# COMPARATIVE ANALYSIS OF ADDITIVE MANUFACTURED INJECTION MOLDING TOOLS

A THESIS

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# Abstract

Injection molding (IM) is a widely used manufacturing technique for thermoplastic materials. Typically, injection molding tools are made of metals such as steel or aluminum. The process to design and manufacture the metallic tooling is time consuming and requires a large capital investment. In the current work, the effect of changing the mold tool material from traditional metals to plastic materials that are produced via additive manufacturing (AM) is investigated. Two plastic mold materials viz. ULTEM 1010 and HI-TEMP 300 AMB produced via the fused deposition modeling (FDM) and stereolithography (SLA) additive manufacturing processes respectively were studied. A Machined 6061 aluminum mold tool was used as the base mold tool material. The thermoplastic material injected is Polypropylene (PP) because it is one of the most widely used thermoplastics for injection molding. The injection molding processing parameters needed minimal changes to produce acceptable moldings with no defects. The density, tensile properties, and percent crystallinity of the moldings showed no significant change when the metallic mold tool was replaced with the AM mold tools. The shore D hardness decreased by 8% and 5% when the ULTEM 1010 and HI-TEMP 300 AMB tools were used. The tangent bending modulus decreased by 17% when the AM mold tools were used. Shrinkage of the parts made by the ULTEM 1010 and HI-TEMP 300 AMB mold tools increased by 2.2% and 2.9% respectively. The AM mold tools used for PP injection molding can be used in place of traditional metallic molds for low volume production without showing large drops in material properties.

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## Abbreviated Phrases:

PP – Polypropylene
PE – Polyethylene
AM – Additive manufacturing
IM – Injection Molding
FDM – Fused Deposition modeling
SLA – stereolithography

## Frequently used Term:

Molding – Part/specimen resulting from one injection molding process.

# CHAPTER 1

# INTRODUCTION

What is a plastic? Plastic is a broad term for any polymer material where a compound is formed by structural units called “mers”. Atoms share electrons to form large molecules or monomers, polymer chains are then formed by the additions of monomer units. Many polymer chains make up plastic. The elemental composition of polymers is typically carbon as well as other elements such as hydrogen, nitrogen, oxygen, and chlorine [1]. Polymers can then be categorized into three main subdivisions: thermoplastic polymers, thermosetting polymers, and elastomers. Thermoplastics can withstand multiple thermal cycles where the polymer can be heated to its melting point and cool to solidify without significant changes to the molecular structure. Thermosetting polymers undergo a chemical change to “cure” into a rigid structure that is irreversible. Elastomers are polymers that display extensive elastic properties. This thesis will focus on the widely used thermoplastic polymer: Polypropylene.

Plastics have been incorporated in most industries and deemed necessary to improve the modern way of living. They can be found in countless consumer and industrial products ranging from bicycle helmets to building materials. Today’s society has become deeply intertwined with plastics whether they be organic or inorganic. The adoption of plastics into our lives is due to the wide spectrum of material properties available and ease of manufacturing. No other material behaves in the same manner. The uses of plastics include, but are not limited to airbags in automobiles, child safety seats, cell phone components, televisions, roofs, walls, flooring, food storage, food packaging, medical devices, engineered biomedical tissues, biomedical devices, paints, glues, adhesives, and sealants. It is quite remarkable the variety of applications that plastics are used for. Some applications are better than others in terms of a life cycle analysis, regardless all have their place in society if disposed of properly [9].

Polyethylene (PE) and polypropylene (PP) are semi-crystalline thermoplastics that are commonly used in industrial applications. They are the most used thermoplastic materials in the industrial setting. For the current work PP was chosen to be the injected material because of its semi-crystalline nature and because the industry will benefit by adding this specialized method of injection molding to their arsenal of IM practices. PP is a common thermoplastic used for injection molding; it can be synthesized in isotactic, syndiotactic, or atactic structures. This material has a high strength to weight ratio for the thermoplastic material category and is one of the lightest thermoplastics. The most common applications for PP are injection molded parts for automotive applications, houseware products, and fiber products for carpeting [1]. Some specialized applications are one-piece hinges that can be trusted under many cycles and small fibers to reinforce concrete for extra strength in freeze thaw conditions.

Thermoplastic processing techniques have come a long way in the past 60-70 years. Common techniques in today's industry include but are not limited to extrusion, compression molding, blow molding, thermoforming, and injection molding.

Extrusion is the process by which a thermoplastic is heated to a molten state and pushed through a die using a screw or plunger mechanism. This process can be used to make the final product or to compound multiple materials that can be pelletized and used in a different plastic processing technique. Extrusion is commonly used to make solid or hollow profiles. This process is great for making tubes, other hollow or solid complex profiles, and wire/cable coats.

Compression molding is a polymer manufacturing process where the "charge" or plastic feedstock material is distributed to the lower mold cavity then the upper half of the mold compresses the plastic to the net shape of the part. Often the polymer is heated or softened before deposition into the mold so that it can take the final shape more easily. This process can be used for thermoplastics, but it is typically used for thermosets because the rate of production of thermoplastic parts via compression molding cannot compete with the high part production volume of injection molding.

Blow molding is the process where air pressure is used to inflate a heated thin plastic film inside a mold cavity to create a seamless vessel. This is the process used to make a large volume of consumer beverage containers and other vessels.

Thermoforming is the process where a flat thermoplastic sheet is heated and deformed to a desired shape. The plastic sheet must be heated to the point where it is soft and can easily be deformed. Thermoforming has three techniques used for the deformation process, the sheet is deformed by a vacuum system, a pressure system, or a mechanical mold. The plastic sheet is forced around a contour via one of the deforming processes and allowed to cool, thus forming the final shape.

Injection molding is the manufacturing process that consists of heating up thermoplastic pellets to a viscous state and the material is forced to flow under pressure into a mold cavity to form the net shape of the part. The mold tools are typically 2 pieces, but more intricate molds are common, the mold tool is separated after injection and the part/molding can be ejected.

Injection molding is the plastic manufacturing technique employed in the current thesis work. It is one of the most widely used thermoplastic processing techniques because of its ability to produce parts with high accuracy, a high production rate, and low part costs for mass production. The large capital investment for tooling makes injection molding only applicable to high volume productions because as more parts are produced the cost of each individual part goes down [4]. The part is typically net shape or near net shape once the mold cools down and the plastic can solidify [1]. Near net shape means the part made requires minimal post processing and produces minimal waste. Any thermoplastic waste that is produced can be recycled and reused. Complex geometries are possible with injection molding but the removal of the part from the mold can become challenging with more intricate mold tools. The process of IM tool design for complex parts is multifaceted and takes years to master. The cycle time to make one part from start to finish takes 10 to 30 seconds for automated industrial IM, but cycle times of 1 minute or longer are common for larger parts [1]. The mold tool may contain multiple cavities which allows for multiple moldings to be produced with each cycle. IM parts can vary in size from 50 grams to 50lbs, where the upper end of the spectrum is represented by automobile bumpers and refrigerator doors. The upfront costs associated with injection molding can be large and this process becomes more economical when the part quantity produced is very large. Time is money and machining metals is time consuming, injection molding tools must be precisely manufactured to ensure a proper seal, uniform thickness of material, and easy part ejection [2]. The current work explores alternative options for injection molding where a small-medium volume of parts is desired, which has been made possible by additive manufacturing a mold tool.

Additive manufacturing (AM) is an umbrella term that is widely used in the science and engineering spaces today, where a part is created layer by layer. AM processes are constantly being developed and improved. Some common techniques that can be used to process plastics are stereolithography (SLA), fused deposition modeling (FDM), and selective laser sintering (SLS). SLA is a process by which resin is laid down in layers and concentrated UV light is used to cure the resin. The FDM process consists of thermoplastic material being heating and extruded through a nozzle to build a part. SLS is the process where plastic powder is fused together on a bed using a laser. The rapid advancement of these technologies has allowed for intricate geometries and low volume specialized parts that are difficult or impossible to manufacture any other way. The materials available for AM consist of thermoplastics, thermosets, biomaterials, metals, and ceramics. The materials, processes, and applications for AM are constantly changing and evolving.

Rapid tooling is the combination of rapid prototyping (often AM) and a manufacturing process that requires a tool or mold to make the part. The principle of rapid tooling is to make the tool more quickly and cheaper using a manufacturing process that is not traditionally used. The tools created using rapid tooling have a shorter lead time and cost a fraction of their traditional counterparts. One benefit of rapid tooling is that is allows for tool design changes if needed. Once results of the rapid tool are approved, the high tooling cost of a permanent tool can be justified for mass production. If low volume production is needed, a rapid tool can be used in junction with a high-volume manufacturing process without the large capital investment. Applications of rapid tooling include casting foams or plastics, injection molding tools, and mold tools for fiber reinforced composite layup.

Among other processes, AM tooling shows great potential in that sophisticated and intricate details can be accomplished. The recent advancements in additive manufacturing have allowed for parts to be printed quickly and cost effectively. Printing injection molding tooling via additive manufacturing has many applications and benefits. AM manufactured tools are perfect for low volume production runs, pre-production series, and prototyping IM parts. Using injection molding for a low volume production run is uneconomical unless an AM mold tool is used. With the cost reduction of the tooling via AM, injection molding quality parts can be made for low to medium part production volumes. This allows for the high rate of production and desired material properties of injection molding without the large capital costs of tooling. The AM tooling can be very useful in the pre-production series which is making a part using the same production method that will be used in mass production. This process is used for testing the market before the capital investment is made [3]. This allows for the designer to fine tune the item or product with much more efficiency. Small volume production parts made with AM are used more and more often to pilot a product and test with consumers [7]. During the R&D phase of a product it can be difficult to test a part made by additive manufacturing when the final part will be made with injection molding because the material properties of injection molding and AM are going to be different. The properties change when the part is built layer by layer versus solidifying at once. AM tooling allows for design revisions of the mold tool at a fraction of the cost of changing a metal mold.

Not all benefits come without challenges, these become apparent when the traditional injection molding tool is replaced by a tool made of a plastic material. AM tooling challenges include: the strength difference of plastic versus metal, the lifetime of the tool, the change of the design rules for the tool, the rougher surface finish, and the material property changes of the part. Injection molding tools must have the ability to withstand the pressures and temperatures that are associated with the injection molding machine. When injection molding with an AM mold tool, the lifetime of the mold is of concern as these tools will wear much more quickly due to the thermal cycles. The AM mold tool needs to have adequate thermal properties to withstand the temperatures associated with injection molding. It also must withstand the injection pressures and compressive stress of the IM machine to avoid premature failure of the mold tool. When plastic material is used for a mold tool the design rules will change because plastic is not as strong as metal and the injected plastic will act differently when in contact with a textured plastic mold tool. A smooth surface finish is desired for IM tooling to extend the life of the mold tool and to produce smooth parts. The modifications to the IM parameters are going to change based on the material used for the AM tool and changing the processing parameters affects the part properties. Plastic materials have a much lower thermal conductivity than metals, this may result in slower cooling as heat takes longer to dissipate. The cooling rate is the most important factor that determines the material properties of semi-crystalline injection molded thermoplastics but, if the injection material is amorphous then the cooling rate will not affect the plastic's microscopic structure.

For AM injection mold tools to be adopted as a common practice in the injection molding field, the material properties of the molding must be understood or the changes in material properties must be deemed non-significant. The best possible outcome is that the molding/part properties are unaffected by the change in the mold tool material, however the cooling rate plays a major role in PP molding properties. The application of focus is the use for low volume part production because it has been proven from the literature that AM tools can produce 10 to 500 parts [5]. The repeatability and high production speed of injection molding can be applied to low volume applications in an economical fashion.

## 1.1 Related Work

Our research suggests that there has been limited investigation into the effects of tool materials on the properties of the parts manufactured. Some work has been completed on the use of AM mold tools as a proof of concept, however, there has not been many in depth research papers studying the difference of the mechanical properties of the parts produced with the AM tool materials chosen in this current work. The most in-depth scientific papers that are related to this thesis are reviewed below. The materials and processes for AM are constantly evolving, the emerging materials need to be tested to find the best suitable material to be used for the application of rapid tooling. The different papers on AM injection mold tools are showing mixed effects on the final molding properties. The feasibility of using AM tooling for injection molding has been proven for ULTEM 1010, Digital ABS, and Fullcure RGD 720. The following shows a literature review of the work that has been done with AM tooling for injection molding applications.

## 1.2 Literature review

Bartlett et al. investigated the effects of mold tools made of Digital ABS material using Polyjet AM on the mechanical properties of PP (semi-crystalline) and PS (amorphous) moldings. The author also studied the survivability or lifetime of the mold tool. The injection molding experiments explored six characteristics: melt and injection temperatures, material crystallinity, filling speed, surface finish, mold stability, and polymer melt residence time in the barrel. The experimentation showed no significant change in the ultimate tensile strength (UTS) and modulus of elasticity of the PP moldings when the AM tool was used. However, there was a significant decrease of 86% in the ductility of the PP tensile specimens. The decrease in ductility was attributed to the lower cooling rate caused by the AM tool which affected the percent crystallinity and the spherulite diameter. The material selected for the IM process will have a different response in ductility when using an AM tool. To help the with low ductility the samples were annealed, but the moldings were still not as ductile as the steel mold. The ductility of PP also increased when the melt temperature was lowered and the injection time was increased, but it was still less than the metal mold. The surface finish of the digital ABS mold is smooth yet more rough than the traditional metal mold. It was determined that the rougher mold material had an insignificant effect on the ductility. The print direction of the AM tool was studied and it was determined that the print direction should be in the direction of the flow when possible.

Simpson et al. studied three different AM tools and three different injection materials: Digital ABS (polyjet), Fullcure RGD (polyjet), ULTEM 1010 (FDM) respectively and acetal, polycarbonate, polypropylene, respectively. The author analyzed shrink, physical properties, and mechanical properties. This was a feasibility study to see if the molds produce comparable moldings to that of the traditional steel mold tool. The crystallinity percentage of the parts was found at two points: the skin and the center of the moldings. The author found that PP moldings were comparable to the P20 steel mold and that the crystallinity was insignificantly different at the core and the surface for the different mold tools. All the different IM materials have approximately the same crystallinity when compared to the metal mold at the skin and the core. The results are more consistent at the core which is more important because that is where the mechanical strength comes from. They performed a modified flex test and the ULTEM 1010 mold produced the closest results to P20 steel mold. The Fullcure and Digital ABS had peak flexural load 25 Newtons below the ULTEM 1010 and metal mold. The large difference of the flexural properties could be from the location of the crystallinity within the test specimens. The strain and extension at the maximum load were comparable for all the specimens tested. The three AM mold tools in this experiment are appropriate for thermoplastic resins that require lower barrel temperatures and injection pressures. With shrinkage in mind, the ULTEM 1010 mold produced moldings that are closest to the metal control mold for both POM and PP, this could be attributed to the fact that the heat deflection temperature (HDT) of ULTEM 1010 is above that of the melting temp of the thermoplastic resins mentioned above where the HDT of the other AM tools is below the melting temperatures of the resins used.

Mendible et al. produced a comparative study of rapid and conventional tooling for plastic injection molding. This paper looked at 3 molds where two were AM tools, digital ABS (polyjet), stainless steel (DMLS), and a traditional stainless-steel mold where the injected material was PP. According to the author the mold tool made of Digital ABS increased the cycle time and decreased cooling rate which led to shrinkage and crystallinity in the moldings. The DMLS mold tool and the traditional steel mold tool were comparative in all aspects. All injection molding parameters were constant except for hold time and cooling time of the digital ABS mold. When looking at the surface roughness of the molds the stainless-steel tool had the roughest surface of 40-60 microns, the AM mold tool had a roughness of 6-11 microns and the machined insert had the smoothest surface of 3-4 microns. The properties of rapid tools are different from the conventional tools in terms of the thermal properties of the AM tool, the dimensional tolerances due to the increased shrinkage, and lifetime of the mold tool. In the realm of tool design the AM tool life can be extended by modifying the draft angle, surface finish, and injection pressure.

All the papers above have provided a basic understanding of AM tools to be used in injection molding; these papers were the first of a kind. This paper aims to further examine the mechanical properties and material characteristics of the PP moldings when AM mold tools are used. New engineered AM materials are constantly developed with the appropriate properties for rapid tooling within injection molding. To the best of my knowledge not much work has been done in this area and the outcomes of this research can benefit the injection molding community significantly.

## 1.3 Thesis Organization

This thesis is organized in the following manner. Chapter 2 explains the chosen materials, mold tool design, and PP manufacturing process. It also describes the design of the mold tools and processing parameters used to create the PP moldings that are tested. Chapter 3 dives into the physical and mechanical tests performed on the PP moldings as well as the mold tools. Chapter 4 displays the results from the testing and discusses the gathered data. Chapter 5 closes with the conclusions of the thesis and future work that could be performed in the realm of rapid tooling for low volume injection molding.

# CHAPTER 2

# MATERIALS AND METHODOLOGY

## 2.1 Materials

Aluminum 6061, ULTEM 1010, and HI-TEMP 300 AMB materials were used for the comparative study of rapid tooling for injection molding applications. The latter two mold materials used are plastic materials made with AM from Stratasys$^{TM}$ and 3-D Systems$^{TM}$, respectively. The selection of the AM injection mold tool material needs to be correlated with the material that will be injected into the mold as thermoplastics can have various melting temperatures. The most used thermoplastics for injection molding have a melting temperature in the range of 370-450 °F. ULTEM 1010 is a thermoplastic that is produced using the FDM process, it features high chemical resistance and high heat defection temperatures (HDT) which is the temperature a polymer deforms under a certain load. HI-TEMP 300 AMB is a UV-curable thermoset produced using the SLA process. These materials were chosen because of the high HDT. The respective HDT for the AM mold tool materials can be seen in Table 3. The AM mold tool materials were also selected because of the high flexural strength to ensure the mold tool will maintain its shape under the clamping pressures and the mold cavity will not expand under the injection pressures. Stratasys$^{TM}$ produced the ULTEM 1010 mold using a Fortus 900mc printer and the print lines within the mold cavity were sanded down to reduce the surface roughness. 3-D Systems$^{TM}$ produced the HI-TEMP 300 AMB mold using a Figure 4 SLA printer where the cavity was sanded and sandblasted to get a smooth surface. The traditional aluminum mold tool is made of 6061 aluminum and manufactured by machining.

The Polypropylene pellets came from MHolland$^{TM}$ with the processing specification of injection molding. This PP is a homopolymer so all the repeat units within the polymer chains are the same, unlike the polymer chains for copolymers which are made of two or more repeating units. There are three types of tacticity or spatial arrangement of the molecules within thermoplastic polymers: isotactic, atactic, and syndiotactic. The PP that is used most of the time for industrial applications is isotactic PP and this is the molecular structure present in the PP used in experimentation for this thesis. The various types of spatial arrangement can result in a change in morphology of the polymer, isotactic PP has crystalline regions, a melting temperature 160-170 °C, and high strength.

The PP pellets feature good stiffness, high crack resistance, and heat aging resistance. The material properties of the PP resin can be seen in Table 1. The recommended uses for these thermoplastic pellets are automotive applications, closures, sporting goods, caps, and containers. The tensile tests for the datasheet were performed using a crosshead speed of 2 (in/min) and the flexural tests were performed using a crosshead speed of 0.051 (in/min). These crosshead parameters are different than the values found to be appropriate for the tensile and flexural tests that were performed on the moldings in the current work. When comparing the mechanical properties from the datasheet to the experimental mechanical properties one should have some skepticism as the crosshead speed plays a major role in the mechanical testing such as tensile and flexural tests.

**Table 1:** Material properties for PP from the Mholland$^{TM}$ datasheet

| **Polypropylene** | |
|---|---|
| Density (g/cm^3) | 0.9 |
| Melt Flow Rate (g/10 min) | 12 |
| Ultimate tensile strength (psi) | 4930 |
| Flexural Modulus (psi) | 210000 |

The mechanical properties of AM mold tool materials chosen can be seen below in Table 2. The HI-TEMP 300 AMB does not have a glass transition temperature or a tensile elongation at yield because it is a thermoset. Thermoset polymers exhibit no or minimal plastic deformations before failure and do not melt so it does not have a glass transition temperature.

**Table 2:** Mechanical properties of AM mold tool materials

| | **ULTEM 1010** | **HI-TEMP 300 AMB** |
|---|---|---|
| UTS (psi) | 11700 | 10733 |
| Tensile modulus (psi) | 402000 | 551143 |
| Flex strength (psi) | 21000 | 14214 |
| Flexural modulus (psi) | 409000 | 609159 |
| Tensile Elongation @ yield (%) | 3.3 | N/A |
| Tensile Elongation @ break (%) | 2.2 | 2.3 |

**Table 3:** Thermal properties of the AM mold tool materials

| | **ULTEM 1010** | **HI-TEMP 300 AMB** |
|---|---|---|
| Glass Transition Temp (°F | 419 | N/A |
| HDT 66 PSI (°F) | 421 | 572 |
| HDT 264 PSI (°F ) | 415 | 572 |

## 2.2 Injection Molding

Injection molding of the flexure and tensile test specimens was completed using a Morgan Press G-125T vertical injection molding machine picture below in Figure 1. Common injection molding processing parameters for High Density Polyethylene and Polypropylene can be seen below in Table 4. The aluminum mold tool used to make the PP tensile and flexure samples was a three-piece mold tool where two specimens are produced each run. The metallic mold tool can be seen in Figures 2-3. The center plate can be exchanged for tensile specimens or flexural specimens as seen in Figure 4. The AM mold tools were created so they will sit inside an aluminum enclosure with an aluminum top plate.

**Figure 1:** Morgan Press G-125T injection molding machine used for part manufacturing

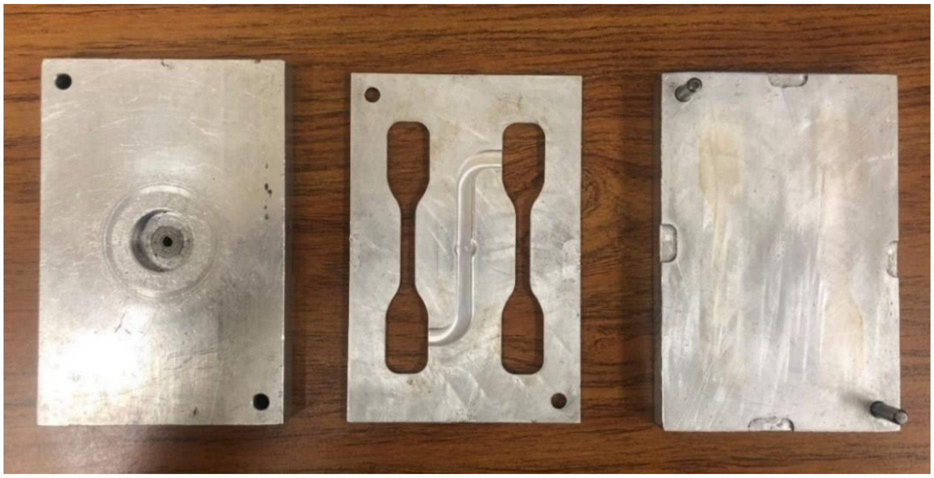

**Figure 2:** 6061 aluminum 3-piece tensile mold disassembled

**Figure 3:** 6061 aluminum 3-piece tensile mold assembled

**Figure 4:** Steel flexural and aluminum tensile center mold tool cutout

**Table 4**: Material properties of High-Density Polyethylene and Polypropylene plastics used for injection molding

| **Property** | **HDPE** | **PP** |
|---|---|---|
| Melting Point (°F) | 410 | 446 |
| Glass Transition Temperature (°F) | 239 | 275 |
| Specific Heat (kJ/kg°C) | 1.9 | 1.8 |
| Young’s Modulus (ksi) | 130.5 | 145 |

Injection molding has numerous variables that influence the final part, such as:

- **Nozzle Temperature**: The temperature of the nozzle from which the plastic enters the gate of the mold tool.
- **Barrel Temperature**: The temperature of the cavity where solid plastic pellets are inserted.
- **Injection Pressure**: The pressure at which the melted plastic enters the mold tool.
- **Clamping Pressure**: The pressure that presses the top and bottom parts of the mold tool together.
- **Injection Time**: The amount of time the hydraulic plunger is pushing melted plastic through the mold tool cavity.
- **Mold Tool Temperature**: The temperature of the mold tool when plastic is injected into it. This is effected by the nozzle, plate, and ambient temperatures.
- **Plate Temperature**: The temperature of the hot plate on which the mold tool rests during injection runs.
- **Hold Time**: The time period between when the mold tool is removed from the injection molding machine and the time when the mold is opened.
- **Cycle Time**: The total time it takes for injecting one plastic molding to the next. This is the total time starting with the heating of the mold tool to the ejecting of the final molding from the tool

**Table 5:** Injection molding processing parameters for the three mold tools

| **Injection Molding Parameter** | **Aluminum Mold Tool** | **ULTEM 1010** | **HI-TEMP 300 AMB** |
|---|---|---|---|
| Nozzle Temperature (°F) | 450 | 450 | 450 |
| Barrel Temperature (°F) | 425 | 425 | 425 |
| Plate Temperature (°F) | 250 | 200 | 200 |
| Hold Time (min) | 4 | 4 | 4 |
| Injection Pressure (psi) | 2000 | 1750 | 1750 |
| Flow rate (# of turns) | 6 | 6 | 6 |
| Injection time (sec) | 13 | 9.1 | 8.3 |
| Injected Material | PP | PP | PP |

As the mold material changes, the injection molding processing parameters need to be adjusted to achieve the same results as the metallic mold tool. However, the changes necessary between the AM and aluminum mold tools were minimal as seen above in Table 5. The main changes of the parameters during injection molding were changes in the injection time, hot plate temperature, and the injection pressure. The parameters for the two AM mold tools were the same besides the injection time. The average for the ULTEM 1010 mold tool was 8.3 seconds and the average for the HI-TEMP 300 AMB mold tool was 9.1 seconds. The aluminum mold differed from the AM mold tools slightly, having the hot plate temperature of 250 °F , injection pressure of 1750 psi, and an average injection time of 13 seconds. The parameters were selected based on what produced the best specimens in terms of physical defects that are common with injection molding. The same cooling time of four minutes was used for all three mold tools. The cycle time for the AM mold tools was 10 minutes to allow the tool to heat up to the appropriate temperature and allow the plastic solidify for four minutes. The cycle time for the metallic tool was 6 minutes because the aluminum heats up much faster than the plastics used.

Defects can also be avoided through proper mold tool design. Some common defects include:

- **Flow Marks** – Wavy lines or patterns on the injected part caused by low injection pressure and insufficient hold time for the material to solidify.
- **Blister**s – Raised zone on the surface of the injected part caused by extreme nozzle temperature and lack of cooling around the mold tool.
- **Flash** – Mold cavity is overfilled allowing plastic flow outside of the allowable injected area caused by too high injection pressure, low clamping pressure, or excessive injection time.
- **Burn Marks** – Burnt areas on the injected part caused by lack of ventilation or excessive injection speed.
- **Jetting** – Injected part has deformed shape caused by turbulent flow of the plastic material from high injection pressure or improper gate location.
- **Sink marks** – Low points in the plastic part that should be flat caused by low injection pressure or short hold time.
- **Polymer degradation** – Oxidation of the polymer caused by moisture in stock material or excessive barrel temperature.
- **Short shot** – Mold cavity not completely filled caused by insufficient injection pressure or short injection time.

## 2.3 Additive Manufacturing Tool Design

Changing the injection mold tool material from metal to plastic results in changes of the mold tool design process. The changes in the design process help extend the lifetime of the mold tool and allow for easy ejection of the part. Injected plastic will stick to an AM mold tool more than a smooth metal tool because it is textured due to the print lines. To avoid the part getting stuck in the mold tool, the mold cavity should be made as smooth as possible using a post processing technique and the draft angle should be increased.

To extend the lifetime of the AM mold tool the surface finish, draft angles, and undercut interferences must be modified [9]. A draft angle of one to two degrees is common practice when using metallic tooling to allow for easy molding ejection. When using an AM mold tool, it is suggested to use draft angles of three to five degrees [10]. A draft angle of five degrees was chosen for the mold tool insert design used in the current work.

If the mold tool is only AM plastic and not a hybrid setup where a metal enclosure acts as a backbone, then the AM mold tool itself must be able to withstand the clamping pressure of the injection molding machine. The hybrid mold tool was chosen for the current work to ensure the AM mold tool inserts will survive the clamping pressure. The hybrid mold tool also reduces the amount of plastic used during printing of the AM tools, which in turn reduces the cost of the insert. A Solidworks$^{TM}$ rendering of the insert design utilized in the current work can be seen in Figures 5-6. The hybrid mold tool used in experimentation can be seen in Figures 7-8.

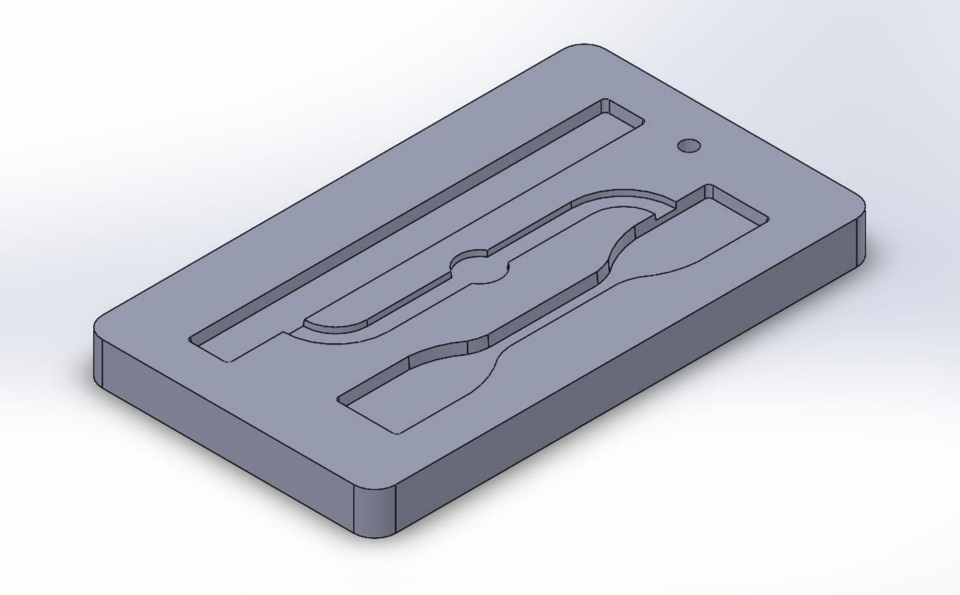

**Figure 5:** Mold Insert Solidworks$^{TM}$ design. Flexure and tensile specimens in one mold

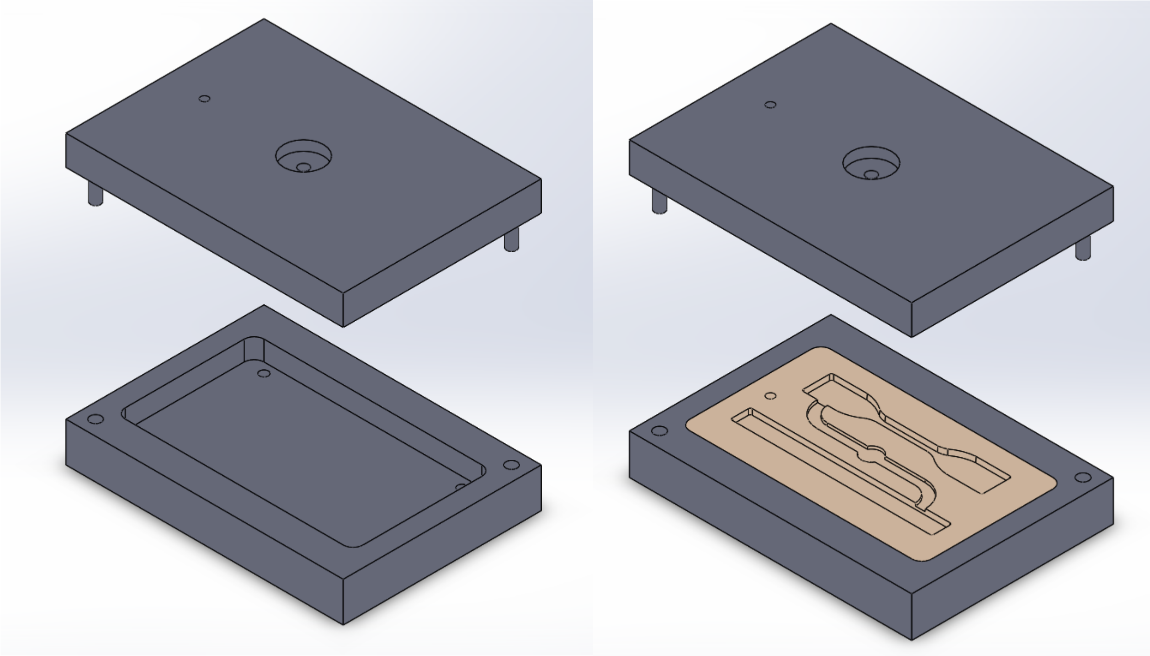

**Figure 6:** Aluminum mold enclosure Solidworks$^{TM}$ rendering: without insert (left) and with insert (right)

**Figure 7:** ULTEM 1010 mold insert within the aluminum enclosure (left) and HI-TEMP 300 AMB mold tool within the aluminum enclosure (right)

**Figure 8:** HI-TEMP 300 AMB and ULTEM 1010 mold tool inserts

The AM mold tool inserts consisted of a flexural and tensile sample cavity so only one mold tool insert would need to be manufactured. This also allows for one injection run to have the exact same processing parameters between the flexure and tensile specimens. The left mold cavity is the flexure specimen designed in accordance with ASTM D790-17 and the right cavity is the tensile specimen in accordance with ASTM D638-14. The flexure test specimen dimensions can be seen in Figure 9 and the tensile specimen cavity is a modified type IV dog bone where the dimensions can be seen in Figure 10.

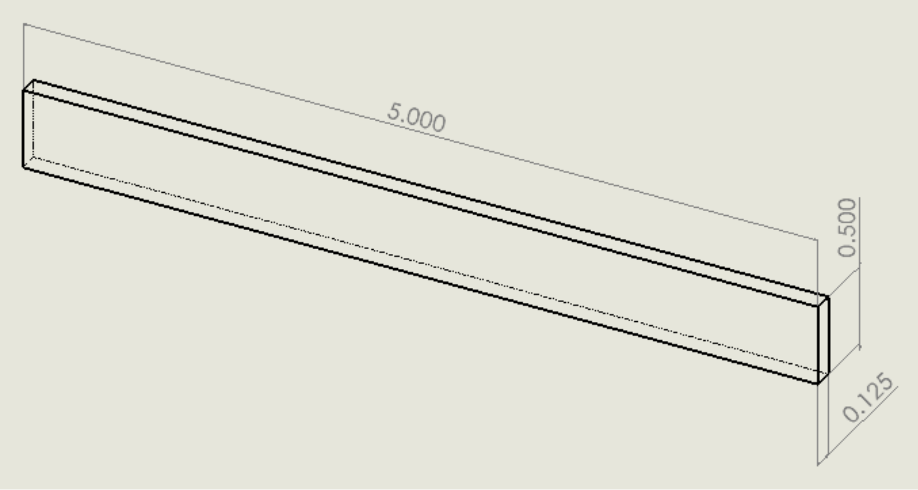

**Figure 9:** Dimensions of flexural specimen

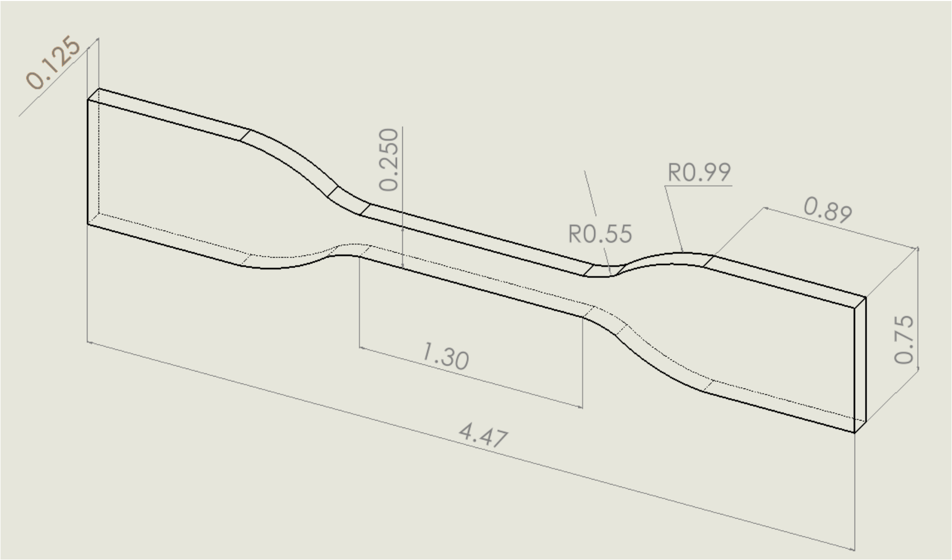

**Figure 10:** Dimensions of modified type 4 dog bone specimen

## CHAPTER 3

# MATERIAL TESTING

A series of physical, mechanical and thermal tests were conducted on the samples created from the three different injection molding tools. The tests performed consisted of differential scanning calorimetry, density, shrinkage measurements, surface roughness, shore D hardness, tensile, and flexural tests.

### 3.1 DSC Testing

Differential scanning calorimetry (DSC) is the process where two small, enclosed pans are subjected to the same thermal cycle; one pan has a sample and the reference pan is empty. To keep the two pans the same temperature the pan with a sample requires more heat to maintain the same temperature as the reference pan. DSC measures how much more heat is required to heat the pan with the sample. Using the DSC thermographs, the crystallization temperature, melting temperature, exothermic enthalpy, and endothermic enthalpy can be measured. The machine ensures that the temperature change is consistent between the two pans. The instrument used was the TA Instruments Discovery 250 DSC which was calibrated prior to performing tests using the sapphire and indium standard pieces. The thermal cycle used to test each sample (seen below in Figure 11) consisted of a ramp up to 70 ℃ , ramp to 180 ℃ , isothermal for 5 min, ramp to 60 ℃, isothermal for 5 min, and lastly ramp back to 180 ℃ . All temperature change ramps happened at a rate of 10 ℃ /min. The mass of the samples was kept around 5 mg to ensure the best results.

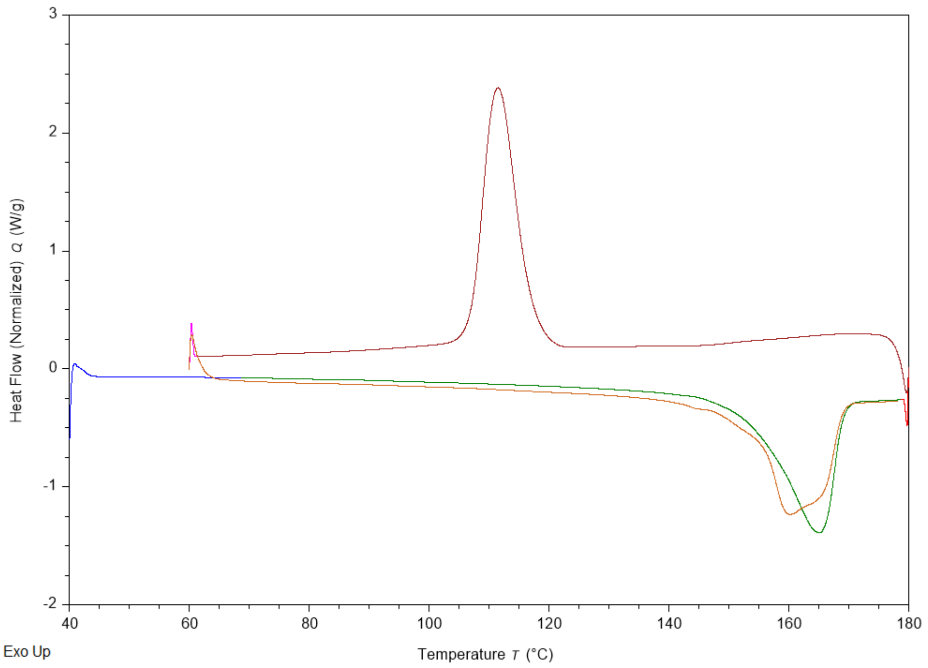

**Figure 11:** A thermograph of a PP molding manufactured with the aluminum mold tool; the thermal cycle begins on the left

In the current study, DSC was used to find the melting temperature and crystalline temperature of the injection molded parts to determine if there was a change in morphology of the moldings when the different mold tools were used. The peaks were integrated to obtain the enthalpies of each respective peak. The percent crystallinity was calculated using the exothermic enthalpy. The DSC tests were performed according to ASTM D3418-15 and a total of 63 DSC runs were performed. The first set of DSC runs tested three samples from five tensile specimens for each of the three different mold tools for a total of 45 runs. The second set of DSC runs was to determine if there was a significant change in the percent crystallinity between the faces of the molding that contact the AM mold tool and the aluminum top plate. This set of runs consisted of three samples from three tensile specimens with two different mold tools for a total of 18 runs performed. The second set of samples from the ULTEM 1010 and HI-TEMP 300 AMB mold tools were categorized into three types: the face of the tensile specimen that is in contact with the top aluminum plate, the face of the tensile specimen that is in contact with the AM portion of the mold insert, and the full cross section of the tensile specimen.

The mold contacting samples were taken using a quarter of the tensile specimen's thickness. Keeping track of the different contact surfaces on the molding was an attempt to establish a percent crystallinity gradient depending on what portion of the mold tool that the molding was in contact with.

Thermoplastic morphology can be broken into two different categories: amorphous and semi-crystalline. Crystallinity within polymers is different than ceramics or metals because instead of individual atoms or ions, the atomic arrangements for polymers involve repeated molecular chains, making it more complex [13]. Semi-crystalline polymers are a combination of amorphous and crystalline microstructures, no thermoplastic is ever 100% crystalline, but it has a percentage that is crystalline and a percentage that is amorphous. The amount of percent crystallinity present in a semi-crystalline thermoplastic is dependent on the cooling rate of the injected plastic [13]. The different thermal conductivities of the aluminum and the AM materials allowed for the hypothesis that the moldings from the aluminum mold tool would cool more quickly resulting in lower percent crystallinity than the AM mold tools. When a semi-crystalline thermoplastic cools more quickly, it results in lower percent crystallinity because the amorphous polymer chains have less time to organize and align themselves to form crystalline regions.

As the cooling rate of the injected plastic material determines the percent crystallinity there are certain injection molding parameters that affect the cooling rate. The main injection molding parameters that affect the percent crystallinity of isotactic PP are the mold temperature and barrel temperature. Also, as the mold temperature is increased the crystalline phase becomes more prominent [11]. The percent crystallinity within the molding relates to the mechanical properties. Amorphous thermoplastics have a very high ductility, but lack the strength that can be achieved with semi-crystalline thermoplastics. Semi-crystalline thermoplastics such as PE and PP exhibit good strength properties and depending on the percent crystallinity, good ductility. As the crystallinity increases the yield strength, elastic modulus, and flexural modulus also increase. However, the impact properties and ductility are decreased.

### 3.2 Density

Density tests were performed using a Mettler Toledo precision balance (Model: ME430TE/00) according to ASTM D792-20 where the mass of the tensile specimens was found in air and while submerged in water. PP is less dense than water, so it floats, for the plastic sample to be fully submerged a weight was used. The volume of the sample is found by subtracting the mass of the sample in air by the mass of the sample in water because water has a density of 1 g/cm^3. This method of calculating density uses Archimedes' principle and the net buoyant force. The masses of samples are measured to the nearest 0.1 mg and five samples from each mold tool were analyzed. A quarter inch nut was used as a weight to submerge the plastic sample. The setup to measure density can be seen below in Figures 12-13.

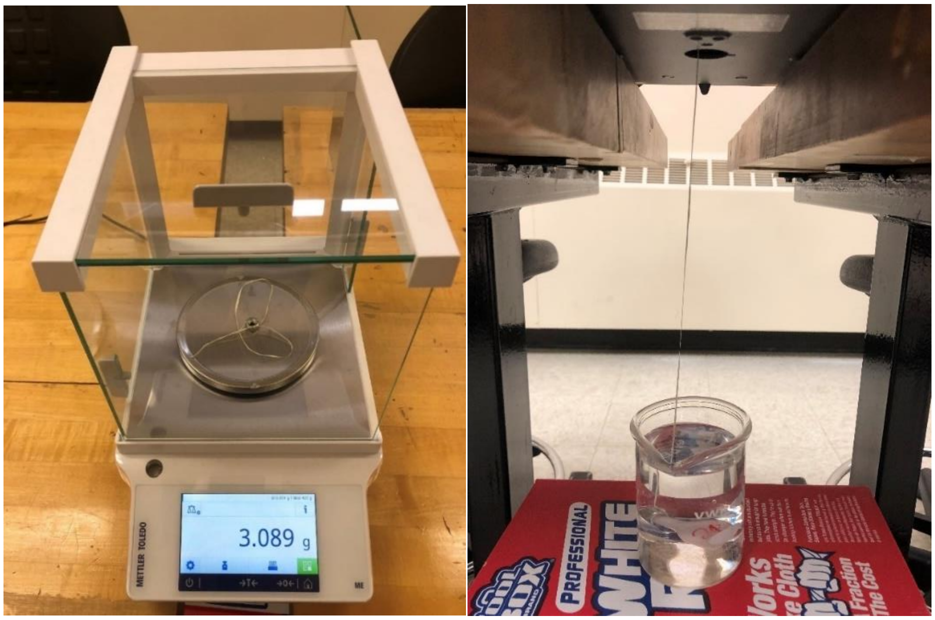

**Figure 12:** Mettler Toledo Precision Balance to measure the mass of sample in air (left) and water (right).

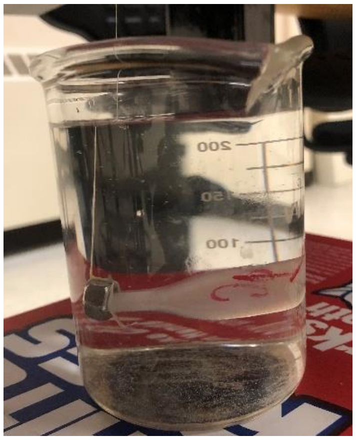

**Figure 13:** PP sample submerged in water to measure the net buoyancy force or mass in water.

## 3.3 Shrinkage

The percent shrinkage of the moldings was found by measuring the mold tool cavity and comparing it to the measurements of the moldings. All measurements were performed using a digital vernier caliper with accuracy to the thousands. The difference in the measurements were used to find the percent shrinkage. The shrinkage of IM parts is important because it allows parts and mold tools to be designed in a way that once the part is cooled it has the dimensions intended. If the shrinkage of moldings is not accounted for then the thermoplastic part may not work or fit as planned.

## 3.4 Surface Roughness

Surface roughness measurements were taken on each of the three mold tools using a Mitutoyo surface roughness tester which can be seen below in Figure 14. The AM mold tool surface roughness measurements were taken in two different directions: parallel to the flow of the injected plastic and perpendicular to the flow of the injected plastic. The Mitutoyo surface roughness tester was calibrated using a known standard surface roughness block (seen below in figure 15) with a Rayleigh number of 117 µinches. The Rayleigh number stands for roughness average or the arithmetic average of absolute values of the height deviations from the mean line.

**Figure 14:** Mitutoyo surface roughness tester (left) and testing the surface roughness of the ULTEM 1010 mold tool (right)

**Figure 15:** Surface roughness calibration surface

### 3.5 Hardness Test

Hardness tests were performed according to ASTM D785-08 using a PTC Instruments shore D hardness tester seen below in Figure 16. Shore D hardness values were measured for the moldings created from the three different mold tools. Ten moldings were tested from each mold tool with three replicate measurements on each molding.

**Figure 16:** PTC Instruments shore D hardness tester (model 307L)

## 3.6 Tensile Tests

The tensile tests were performed according to ASTM D638-14 with a modified type 4 dog bone test specimen using the Applied Test System (ATS) 910-2 Universal testing machine that can be seen below in Figure 17. An Interface 500 LBS load cell (seen below in Figure 18) was used to measure the force sustained by the samples. Four tensile specimens from each of the three injection molding tools were tested. The only modifications done to the dimensions of the dog bone was the shortening of the grip length to allow for the tensile specimen to fit in the injection molding tool area and the increase of the draft angle to allow for easier ejection from the AM mold tool. The ASTM standard calls for the samples to be fractured within a time window of 30 seconds to 5 min and if the sample does not break in this window the strain rate must be adjusted. The strain rate used was 0.2 inches per minute because PP is a semi-rigid plastic material and the plastic fractured within the allowable time window.

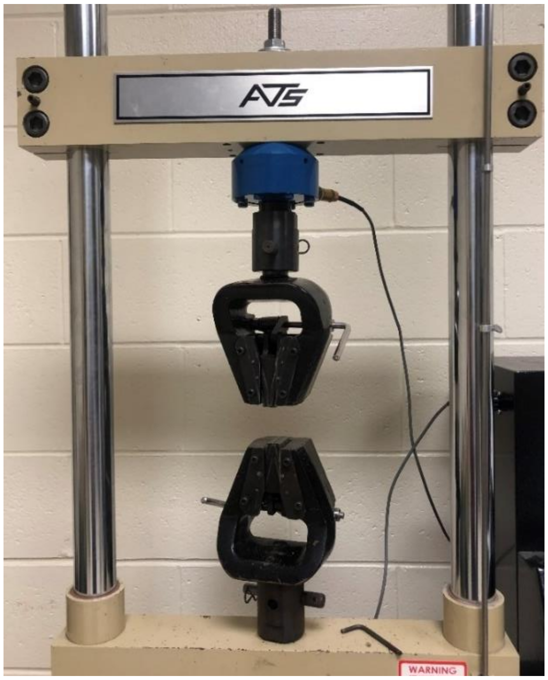

**Figure 17:** ATS machine with plastic tensile testing grips

**Figure 18:** Tensile and flexural tests were performed with an Interface 500 LBS load cell (model 1210AF-500-B)

Each individual cross-sectional area was measured using a digital vernier caliper. Injection molding specimens made with a metallic mold tool do not need to be individually measured because there should be less than 1% dimensional variation between the specimens. However, two-thirds of the specimens tested were manufactured using an AM mold tool where the dimensional variation was unknown. Each cross-sectional area was measured to get the most accurate stress values. The ATS machine recorded the raw data for load versus displacement for the tensile tests, the raw data is then converted to stress and strain values. The stress versus strain curve is then produced using Excel where the ultimate tensile strength and elastic modulus can be extracted.

## 3.7 Flexural Tests

The flexural tests were performed according to ASTM D790-17 using a 3-point bending test with a support to span ratio of 16:1. The span of the sample is 4 inches with 0.5 inches of overhang on each side of the supports. The calculated speed of the crosshead was 0.2 inches per minute. The calculated maximum displacement was 1 inch. The maximum displacement was measured during testing using the lower crosshead displacement where the test was stopped at the maximum displacement of 1 inch, this be seen below in Figure 19. The maximum displacement must be calculated because PP is a very flexible plastic and will not fracture under a 3-point bend test. All the flexural tests were performed on virgin samples that have not been previously loaded.

Specimen details:

- L = Support span (distance between the two bottom supports) = 4in
- d = depth or thickness of specimen = 0.125in
- Z = rate of straining of the outer fiber (shall be equal to 0.01)
- r = strain

$$\text{Calculated rate of crosshead motion: } R = \frac{ZL^2}{6d}$$

R = rate of crosshead motion = 0.2 in/min

- r = set to 0.05 to find when 5% strain will occur

Calculated maximum deflection of beam: $D = \frac{rL^2}{6d}$

D = maximum midspan deflection = 1.02 in

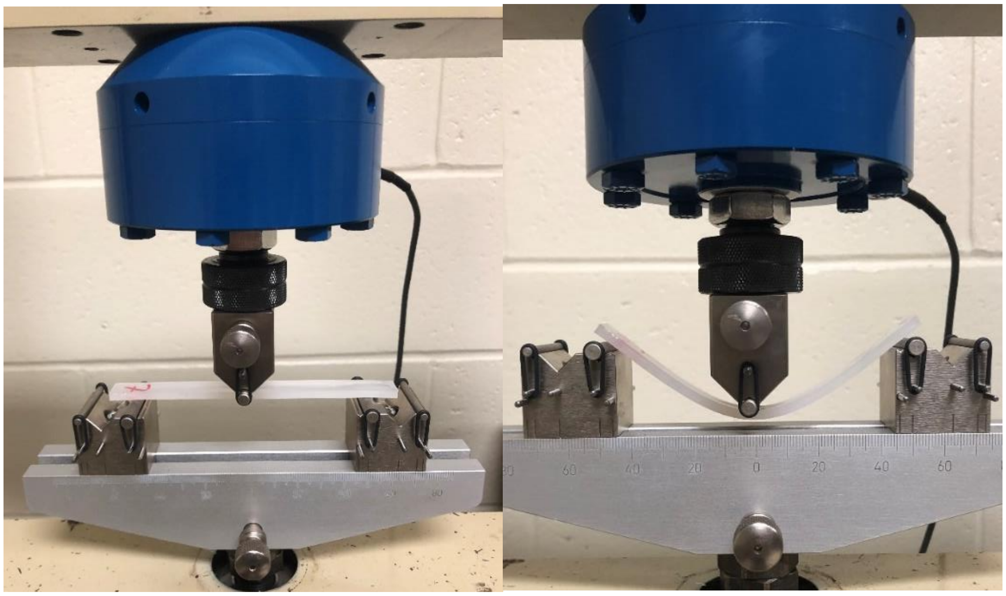

**Figure 19:** ATS machine flexure testing fixture with unloaded sample (left) and flexure testing fixture at maximum displacement of 1 inch (right)

# CHAPTER 4

# RESULTS AND DISSCUSSION

## 4.1 DSC Results

Figures 20-21 show the crystallization and melting peaks in the DSC thermograms of the PP moldings produced using the aluminum, ULTEM 1010, and HI-TEMP 300 AMB mold tools. The crystallization temperature is defined as the highest point of the peak during the cooling cycle. Since crystallization is an exothermic reaction, heat is released from the polymer to the surroundings. Whereas the melting temperature is defined as the lowest point of the dip during the heating cycle. The melting peak is an endothermic reaction because heat is absorbed by the polymer as it melts. As shown in the Figures below, the three curves are overlayed quite well, demonstrating that the moldings from the three respective mold tools have the same melting temperatures and crystallization temperatures as well as the same peak geometries. These results show that there is no significant change in the thermal behavior of the moldings between the traditional metal tool and the AM tools. Typically, semi-crystalline thermoplastic materials produce three distinct features in their DSC heat flow versus temperature curves: glass transition, crystallization peak, and melting peak. Since one of the main goals of the DSC experiments in the current work is to study the crystallinity of the samples, samples were not cooled to their freezing temperature to find the glass transition temperature.

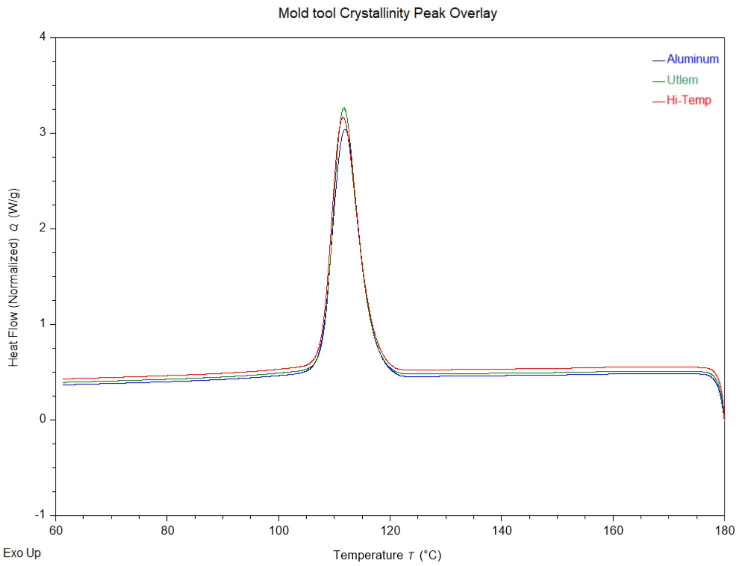

**Figure 20:** DSC thermograms of the crystallinity peaks for the three different mold tools

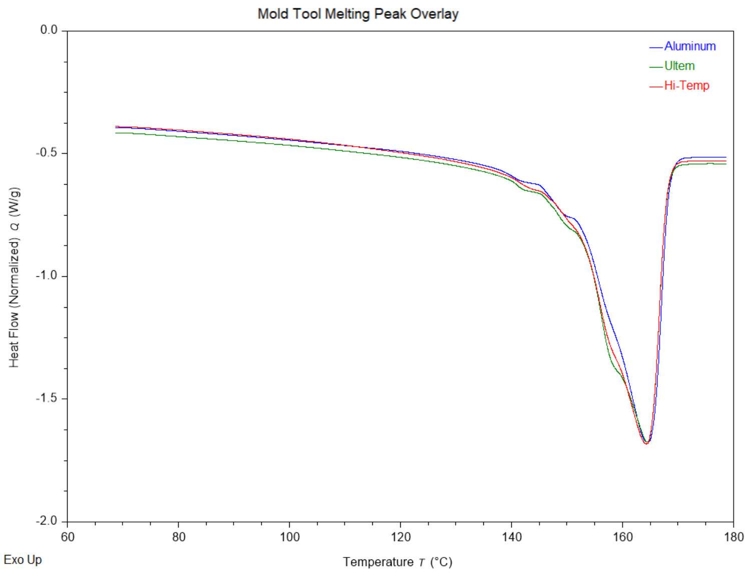

**Figure 21:** DSC thermograms of the melting peaks for the three different mold tools

From the DSC thermographs, the percent crystallinity values of the PP samples are measured. By integrating the areas under the crystallization peak and melting peak, the enthalpies of each respective property is calculated. The crystallization enthalpy is then divided by the heat of fusion of a perfect crystal of PP to find the percent crystallinity as shown in the equation below.

Percent crystallinity equation: $X_c = \frac{\Delta Hm}{\Delta H°m} x100\%$

where $X_c$ is the percent crystallinity, $\Delta Hm$ measured heat of fusion from the crystallinity peak, and $\Delta H°m$ is the heat of fusion of a perfect crystal. The heat of fusion of a perfect crystal of PP is known to be 207 (J/g) [6]. The average percent crystallinity of the moldings made with each respective mold tool is presented in Table 6 and the comparison is shown in Figure 22. Results show that no significant change in percent crystallinity of the moldings was observed. These results are similar to what Simpson et al. observed in his study using ULTEM 1010, Fullcure RGD, Digital ABS and compared it to the P20 steel mold tool. However, in his work, Bartlett et al. found 5% change in crystallinity when the mold tool was changed from steel to the AM based ones. This can be attributed to the significant variation in hold time by Bartlett et al. changing the value from 10 sec for P20 steel tool to 240 sec for the Digital ABS tool. In addition, Bartlett et al. did not report the mold tool temperature used during the injection molding process which can also greatly influence the cooling rate of the moldings. Simpson et al. also changed the hold time from one mold tool to another unlike the current study. However, that variation is less than 35 sec, and is not big enough change to influence the crystallinity. Also, since the tool temperature is lowered for the AM tool, it will be counteracting the change in crystallinity.

Another variation in the results is reported by Bartlett et al. in that an additional exotherm was observed in the DSC thermographs which was not present in either the current work or work reported by Simpson et al. Additional exotherm can further vary the reported percent crystallinities. However, since increasing the hold time 24 times the original value, and potential change in tool temperature (which was not reported) only resulted in 5% change in crystallinity, one can conclude that changing the mold tool does not have a significant effect on the change in crystallinity.

**Table 6:** Percent crystallinity of PP with respective mold tools

| Aluminum Mold Average % Crystallinity | Standard Deviation | ULTEM 1010 Average % Crystallinity | Standard Deviation | HI-TEMP 300 AMB Average % crystallinity | Standard Deviation |
|---|---|---|---|---|---|
| 43.8 | 0.825 | 44.7 | 0.956 | 44.6 | 0.759 |

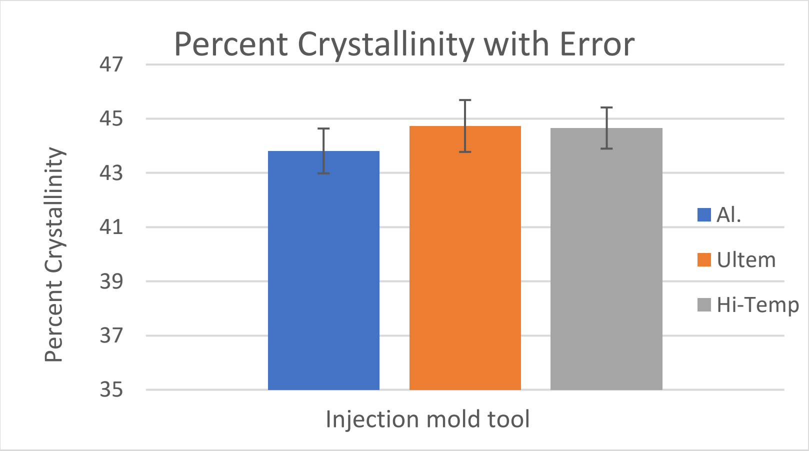

**Figure 22:** Percent crystallinity

Another interesting observation is the variation in the design of the mold tool in all the three studies. While Bartlett et al. used AM mold inserts in both the top and bottom halves, Simpson et al. and the current work used AM mold insert only for the bottom half. This variation influences how the heat is dissipated. When the top mold is fully made from metal, it acts as a heat sink and the cooling rate of the moldings will be closer to what we see in fully metallic molds. It is also less dependent on the thermal conductivity of the AM mold insert. This is evident in the crystallinity results and the tensile results showing no significant change. Hence, when the properties of the molding are desired to be close to those made from metallic mold tools, it is recommended for the top mold plate to be metal as the geometry of the molding permits.

Since the top and bottom faces of the molding are in contact with two different materials with very different thermal conductivities during the IM process, a second set of DSC tests were performed to study the variation in percent crystallinity through the thickness of the samples. DSC samples were collected from three locations within the moldings: the top face (aluminum contact), full cross section (a section of the gauge that is in contact with both the aluminum and AM material), and the bottom face (AM tool contact). The results from this experiment can be seen below in Table 7. The second DSC study shows that there was no crystallinity profile identified between the three different faces measured and percent crystallinity proved to be consistent between the three locations measured. No difference in the crystallinity of the moldings through the thickness shows that the moldings made by the AM mold tools are cooling uniformly. This also strengthens the credibility the results found during the first DSC runs because the samples tested are taken from specific locations that were recorded.

**Table 7:** Percent crystallinity profile results from the AM tools

| **Location** | **ULTEM 1010** | **HI-TEMP 300 AMB** |
|---|---|---|
| **Top (%)** | 45.2 | 45.2 |
| **Bottom (%)** | 45.2 | 44.6 |
| **Full CS (%)** | 45.4 | 44.3 |

## 4.2 Density Results

Density measurements of the samples are shown in Table 8 and a comparison is shown in Figure 23. The measured values are in close agreement with the value (0.900 g/cm$^3$) reported in the data sheet by the supplier. Results show that there is minimum variation in the densities of the samples made with the different mold tools. Hence it can be concluded that the density of the moldings is not affected by the material of the mold tool.

**Table 8:** Densities of tensile specimens from the three mold tools

| | **Aluminum** | **ULTEM 1010** | **HI-TEMP 300 AMB** |
|---|---|---|---|
| **Average Density (g/cm3)** | 0.906 | 0.913 | 0.909 |
| **Std. Deviation** | 0.002 | 0.004 | 0.002 |

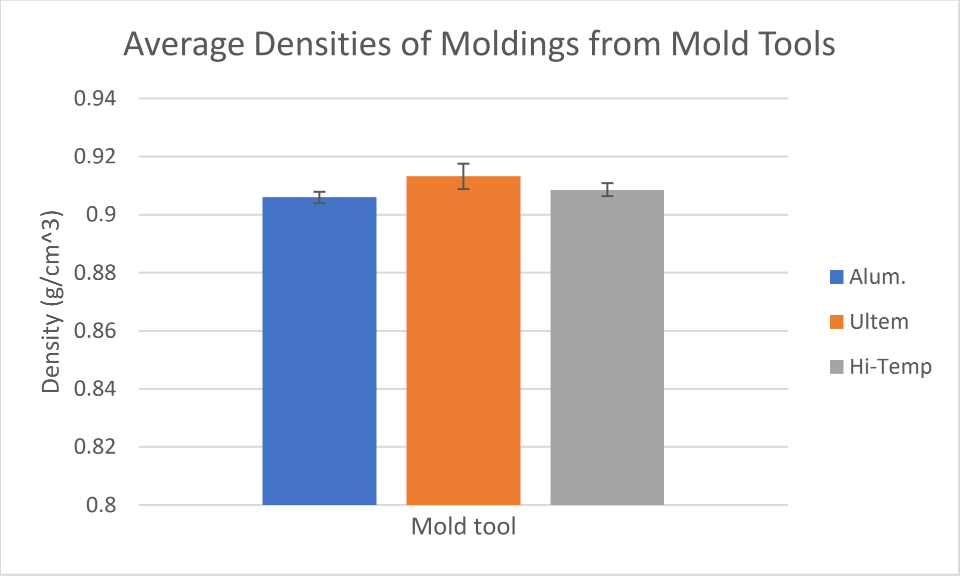

**Figure 23:** Densities of injection molded specimens from respective mold tools

## 4.3 Shrinkage

When a molding shrinks non-uniformly, it can cause residual stresses resulting in undesired warpage. The moldings from the three mold tools showed no warpage, this confirms that the moldings cooled uniformly. The shrinkage is also important when designing a part for tolerances and fit. Shrinkage results are shown in Table 9. The molding from the aluminum mold tool showed the smallest shrinkage of the molding of one hundredth of an inch. The ULTEM 1010 and HI-TEMP 300 AMB mold tools showed comparable shrinkage values, but the HI-TEMP 300 AMB mold tool had a slightly larger shrinkage. The ULTEM 1010 mold tool had a shrinkage 5 times the aluminum mold and the HI-TEMP 300 AMB mold tool had a shrinkage 6.5 times greater than the aluminum mold tool. These results agree with the trends reported in the literature [8][10][12]. Research from multiple authors showed that the moldings from the AM mold tools tend to shrink more than those made using the metal tool. This can be attributed to the lower thermal conductivity values of AM mold tools. ULTEM 1010 has a thermal conductivity of 0.22 W/m K whereas the thermal conductivity of P20 steel is 29 W/m K. The difference in these values influence the cooling rate which in turn induce different in-mold stresses and cause different shrinkage effects [10]. The higher shrinkage values are still within the acceptable limits and can be accounted for, by increasing the tolerance limits when the designing the part. Hence it is not a reason for AM tools to be avoided.

**Table 9:** Shrinkage of the PP moldings from respective mold tools

| | **Aluminum** | **ULTEM 1010** | **HI-TEMP 300 AMB** |
|---|---|---|---|
| **Shrinkage (in.)** | 0.0011 | 0.0051 | 0.0065 |
| **Shrinkage percentage (%)** | 0.8 | 2.2 | 2.9 |

## 4.4 Surface Roughness

Mold tool roughness is a significant factor in dictating the final surface quality of the molding and the overall usability of the tool. If the tool is too rough, the ejection of the parts can be challenging which makes the AM tool not a good alternative to the metallic mold tool. Surface roughness of the mold tools was measured parallel and perpendicular to the plastic flow direction and the results are shown in Table 10. The aluminum proved to be the smoothest mold tool material. The HI-TEMP 300 AMB mold tool is 12 times as rough as the aluminum mold tool in the direction parallel to plastic flow. The ULTEM 1010 AM mold tool is 42 times as rough as the aluminum mold tool in the direction parallel to plastic flow. The ULTEM 1010 mold tool roughness was comparable in both perpendicular and parallel to the plastic flow, however the HI-TEMP 300 AMB mold was 2.9 times rougher in the direction perpendicular to the plastic flow. Therefore, if the HI-TEMP 300 AMB mold tool was re-manufactured the print lines could be aligned with the plastic flow so that there is minimal resistance to plastic flow direction in the mold tool. When possible, the mold tool insert should be printed in an orientation so the main direction of plastic flow is parallel to the print lines to reduce flow induced residual stress in the moldings.

**Table 10:** Surface roughness values of mold tools

| | **Aluminum** | **ULTEM 1010** | **HI-TEMP 300 AMB** |
|---|---|---|---|
| **Parallel to Flow (μ in.)** | 13.8 | 582.3 | 177 |
| **Perpendicular to Flow (μ in.)** | | 605.7 | 60.9 |

## 4.5 Tensile Test Results

Figure 24-26 show the tensile stress versus strain curves of the moldings from different mold tools. The ultimate tensile strength (UTS) is the maximum value from the stress versus strain curve and the stiffness value is the slope of the curve within the linear portion. Plastics do not have a distinct linear portion of the stress versus strain curve like metals, so the stiffness was measured from the linear region of the curve directly after the toe of the curve for 15 data points. The average UTS and average tensile stiffness values were calculated from the curves that are shown in below. The measured UTS value agrees with the values reported by the supplier in the data sheet (4500-4900 psi). When the measured experimental properties agree with those reported by the supplier in the datasheet, it acts as an extra control group.

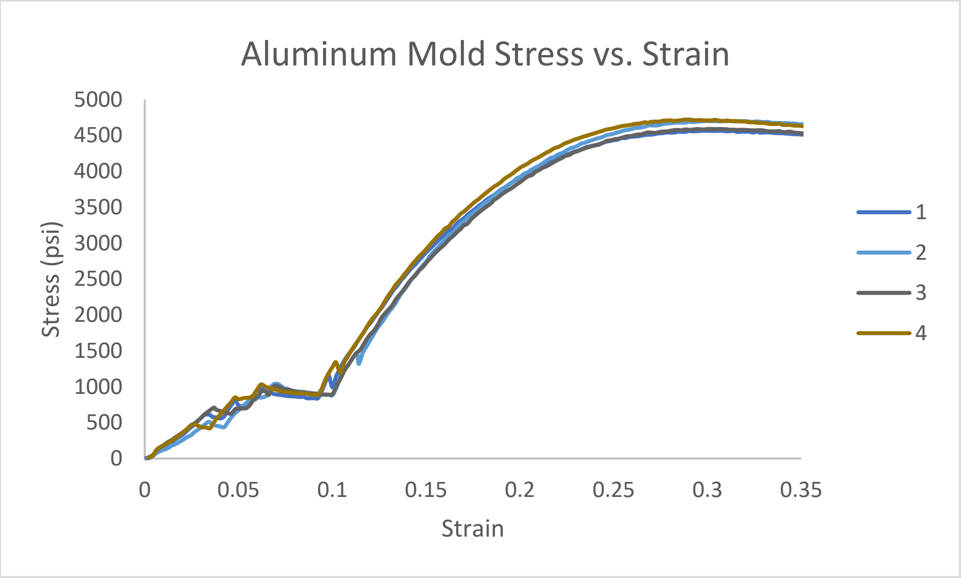

**Figure 24:** Tensile stress versus strain curves for PP moldings with the aluminum mold tool

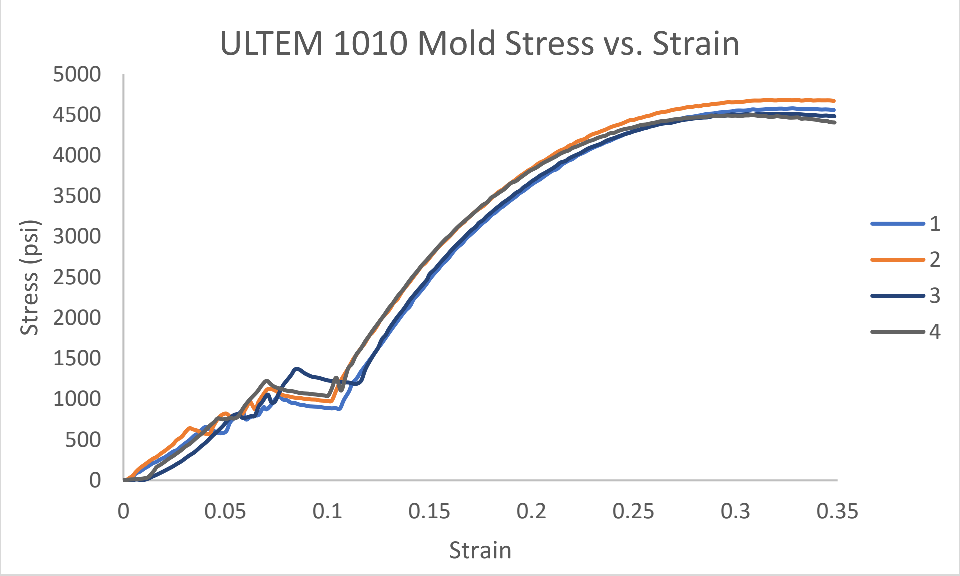

**Figure 25:** Tensile stress versus strain curves for PP moldings with the ULTEM 1010 mold tool

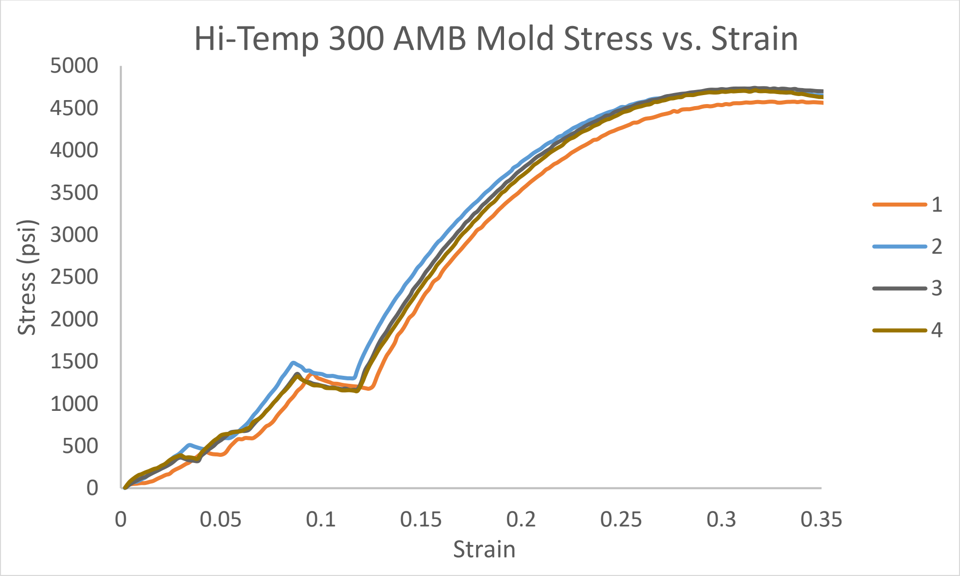

**Figure 26:** Tensile stress versus strain curves for PP moldings with the HI-TEMP 300 AMB mold tool

As seen in the Figures 27-28 and Table 11 below, no significant change in the tensile properties of the moldings was observed when different mold tool materials were used. The calculated values are all within the range of error limits. These results agree with those reported by Bartlett et al. Since tensile properties are highly influenced by the crystallinity in a polymer, it is no surprise that tensile strength and stiffness values did not vary as different mold tools were employed.

**Table 11:** Ultimate tensile strength (UTS) and Stiffness for the three mold tools

| | **Ultimate Tensile Strength (psi)** | | **Stiffness (psi)** | |
|---|---|---|---|---|
| | **Average** | **Std. Dev** | **Average** | **Std. Dev** |
| **Aluminum** | 4647.8 | 66.7 | 37018.8 | 839.5 |
| **Ultem 1010** | 4567.7 | 85.7 | 38028.2 | 1293.9 |
| **HI-Temp 300** | 4685.2 | 72.6 | 37013.7 | 1238.6 |

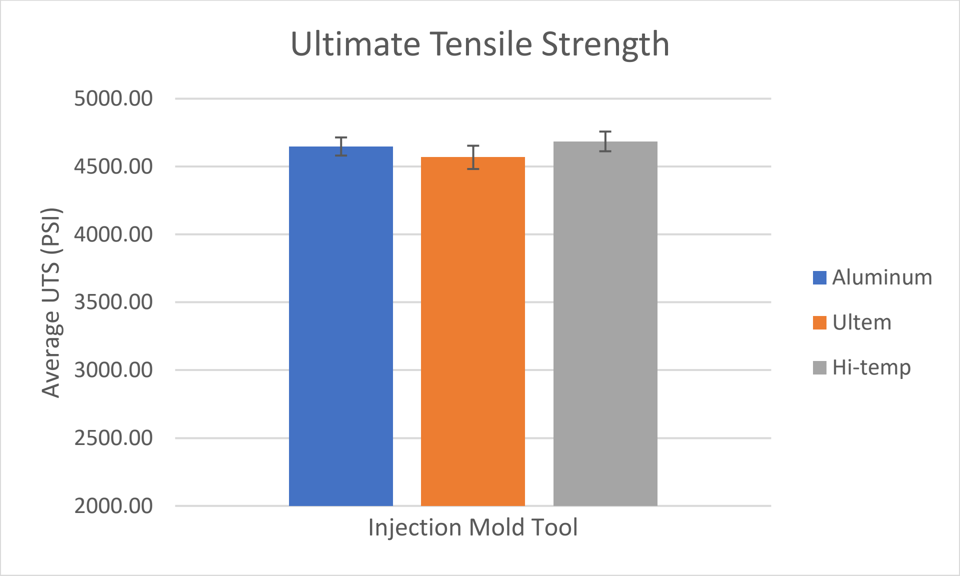

**Figure 27:** Average ultimate tensile strength of the PP moldings made using the three different mold tools

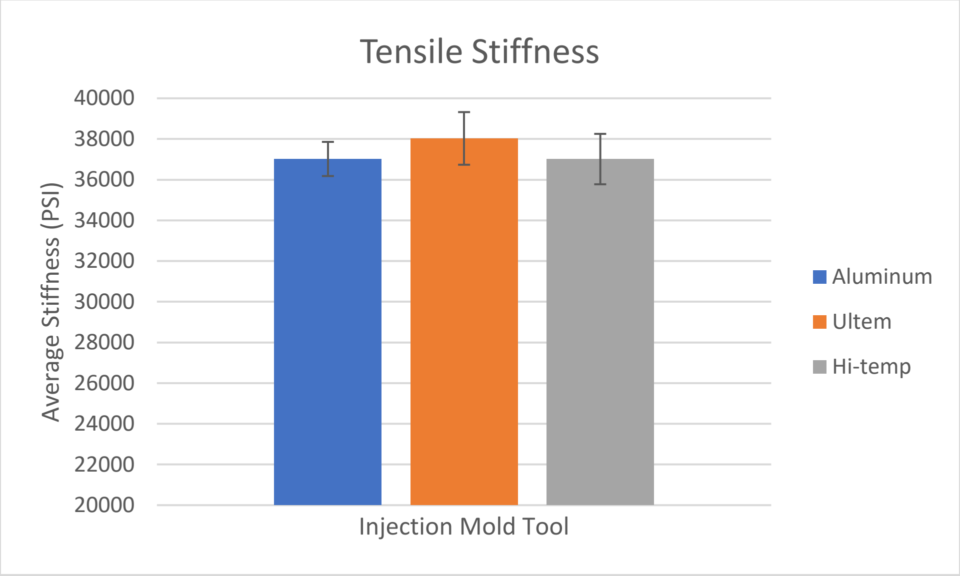

**Figure 28:** Average stiffness of the PP moldings made using the three different mold tools.

## 4.6 Flexural Test Results

Figures 29-31 show the stress versus strain curves of the molding samples in flexure. The maximum strength, strain, and tangent bending modulus of the samples are calculated as shown below are reported in Table 13:

$$\text{Stress in test specimen: } \sigma = \frac{Force}{Area}$$

$$\text{Strain in the outer surface: } \varepsilon_f = \frac{6Dd}{L^2}$$

$$\text{Tangent bending modulus of elasticity: } E_B = \frac{L^3 m}{4bd^3}$$

Where,

- L = support span (distance between the two bottom supports) = 4in
- D = maximum deflection of the center of the beam =1in
- d = depth or thickness of specimen = 0.125in
- b = width of the beam

- m = slope of the tangent line within the initial linear portion of the load deflection curve
- r = strain

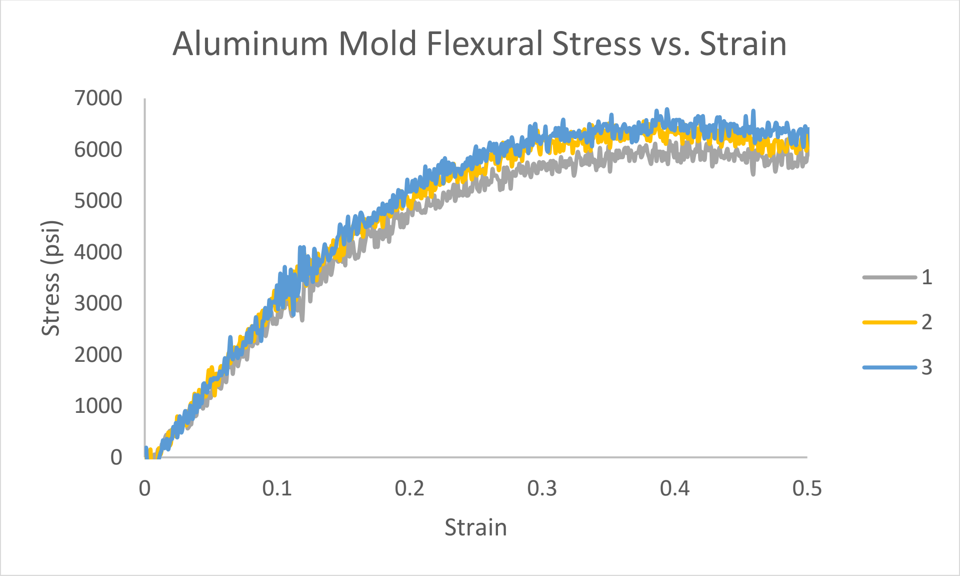

**Figure 29:** Flexural stress versus strain curves for the PP moldings made with the aluminum mold tool

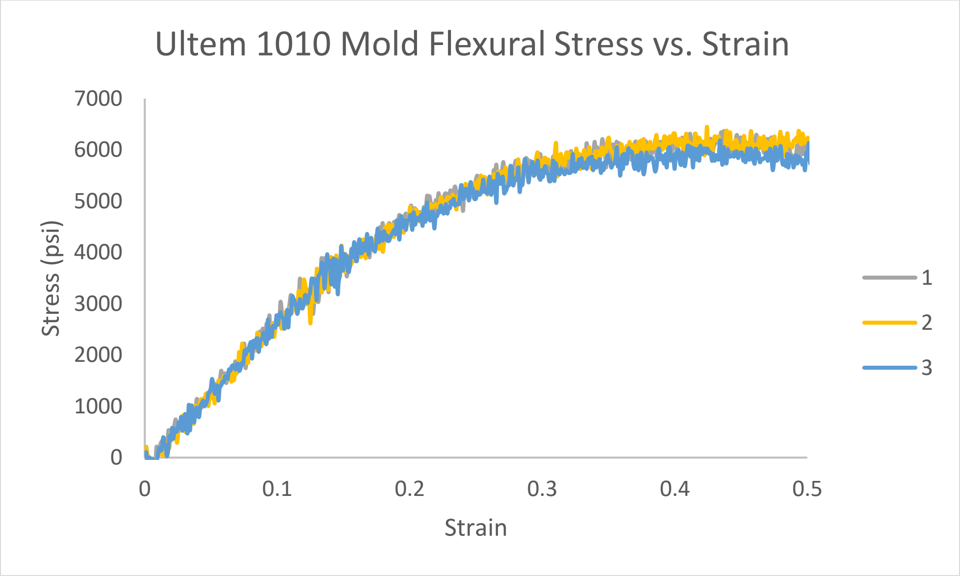

**Figure 30:** Flexural stress versus strain curves for the PP moldings made with the ULTEM 10101 mold tool

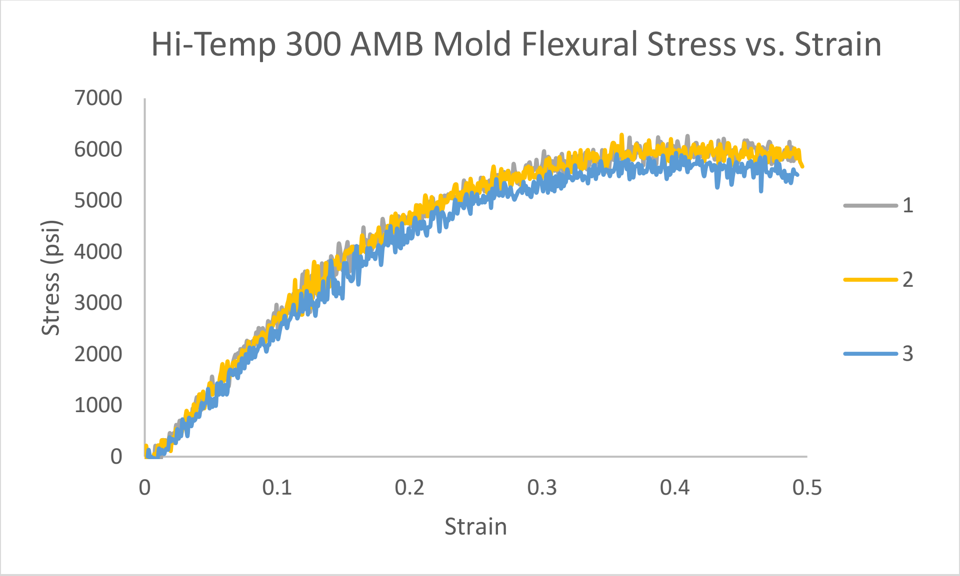

**Figure 31:** Flexural stress versus strain curves for the PP moldings made with the HI-TEMP 300 AMB mold tool

**Table 12:** Maximum Flexural Stress and Tangent Bending Modulus

| | **Max Flexural Stress (psi)** | | **Tangent Bending Modulus (psi)** | |
|---|---|---|---|---|
| | **Average** | **Std. Dev** | **Average** | **Std. Dev** |
| **Aluminum** | 6586.00 | 299.16 | 174298.30 | 4951.25 |
| **ULTEM 1010** | 6422.36 | 37.382 | 145167.70 | 1816.61 |
| **HI-Temp 300 AMB** | 6097.66 | 131.86 | 145077.3 | 4745.45 |

Seen in Table 12 and Figures 32-33, the maximum flexural strength of moldings from aluminum and ULTEM 1010 remained almost the same while a 7% decrease was observed for those made from HI-TEMP 300 AMB. These results agree with those reported by Simpson et al. When it comes to tangent bending modulus, the values remained same for those made from AM mold tools while a 17% decrease was observed when compared to those from aluminum tool. In ideal conditions, the tensile modulus of elasticity and the tangent bending modulus should be the same since both properties are the materials’ ability to resist deformation under load. However, the two properties are usually different.

The drop in the tangent bending modulus between the parts made by the aluminum mold tool and the AM mold tools is attributed to the skin morphology as described in the next section on hardness. The thermal conductivity of the AM mold tools resulted in a slower cooling rate until the moldings were ejected, then the molding surface cooled very quickly once in contact with the air. This rapid surface cooling causes more amorphous structures to form on the skin of the part which results in a less steep linear portion within load vs. deflection curve. During a flexural test, the outer faces of the test specimens experience the largest stresses. If the skin of the flexural specimen has more crystallinity, it can take higher loads at lower deflections which results in a steeper linear portion of the load vs. deflection curve. The tangent bending modulus is only affected by the slope of the linear portion of the load versus deflection curve. This is due to the rest of the inputs being consistent because they are based on the specimen dimensions. Therefore, the drop in tangent bending modulus is attributed to the difference in the skin morphologies of the parts.

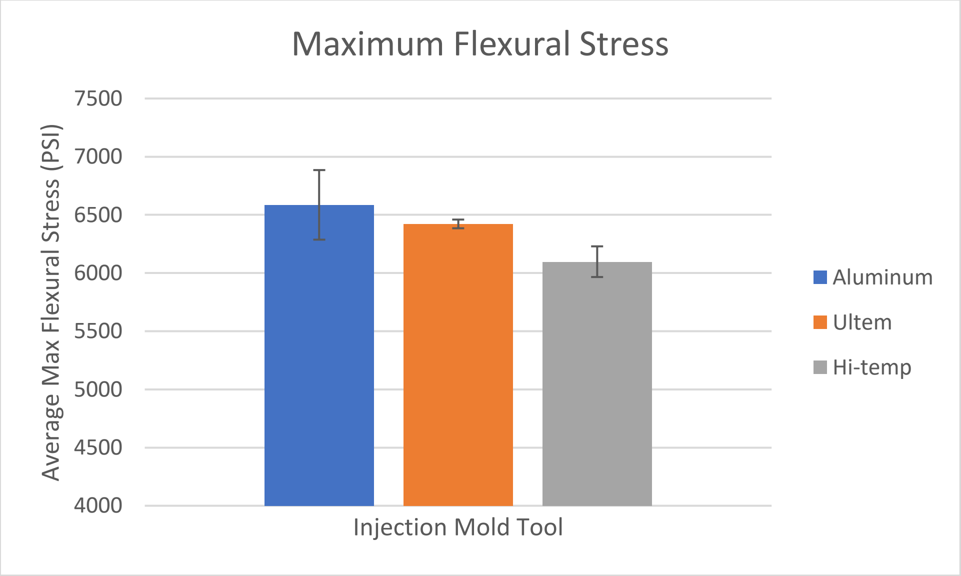

**Figure 32:** Average maximum stress of flexural samples

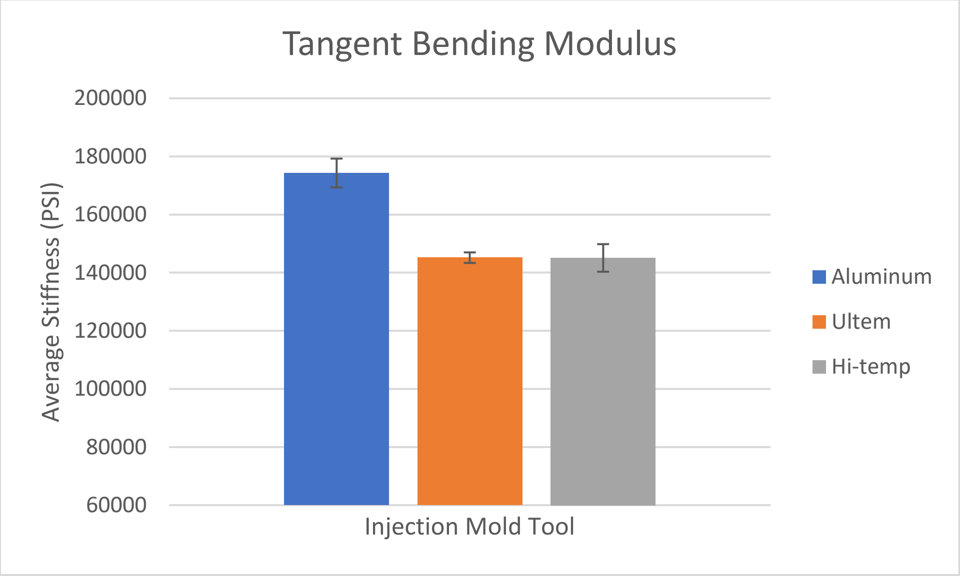

**Figure 33:** Average tangent bending modulus of the flexural samples

## 4.7 Hardness

Hardness of plastics is a key engineering property that is often overlooked. It is very useful in designing consumer products or industrial parts when motion is involved that results in the contact of materials. Since injection molding is a widely used polymer processing method for consumer goods, the influence of the mold tool on the hardness of the plastic part is considered. Using the shore D hardness tester, an average hardness was measured for 10 samples each from the respective mold tools. This test measures how deep an indenter protrudes into a sample. The results are shown in Table 13 and Figure 24. It is important to note that the hardness and other mechanical properties of plastics cannot be directly related like metals.

**Table 13:** Shore D hardness values

| | **Aluminum** | **ULTEM 1010** | **HI-TEMP 300 AMB** |
|---|---|---|---|
| **Shore D hardness** | 74.4 | 68.5 | 70.0 |

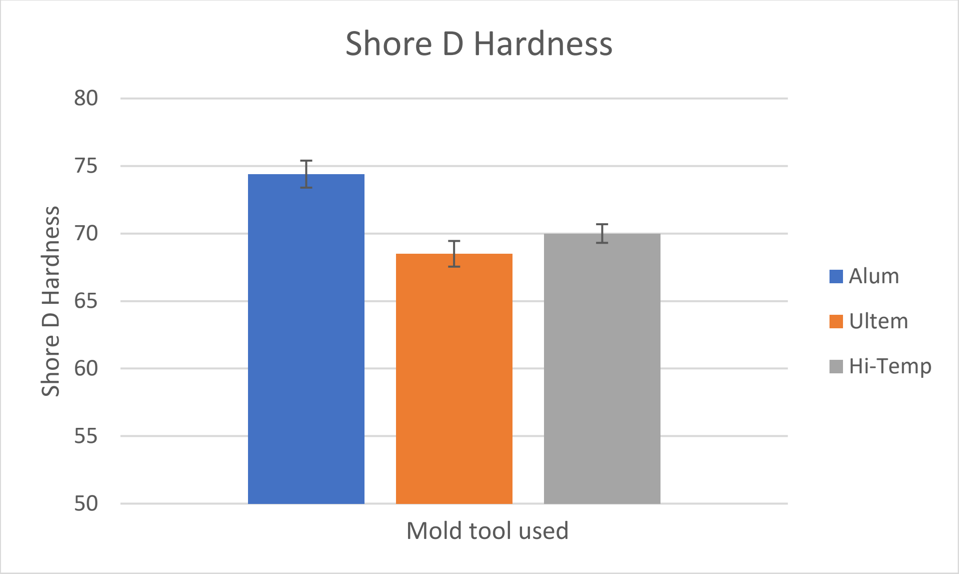

**Figure 34:** Shore D hardness values

The moldings from the ULTEM 1010 and HI-TEMP 300 AMB showed 8% and 5 % reduction in hardness respectively when compared to those made from the aluminum mold tool. Slower cooling rate typically results in more crystallinity and higher hardness values, but this is not the case in the current work. All the three mold tools had the same hold time duration, but the different thermal conductivities of the mold tools is hypothesized to have an effect on the skin morphology of the parts. The four minutes of hold time allowed the aluminum mold tool to cool and fully solidify. However, the four minutes of hold time for the AM mold tool allowed for only a partial solidification. This was evident by the translucency and softness observed in samples ejected from AM tools while the samples from aluminum tool were opaque and harder. So, when the moldings were ejected from the AM tools the surfaces cooled quickly which acted like an air quench. This faster cooling rate on the surface of the moldings made with the AM mold tools allowed for less skin crystallization, resulting in a slightly lower hardness value.

The DSC results, tensile properties, and maximum flexural stresses show that the core of the moldings cooled similarly as the material properties show no significant change between the three mold tools. There was no significant changes in hardness between the two AM mold tools. This trend in the mechanical properties is also evident in the tangent bending modulus. The drop in tangent bending modulus is amplified because the surfaces of the flexure specimen are where the maximum stresses occur. The strength of injection molded parts comes from the core and it is hypothesized that the cores had relatively the same cooling rate.

# CHAPTER 5

# CONCLUSION

It has been demonstrated that injection molding AM mold tools can produce moldings with minimal material property deviations from the traditional metallic mold tools. The question asked at the start of the project was whether the use of an injection molding tool made of an additive manufactured plastic would have a significant effect on the material properties of the PP moldings. It was hypothesized that the change in mold tool material from metal to plastic would significantly impact molding's mechanical properties because of the slower cooling rate of the mold tool. For semi-crystalline thermoplastics, the cooling rate determines the percent crystallinity of a molding and the percent crystallinity can change the mechanical properties. However, the mechanical properties and percent crystallinity of the moldings made with the AM mold tools showed minimal changes. The surface roughness of the mold tool directly impacts the smoothness of the moldings surface which may be undesired when making injection molded parts.

If this AM mold tool is to be used in low volume production the mechanical property changes need to be known and understood. If the material properties of the moldings change these can be accounted for in the design phase of the part. Alternatively, AM mold tools can be used in specific applications where the mechanical property changes of the molding are desired. The tensile properties, density, and percent crystallinity showed no significant variation between the three mold tools. The tangent bending modulus and the shore D hardness values did show a significant change which was attributed to the skin morphology difference in the parts. The moldings made by the AM mold tools had a larger amount of shrinkage. With the significant material changes in the moldings known, these properties can be accounted for in the part design phase of the tool and part. The AM mold tools and traditional tools can be used interchangeably depending on the volume of parts needed. The AM mold tooling moldings showed more shrinkage than the aluminum mold tool. The material property changes are not enough to discredit the advantages that the AM mold tools can provide.

Based on the experiments in this current work, using an AM mold tool insert where the top of the mold tool is metallic can achieve parts with similar properties to the traditional metallic mold tool. This is achieved by keeping the IM processing parameters constant and only making small changes that are needed to manufacture an acceptable part with no defects. The aluminum top plate of the tool acts as a heat sink to allow for a similar cooling rate to the traditional mold tool. It is hypothesized that the skin of the AM moldings is less crystalline because these moldings did not fully cool and solidify during the four-minute hold time as the moldings from the aluminum mold tool did. This is shown as the hardness and tangent bending modulus showed a significant decrease. However, the density, tensile properties, and percent crystallinity results demonstrate no significant change, this shows that the core of the samples had similar cooling rates.

The AM mold tools allow for faster and cheaper mold production for injection molding. When an IM product is beyond the initial trial & error prototyping phase but not ready for the large capital investment needed for a metallic mold tool, AM mold tools are a good alternative. AM mold tools are viable for the in-between of low-volume highly specialized production parts and high-volume production parts. This technique is applicable to make 10-500 moldings quickly and economically for large scale testing or pre-production market testing. Another area where the AM mold tools can flourish is in medium-volume production where the capital for a metallic mold tool cannot be justified, yet injection molding is the most appropriate manufacturing process for the part. Another application of the AM mold tool is to tests how a mold tool will work and discovering any problem areas that may arise in the injection molding part or mold tool geometry before having a metallic mold machined. Having a dedicated metallic enclosure for AM mold tool inserts would greatly reduce the cost and plastic used for the AM mold tool. This metallic enclosure also increases the longevity of the AM mold tool as the clamping force is distributed on the enclosure, not on the plastic tooling.

Properties to consider when making an AM mold tool are shrinkage of the molding, surface roughness, ejecting the molding, and lifetime expectancy of the tool. If the plastic being injected is PP then the shrinkage of molding may be 1-2% more than that of the aluminum mold tool and needs to be accounted for in the tolerancing. The surface roughness of the mold tool determines the surface finish of the molding. If a smooth surface finish is needed then the AM mold tool needs to be post processed to smooth the mold cavity. Ejecting the molding from the tool needs to be considered, the molding sticks to the AM mold tool more because it is plastic on plastic and the AM mold tool cavity has a textured surface allowing the molding to grip the mold tool more than that of the smooth metallic mold. If the AM mold tool cavity is further smoothed by a post processing procedure, then the ejection of the molding should not be an issue. The lifetime of the AM mold tool will be much less than the metallic counterpart but has applications that make it economical and efficient.

The two AM mold tools tested created moldings with similar mechanical properties to each other and the AM mold tool heat properties were adequate to IM PP without degradation of the tool. The ULTEM 1010 mold tool could soften and deflect at higher IM temperatures and pressures because it is a thermoplastic. The HI-TEMP 300 AMB mold tool will not soften or deflect under high temperatures and pressures, but it does exhibit brittle properties. One main drawback is the surface finish of the AM mold tools, both are rougher than the metal mold. ULTEM 1010 mold tool is much rougher than the Hi-Temp 300 AMB tool because of the manufacturing processes. SLA (AM process for Hi-Temp 300 AMB) has a much finer resolution than FDM (AM process for ULTEM 1010) which allows for a smoother surface and less defects. Based on the experiments the HI-TEMP 300 AMB mold tool is a better option because the surface quality of the moldings is much more comparable to the metal mold tool and has higher thermal properties allowing for more extreme IM processing parameters.

The moldings from the AM mold have simple geometry but it was shown that with fine tuning of injection molding processing parameters the usual IM defects could be avoided. These defects include flow marks, short shot, jetting, blisters, sink marks, polymer degradation, and flash. With the ability to make moldings with the similar material properties as the traditional metallic mold tool and showing that the common injection molding defects can be avoided, the additive manufactured mold tool is a viable technique that can benefit many industries. For future work it is recommended to test new materials for both the mold material and injection material. The surface roughness of the moldings that is induced by the print lines of the AM mold tool are a drawback in most situations, a post processing method or a more fine AM process to minimize the roughness would only improve the usability of the AM mold tool. More complex mold tool geometries should be produced to better define the AM mold tool design parameters. The impact properties of the moldings are also very important property that was not covered in this thesis. This project can be expanded further by experimenting with more complex geometries and conducting the mentioned research so that the gap between research and production of a part can be filled.

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