value for Young’s Modulus is 0.2367. The p-value for UTS is <0.0001. The graphs showing these results are below in Figures 47 and 48. The ductility results from the same experiment are shown below in Figure 49. It is recommended that more work is performed in looking how molding with a plastic mold effects other mechanical properties of polystyrene.

**Polystyrene- Average Tensile Stress Varying Mold Material**

![Figure 47: Average Young’s Modulus of Polystyrene Varying Mold Material](image-url)

Figure 47: Average Young’s Modulus of Polystyrene Varying Mold Material
Figure 48: Average Tensile Stress of Polystyrene Varying Mold Material

Figure 49: Average Strain at Break Results of Polystyrene Showing Significant Difference Despite Similar E and UTS
Bibliography


