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Effects of Conformal Cooling Channels on Additively Manufactured Injection Molding Tooling

Tyler Blaine Whatcott

A thesis submitted to the faculty of
Brigham Young University
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Master of Science

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ABSTRACT

Effects of Conformal Cooling Channels on Additively Manufactured Injection Molding Tooling

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This study focuses on the cycle-averaged mold temperature of additively manufactured injection molding tooling and how it is affected by conformal cooling channels. This was done by producing a benchmark mold out of Digital ABS produced by Stratasys, an acrylic based photopolymer, which was then used to produce injection molded parts until tool failure. Another, more cost-effective material, High Temp Resin produced by Formlabs, another acrylic based photopolymer, was also tested but yielded very little success. Then the mold design was altered by adding conformal cooling channels and again tested by producing injection molded parts while tracking the mold temperature. This experimentation was then compared to an injection molding cooling channel model in order to validate the model for use with additively manufactured tooling with conformal cooling channels for use in injection molding.

The benchmark Digital ABS mold was able to produce 66 shots in the injection molding machine before complete mold failure. The Digital ABS mold had a cycle-averaged mold temperature of about 155°F. The High Temp Resin mold was able to produce 3 shots before complete mold failure. The High Temp Resin material is much more brittle, and the mold design did not take into account how brittle the material was. The Digital ABS mold with conformal cooling channels had a cycle-averaged mold temperature of 111°F. This is significantly lower than without cooling channels and has a high potential for improving tooling life. The cooling channel model predicted the cycle-averaged mold temperature to be 116°F. This proved to be a very good model and can be used as a design tool when choosing cooling channel geometry and position in additively manufactured tooling.

This research shows the potential that conformal cooling channels have to help improve additively manufactured tooling life for injection molding. As shown in other research done, the ability to maintain the mold below 120°F significantly improves the life of additively manufactured tooling. The results of this study demonstrate the effectiveness of conformal cooling channels in controlling mold temperature. It should be researched further, but the use of conformal cooling channels has the potential to produce more production or prototype parts with additively manufactured tooling for injection molding.

Keywords: additive manufacturing, injection molding, rapid prototyping, soft tooling, conformal cooling channels, tooling life

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1 INTRODUCTION

1.1 Background

Creating a mold for an injection molded (IM) part is a lengthy process and can take up to 6-8 weeks not including the time it takes to design the mold. Not only does it take a long time, which translates into high cost, but making a mold out of tool steel or aluminum is expensive. The high cost of making an injection molding tool can only be justified when the produced part will be made in the thousands to hundreds of thousands of parts and then the return on investment (ROI) on the mold typically comes after a year or more into production. This is due to the low profit margins made from injection molded parts. This has forced injection molding to become a process that is only used in very high volumes and rarely for any part that will only need to be produced in the hundreds or low thousands.

The design iteration process with any mold design is slow and costly as well. There have been many improvements in modeling and simulation software that allow for the design to be thoroughly vetted before production but there are, at times, unforeseen issues in the design of an IM mold. After the initial design and build, the mold is tested and validated and often, slight changes need to be made to the mold to achieve results that meet the original design criteria. When this happens during initial prototyping and design validation of a part, this can often slow down the validation phase of design and delay product release.

Additive Manufacturing (AM) is a manufacturing process, commonly called 3D printing, that creates a 3D part by depositing or curing a layer at a time of a polymer, resin, metal, paper, or ceramic until a complete part is finished. The layers are combined through sintering, an adhesive, or the deposited layer is hot enough for layer adhesion. This process is slow but the price per part is the same for all volumes of production. AM is used very often for rapid prototyping and has typically been used as a way to prove the form, fit, or function of a part before it is mass produced by another process such as injection molding. Rarely is AM used to produce an end use part because of the slow processing time and typically poor material properties of the additively manufactured part. AM is not very cost effective for large volumes.

In the past two decades, many advances have been made in the field of AM and the technology is being pushed to do things such as producing high quality, engineered, end use parts but in low volumes. Between these two processes, injection molding and additive manufacturing, there is a large gap between the volumes at which they are typically used. IM is impractical in low volumes because of high tooling costs, and AM is impractical in high volumes because of slow production speeds. In the middle lies the marriage of the two processes and a viable solution to lower volume end use parts with better quality materials and faster cycle times. Additively manufactured tooling for injection molding is a new method to cost effectively produce anywhere from 50-500 parts [1, 2, 3, 4, 5].

This method can be used for product testing before the hard injection molding tool is made. The mold can be printed using the same design of the hard tool, usually with only slight modifications, and then test parts can be produced. If the AM mold is used for product testing and validation, it can, at the same time, be used to test and refine the tool design as well. It will help reduce the time it takes to produce a hard tool that can be used for production and in some cases, can produce enough parts to meet the demands of low volume production and completely replace the hard tool.

The advantage that AM has over traditional mold making processes is that there is a lot of freedom in the design of the mold. Many internal features can be added very easily, and the complexity of the design has little to no effect on the time of the build of the tool. This is the exact opposite of traditional methods. The more complex that a hard tool is, the longer that it takes to build. One example, conformal channels, inside of an AM tool saves on printing material and in fact makes the build time faster and less expensive.

An AM injection molding tool can produce 50-500 parts and then fails due to cracks in the mold from the high temperatures and pressures of injection molding [6, 5]. Research has been done on what causes the failures and what causes the cracks to spread the fastest and it is shown to be the temperature of the mold when a cycle is started [6]. If the temperature is too high, the strength of the mold is reduced and causes cracks to propagate and the mold to fail [5]. With this knowledge of how the tools fail, the focus can now shift to discover how the AM IM tooling life can be improved. With a longer production life for AM IM tooling, this technology can be used more and more for low volume production and can enhance the product development process. One proposed method of improving the life of the tool is adding conformal cooling channels in the mold to keep the tool as cool as possible during processing [7]. This will be the focus of this study.

1.2 Problem Statement

This research is being conducted in order to better understand the effects of conformal cooling channels on the cycle-averaged mold temperature of an additively manufactured tool for injection molding and whether or not it has the potential to significantly improve the life of the tool. The AM processes that will be studied are stereolithography (SLA) (particularly the SLA process used in Formlab’s Form 2 SLA printer) and Polyjet (developed by Stratasys). SLA is an AM process that uses a UV laser to cure a photopolymer in a vat one layer at a time until a 3D part is produced. Polyjet jets the photopolymer down onto a build platform (similar to an inkjet printer) and cures each layer with a UV light until a 3D part is produced. The SLA process will be compared to the more commonly used Polyjet method used in industry for additively manufactured injection molding tooling. The main advantage of the SLA process over the Polyjet process being the lower cost and therefore a more industry accessible process for producing AM IM tooling. It is hoped that a less expensive material and process can be used for AM IM tooling so that it is more available to smaller companies or early startup companies. The Polyjet method will then be tested further beyond the SLA process, to see how the life of the tool is affected by adding conformal cooling channels. The hypothesis is that by adding conformal cooling channels to a Polyjet AM IM tool, the tool will have a significantly lower cycle-averaged mold temperature than an AM IM tool without any cooling system and therefore have a longer tool life. From the data that is collected from experimentation, the following questions are to be answered:

1. How effectively do conformal cooling channels lower the cycle-averaged mold temperature of a Polyjet AM IM tool?
2. Using a cooling channel heat transfer model, how well does the model predict the cycle-averaged mold temperature and how can it be used for AM IM tooling design?
3. What are some general troubleshooting guidelines that could be provided to improve the process to make it more streamline and profitable?

2 LITERATURE REVIEW

2.1 Additive Manufacturing

Over the past decade or so, a lot of attention has been placed on additive manufacturing in hopes to improve it and drive down the cost of the process. Traditionally, additive manufacturing has been used solely for producing prototypes of parts. These prototypes were used to test the form, fit, or function of a design. This is a very important capability of additive manufacturing, but research continued to explore more capabilities and applications. This point of research has developed into a vast and continuously growing industry that has proven to demonstrate more and more applications of this once novel technology [8].

One point of research is the use of photopolymers in additive manufacturing processes such as Stereolithography (SLA) or polymer jetting. Photopolymers can be altered and customized to create different mechanical properties [1]. The cured photopolymers can have a range of properties and therefore a range of applications. There are soft and malleable polymers, hard and brittle polymers, and some polymers that are designed for high temperature applications. With this customization, SLA and polymer jetting have been used for some more novel applications such as tooling for injection molding [2].

2.2 Rapid Tooling Injection Molding

Because of the high cost of building an IM tool made from tool steels using traditional subtractive manufacturing, there has always been a drive to make faster and cheaper tooling for injection molding. The high cost is sometimes prohibitive to small companies or products that will only be produced in small quantities. Machining has traditionally been the go-to method for making molds for injection molding so a common way to make cheaper molds, faster has been to look to cheaper materials such as aluminum. Aluminum molds are often used for quick turnaround, low volume production runs or for prototype runs, but even then, there is still room for making molds faster and that cost less.

Rapid tooling (RT) in manufacturing is a point of research that seeks to improve the cost and build time of tooling in order to improve the design process and bring products to market faster and at a lower cost [9]. There are different types of RT, typically categorized into hard or soft and direct or indirect. Direct tooling being a tool made either by machining or AM processes that directly produces the mold. Indirect tooling being a master pattern made by machining or AM processes and the mold produced from the master pattern, typically by casting. Each type of RT has its common uses but, this paper, along with many others, will attempt to show how soft-direct rapid tooling can be used for low volume or prototype runs. RT has the advantage of maintaining cost and time to produce despite design complexity and production volume and can therefore be used for smaller runs more economically (as shown in Figure 2-1 below)

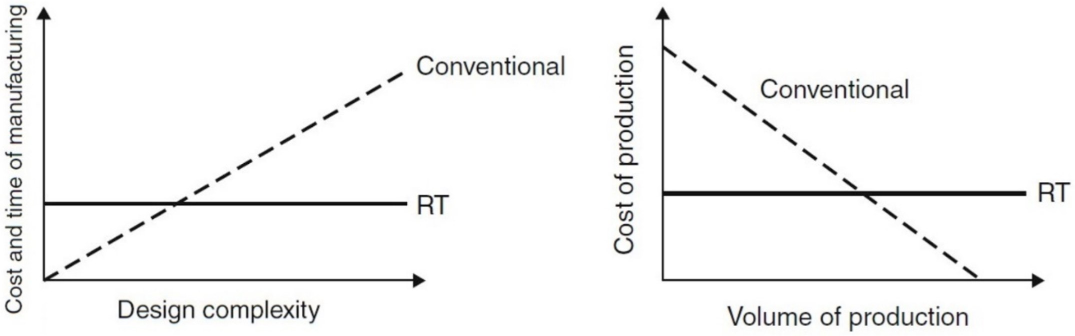

Figure 2-1: Cost of RT vs Conventional Tooling in Manufacturing

One case study of RT was done with EP250 epoxy resin (25%) mixed with an aluminum powder (75%) for a soft tool for injection molding [10]. This demonstrated that a mold made from a polymer (epoxy) was able to function as a mold for injection molding and stand up to the temperatures and pressures of injection molding. The lead time was cut in half and the price of the soft tool was 25% that of a tool made in conventional tool steel. Approximately 500 parts were molded off the tool which is significantly less than a steel mold can produce. Despite the low number of parts produced, soft tooling still has its place in low volume production runs and prototype runs due to quick tooling production time and lower cost. This type of RT would be investigated further but it has its disadvantages as well. It is difficult to create the mold because it requires several casting operations and is time consuming. Which is where AM tooling excels, being very easy to produce high quality tooling by simply printing the mold.

2.3 Additive Tooling for Injection Molding

Rapid tooling for injection molding has been done with many different materials but soon after additive manufacturing emerged, it became one of the primary methods for producing soft-direct tooling for injection molding. It is much simpler to produce than other rapid tooling production methods such as casting and produces higher quality molds as well. Research has shown that the cost of tooling can be reduced by 82% and that the tooling production lead time can be reduced by 66% by using AM for injection molding tooling [11]. The most common methods used for producing AM IM tooling is SLA and polymer jetting. Both of these processes use photopolymers which, “due to the fact that the network density of the photopolymer can be varied to a large extent, the mechanical properties (strength, Young’s modulus) of the final photopolymer can be tailored over a wide range” [2]. The mechanical properties of AM parts produced by SLA and polymer jetting can be “tuned” for specific applications by the producers of the photopolymers, which, makes them very attractive for harsh environments such as injection molding (high temperatures and pressures).

Other processes that are commonly used in AM are fused deposition modeling (FDM), selective laser sintering (SLS), and binder jetting. SLA and polymer jetting are more commonly used over these processes because of their ease of use, their high-quality production capabilities (high resolution), and the fact that they use the photopolymer materials that are so tunable. FDM is comparatively low quality and the materials available can’t withstand the high temperatures of IM. SLS and binder jetting are strong candidates and are used for AM IM tooling but mostly for metal tooling [12]. This is a great option but is more costly and requires more post processing than SLA and polymer jetting.

A very common material that is used for AM IM tooling is a photopolymer produced by Stratasys called Digital ABS. This material has been heavily studied and compared to different materials. The surface quality of parts produced has been studied and is shown to be able to produce high quality parts. In the study done by Volpato, 50 parts were made before mold failure and the parts produced were comparable to those made with a steel tool with only some slightly different properties [4].

The company Stratasys has recognized the market for this material and has written several white papers on the topic of using their Digital ABS material for AM tooling for injection molding [13.] Their white paper gives guidelines and tips on how to successfully design and print a mold. They give general guidelines for better results such as:

- using injection plastics that have a lower melt temperature (<570°F)
- small to medium sized parts (<10 in^3)
- using injection molding machines with under 200 tons of clamping force

- increase draft angles to 5°
- enlarge all gates
- and other general guidelines

Their white paper features a large number of case studies with many different mold features being incorporated into the Digital ABS molds, just as a normal steel mold. Features such as ejection systems, cooling systems, and multiple inserts or side action pieces. They suggest increasing the cooling time for the injection cycle and after ejection, to allow the surface of the tool to cool to 120°F.

Two other materials that can be used and that are an even less expensive option compared to Digital ABS are acrylic based photopolymers produced by Formlabs called “Clear Resin” and “High Temp Resin”. In a white paper written by Formlabs on a case study of tooling made for injection molding, they compare the two materials and discuss their capabilities [14]. The Clear and High Temp resins have similar properties to Digital ABS but are slightly more brittle [3, 15, 16, 17]. The case study done by Formlabs was only done on a benchtop style injection molding machine and they do not recommend using their molds with industrial injection molders. It is worth noting though, that the molds can still produce up to 100 parts which, for some applications may be the best option. No data has been given on the negative results of using this material in an industrial injection molding machine.

More studies have been done to compare Digital ABS to P20 tool steel molds and have found that parts that are produced from Digital ABS are comparable to those produced from P20 [18]. Simulation work has been done with AM tooling for reaction injection molding and has been found to be a viable option for producing at least 200 parts and has the potential “to reduce costs by up to 98.75%” [19]. One particular case study was done with Digital ABS and reported producing more than 10,000 parts [20]. This is most likely attributed to the part design being very simple, the insert being very small, and only one half of the insert was additively manufactured, with the other half being a metal plate that could have taken the brunt of thermal and mechanical stresses.

2.4 Methods for Improving Tooling Life

The most common reported causes of AM IM tool failure have been two major factors, the injection pressure, and the temperature of the mold at the time of injection [3, 6, 21, 22]. The focus of this paper is on the thermal failures of the molds and how to improve the longevity of the tooling by better controlling the temperature of the mold. There have been many different benefits found resulting from controlling the temperature of the tool. One study reports better dimensional accuracy of parts produced by maintaining a cool mold [21]. Mechanical properties of the AM IM insert are much better at lower temperatures, as well as uniform cooling in the part and uniform shrinkage of the part [3].

Once research had demonstrated that AM tooling for injection molding was a viable and cost effective method for producing prototypes and small volume parts, research continued to push this technology forward to find ways to improve the life of the tooling. Davoudinejad found, as mentioned previously, that the temperature of the mold had the greatest influence in the life of the mold [6]. This study was done by conducting a DOE with packing time, packing pressure, melt temperature of injected polymer, injection speed, mold temperature and cooling time as the factors of the experiment. Simulations were done as well to show where the tool would fail which were found to be the corners and side walls of cavities. The “hot spots” in the simulation were where the tool failed in experimentation. Inserts that were allowed to cool longer and that did not proceed with injection until the mold reached a temperature of 77°F lasted the longest.

Some test materials were tested by Etesami with the heat deflection temperature of the materials being the focus of the study [23]. Samples were placed in an oven and the deflection and indentation depth of the samples were recorded and compared to the temperature in the oven. This study showed that a possible way to improve mold performance is to add a chopped fiber to the mold, either carbon fiber or glass. This may be problematic for most photopolymers because it may interfere with the polymerization of the polymer but may be an option for other AM processes and an area that could use further research.

Research that focused on the tool strength as affected by the temperature of the mold showed that after allowing the tool to cool to 104°F-122°F before injection, the mold's "strength *was* still maintained and the low conductivity of the" mold "*worked* in favor of the process initially" [5]. This research points out that by lowering the temperature of the mold before injection, the chance of flexural failure is reduced. It is suggested that the tool be cooled by free convection or air jet. It also suggests reducing the aspect ratio of mold features to reduce the risk of flexural failure. As this is often not an option because of the design of the produced part, controlling the temperature of the mold is the preferred solution.

Temperature control was the main focus of the research done by Schuh in 2020 [7]. Three main methods were offered as means to controlling the temperature of AM tool. They are:

- Process features (such as cooling the surface of the mold with jet air between cycles)
- Mold features (such as cooling channels, especially conformal cooling channels)
- Insert features (such as additives in the AM material to control the thermal conductivity)

This study provides a selection model for which features should be incorporated into a mold design. The most promising method for mold temperature control is internal conformal cooling channels. It provides the most efficient way to remove heat from the AM insert and maintaining the mold below temperatures that lead to failure.

2.5 Conformal Cooling Channels in Additive Tooling for Injection Molding

This paper will focus on the benefits of conformal cooling channels and how they improve the life of AM tooling. Much research has been done on the subject and this paper will attempt to expound on previous research done. Some early research done with conformal cooling channels was done without the AM technology and was a good foundation for future research [24]. Copper pipes were bent to conformal shapes and then a soft RT insert was cast using an epoxy resin and a master. This research pointed out the difficulties of the RT process and that improvements still needed to be made.

A lot of work that has been done with conformal cooling has mostly been simulation work [25, 26, 27]. This work is beneficial as it helps direct studies into new areas that have great potential for success, e.g. porous conformal structures that allow for more uniform cooling of the AM insert [26]. It also shows how the structure of the channels can be designed to minimize structural strength loss and allow the channels to be even closer to the surface of the insert cavities [27]. But as Shinde points out, this work only goes so far, and more work needs to be done with actual experimentation to help solve issues that are sure to arise while implementing these new technologies [25].

Another early study was done using the SLA AM process to compare the effectiveness of different cooling channel geometries [28]. It was found that the most effective geometry for cooling is a square channel that is approximately 1.5 x the width of the channel away from the surface of the cavity of the mold. It was shown that by using this geometry of channels, the temperature of the AM insert was reduced by up to 170°F as compared to an insert with no cooling channels. Although a general rule was given for the depth of the channel below the cavity surface, a more calculated approach was taken by other researchers that took into account the thermal properties of the insert [12, 29, 30, 31, 32]. This calculated approach will be applied here.

Work has previously been done on implementing cooling channels in a Digital ABS AM insert but no detailed findings have been published [13]. Stratasys reports a 20% increase in tool life but does not release much more information than this. The hope with this study is to verify and provide data to the findings and to verify a model that can be used as a design tool for AM IM tool design. It is hoped that by changing the geometry of the channels and precisely calculating the correct position of the channels below the surface of the mold, a significantly lower cycle-averaged mold temperature can be achieved. It is also the goal of this study to help add to the body of knowledge of how to make a more rugged design and molding setup so that future users will achieve better results.

2.6 Tooling Life Analysis

It is often difficult to determine the effectiveness of an improvement made to a process without using statistically significant data. The best way to determine the effectiveness of the addition of conformal cooling channels to a Digital ABS AM injection molding tool would be to run a large sample size of inserts with and without channels and compare results. Without doing this, other methods to determine the cooling channel's effectiveness will need to be put into place. In order to ensure that there are clear results for this study, the metrics that will be used to determine success will be laid out here.

As used in almost all the studies cited in this paper, the metric used for the life of a tool is the number of parts produced from the mold before catastrophic failure of the mold. This method is a good metric because it shows how well the insert performs where it counts, which is producing parts. This method will be applied to the benchmark mold that is used in the study (a Digital ABS AM insert with no cooling channels). Because of difficulties in producing the mold with conformal cooling channels (which will be discussed in greater detail later in this work), a different method will be used to compare the improvements found from adding cooling channels. The mold and cooling channel performance will be compared to the cooling channel models and the cycle-averaged temperature will be the main metric to determine performance [30, 31, 32].

As discussed earlier, another common metric for the longevity of the mold is how well the temperature of the mold can be controlled. In different articles, it is shown that if the temperature of the mold can stay at or below 120°F at the time of injection, the life of the tool will be increased significantly [5, 6, 13]. This will be used in the latter half of this study as a metric to determine the effectiveness of conformal cooling channels. The ability of the channels to control the cycle-averaged temperature of the insert and keep it as close to or below 120°F will determine how well the channels are performing and will show how much of an improvement they make on the life of the tool.

3 METHODOLOGY

3.1 Test Part and Mold Design

With the effectiveness of conformal cooling channels being the focus of this study, a part that would most benefit from this feature was designed as the test part. Traditional tooling doesn’t have the capability to create cooling channels in deep cavities and therefore can sometimes have a difficult time controlling the temperature. A deep pocket part was designed so that this could be tested. A simple box was designed with some simple corner gusset features (see figures 3-1 and 3-2). This design is similar to what may be found for an electronics housing or some similar application. Some finer detail was added to the bottom of the part as well to test how well the finer detail molded. The part was molded using acrylonitrile butadiene styrene or ABS (CYCOLAC FXS610SK). This was chosen because it has a higher injection temperature than other commodity plastics and would heat up the mold faster and give data faster than polypropylene or polyethylene. It is also a common plastic used for this type of application.

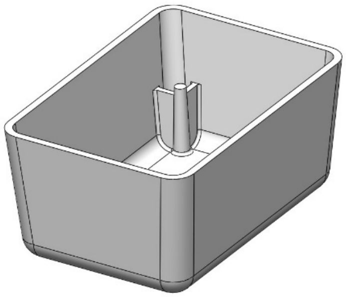

Figure 3-1: Test Part Top View

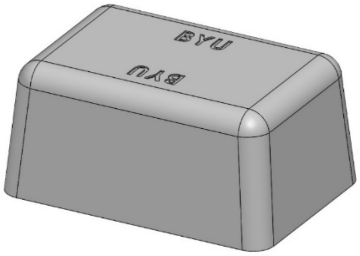

Figure 3-2: Test Part Bottom View

The mold was designed using the part design. Stratasys recommends not allowing the nozzle of the injection molder to make direct contact with the AM insert so a sprue bushing was added to the assembly to prevent this [13] (see mold setup in Figure 3-3). The mold design was a simple direct sprue gate design. The downsides of this gate design will be discussed later on. The mold was designed using guidelines form three different sources, *Plastics Materials and Processing* [33], *Injection Mold Design Engineering* [34], and *Polyjet For Injection Molding Technical Application Guide* [13].

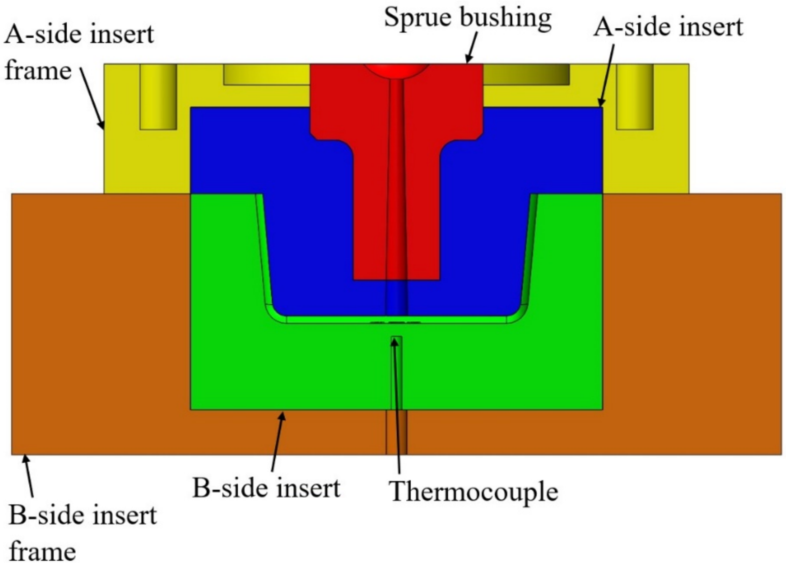

Figure 3-3: Mold Assembly

This first mold was designed as a benchmark mold that final experimentation could be compared to. The cooling channel test parts that were designed and built were a simpler test part without the corner gussets (the reason for a simplified test part design will be discussed later) and a mold with conformal cooling channels. The channel design was modeled after the work done by Janczyk on the different geometries of cooling channels and their effectiveness on cooling the AM inserts [28]. They concluded that a square channel yielded the best results and helped maintain the surface temperature of the insert below 150°F. The distance of the channel from the surface of the cavity was calculated using methods and equations used by Sachs and is shown below(equations 3-1 and 3-2) (Sachs goes into detail on how and why these equations are used and their paper can be referred to for more information) [12, 35]. Also refer to Table 3-1 for material properties used in the calculations as well.

$$\boldsymbol{a = \frac{k}{\rho_m c_{pm}}} \tag{3-1}$$

Equation 3-1 is used to calculate the thermal diffusivity of the mold material (a) using the thermal conductivity (k), density (ρ_m), and specific heat (c_{pm}) of the mold.

$$\boldsymbol{l < \sqrt{a t_k}} \tag{3-2}$$

Equation 3-2 uses the thermal diffusivity and the cycle time (t_k) to calculate the distance that a “heat pulse can travel by conduction to a solid in a given time” [12]. In other words, it calculates the minimum distance that the cooling channels need to be beneath the surface of the cavity to effectively function as a cooling channel. This model is simplified and a is a good way to quickly get a good estimate of what dimensions should be used but a more involved model was used as well in hopes to validate the model for use with AM IM tooling for future experimentation or industry use. (equations 3-3, 3-4, and 3-5) [30, 31, 32]. The model in equations 3-5 predicts the cycle-averaged mold temperature which will be a key metric for high performance.

$$\boldsymbol{Re = u \cdot \frac{d_h}{v}} \tag{3-3}$$

Equation 3-3 is used to calculate the Reynolds number (Re) of the coolant using the hydraulic diameter of the channel (d_h), the viscosity of the coolant (v), and the velocity of the coolant (u).

$$\boldsymbol{\alpha = \frac{.031395}{d} \cdot Re^{0.8}} \tag{3-4}$$

Equation 3-4 is used to calculate the heat transfer coefficient (α) between the mold and cooling channels using the Reynolds number calculated in equation 3-3, the height of the cooling channel (d), and two known constants.

$$\boldsymbol{T_m = T_c + \frac{\rho_p \cdot c_{pp} \cdot \frac{s}{2} \cdot (2 \cdot k \cdot x + \alpha \cdot 4 \cdot d \cdot l) \cdot (T_p - T_e)}{\alpha \cdot 4 \cdot d \cdot k \cdot t_k}} \tag{3-5}$$

This model simplifies the problem by turning it into a 2D heat flow simulation. Using the properties of the polymer melt (c_{pp}, ρ_p) and the thickness of the injected part (s), the thermal mass of the polymer melt is taken in to account. Then the dimensions of the cooling channels (d) and their position (l) and pitch (x) is used along with the thermal conductivity of the mold (k) to take into account the distance that the heat needs to travel before they reach the cooling channels. The temperature of the melt at injection (T_p) subtracted from the temperature of the mold at ejection (T_e) give the temperature that is removed from the system. The heat transfer coefficient calculated in 3-4 is used with the size of the channel, thermal conductivity of the mold, and the cycle time (t_k) to take into account the amount of heat that can pulled away by the channels during the cycle time. This is all added to the temperature of the coolant to calculate the cycle-averaged mold temperature.

Table 3-1:Values Used for Calculation [3, 4, 6, 36, 37]

Property	*Value*
Thermal Conductivity of Insert $(k)\,\frac{W}{mK}$	0.17
Density of Insert $(\rho_m)\,\frac{kg}{m^3}$	1170
Specific Heat of Insert $(c_{pm})\,\frac{J}{kgK}$	1030
Thermal Diffusivity of Insert $(a)\,\frac{m^2}{s}$	8.3 x 10^{-7}
Cooling Channel Depth $(l)\ m, in$	5.33 x 10^{-3}, .21
Temperature of Coolant $(T_c)\ K, °F$	291, 64
Melt Polymer Density $(\rho_p)\,\frac{kg}{m^3}$	1040
Specific Heat of Polymer $(c_{pp})\,\frac{J}{kgK}$	1700
Part Wall Thickness $(s)\ m, in$	2.16 x 10^{-3}, .085
Cooling Channel Pitch $(x)\ m, in$	1.69 x 10^{-2}, .665
Heat Transfer Coefficient $(\alpha)\,\frac{W}{m^2K}$	19114
Cooling Channel Height/Width $(d)\ m, in$	5.84 x 10^{-3}, .23
Polymer Melt Temperature $\left(T_p\right)\ K, °F$	480, 405
Ejection Temperature $(T_e) K, °F$	379, 223
Cycle Time $(t_k)\ sec$	210
Cycle-Averaged Insert Temperature $(T_m) K, °F$	319, 116
Reynolds Number (Re)	27455
Coolant Velocity $(u)\,\frac{m}{s}$	2.36
Hydraulic Diameter of Channel $(d_h)\ m$	1.17 x 10^{-2}
Kinematic Viscosity of Coolant $(v)\,\frac{m^2}{s}$	1.004 x 10^{-6}

The model used from equations 3-3, 3-4, and 3-5 was not used for designing the mold but was tested during experimentation to prove its effectiveness for AM IM molds with conformal cooling channels. Using the simple model from equations 3-1 and 3-2, with a cycle time of 210 sec, the channel needed to be a minimum of .214” below the surface of the cavity of the insert.

This was rounded down to .21” and was the dimension used for designing the cooling channels in the mold. The height of the square profile side was .23” this dimension was used out of necessity, in order to be able to fit the cooling channel inside the insert without getting too close to the outer wall or the inner cavity surface. The channel was centered between the outer wall and inner surface. The thermocouple for the mold was placed .325” below the surface and centered in the cavity. The original design for the cooling channels had a main line that entered the insert, and then similar to a manifold, split off into 3 (A insert) and 4 (B insert) other lines that circled the inset and returned to another outlet manifold as can be seen in figures 3-4 and 3-5. The intent of this design was to allow for a shorter distance for the coolant to travel and therefore, allow for more heat removal. This design proved to be difficult to remove support material which will be discussed more later.

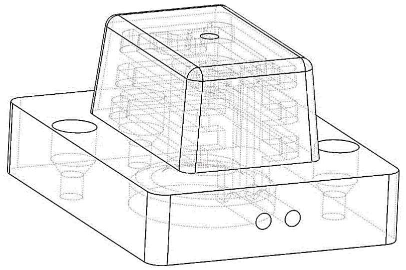

Figure 3-4: A-Side Insert With Square Conformal Cooling Channels (Rev 1)

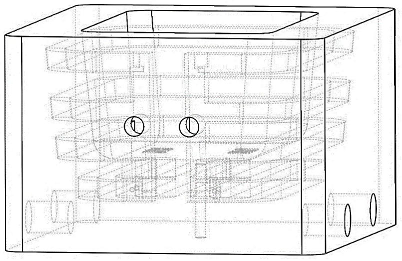

Figure 3-5: B-Side Insert With Square Conformal Cooling Channels (Rev 1)

The improved design was a single line that spiraled around the insert and then exited the insert in the same line (Figures 3-6 and 3-7). This allowed for simpler support material removal. The coolant inlet was placed on the bottom of the mold, closest to the bottom surface of the cavity so that the coolant would first run along the hottest part of the mold. Channel depth and size with the new part design was consistent with the first. The part that was molded using the insert with cooling channels was much simpler as mentioned before. The gusset feature on the benchmark mold proved to be a failure mode that distracted from the real data that was being researched and was removed.

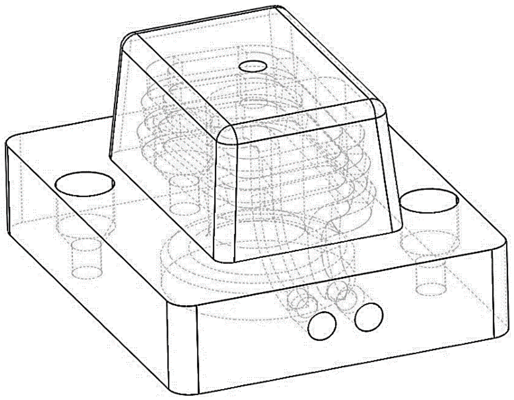

Figure 3-6: A-Side Insert With Square Conformal Cooling Channels (Rev 2)

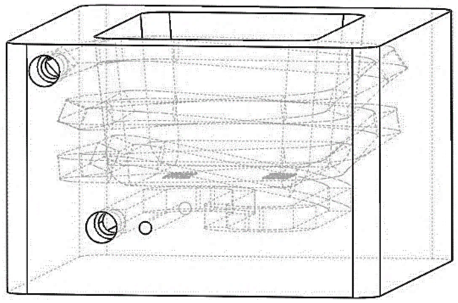

Figure 3-7: B-Side Insert With Square Conformal Cooling Channels (Rev 2)

3.2 Support Tooling Design

In order to help protect the inserts from the brunt of the clamping force of the injection molding machine and to have a way to mount the inserts, support tooling frames were designed and built. The design was very simple. The A-side was made to fit on the injection molding machine that was used, a BOY 22-A. The B-side was made to fit in a standard M.U.D. base (see Figures 3-8 and 3-9). The frames were made out of 6061 aluminum for its high machinability. The frames were then altered after the benchmark mold was tested to accommodate for the cooling channels and to provide a different mounting system for the inserts with conformal cooling channels.

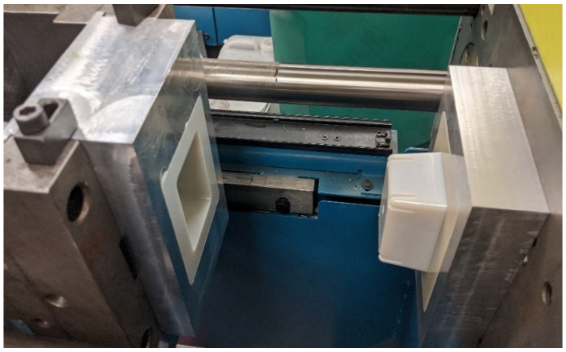

Figure 3-8: Benchmark Mold Setup

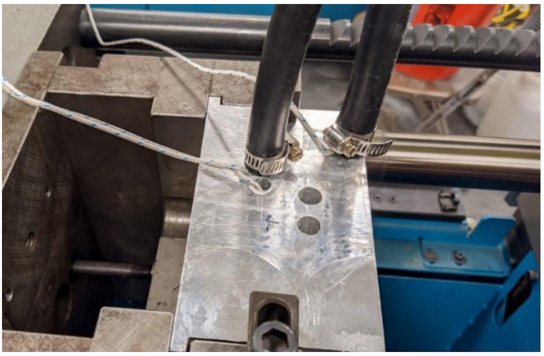

Figure 3-9: Cooling Line Alterations

3.3 Mold Production and Preparation

The benchmark molds were printed in 2 different materials, both the Digital ABS from Stratasys and the High Temp Resin from Formlabs. The Digital ABS material specifically was a combination of the materials RGD 515 and RGD 531 to produce the ivory color Digital ABS. Support material used for the Stratasys print was SUP 705. The Digital ABS mold was printed on an Objet polymer jetting system. The High Temp Resin specifically was FLHTAM02 from Formlabs. The High Temp Resin mold was printed on a Form 2 SLA system.

The Stratasys mold was produced first as the benchmark mold for all tests conducted, it being the most commonly studied material for this application. The mold was prepped by removing the support material using a waterjet and some light sanding. After the support material was removed, holes were drilled in the mold for mounting them to the support frames. In order to install the sprue bushing, some sanding was required on the inside of the mold to allow for a proper fit. After some initial trials to ensure proper function of the mold, a design flaw was discovered in the mold design. There were no issues with the B-side design, but the A-side had serious flash issues where the sprue bushing and insert mated (see Figure 3-10).

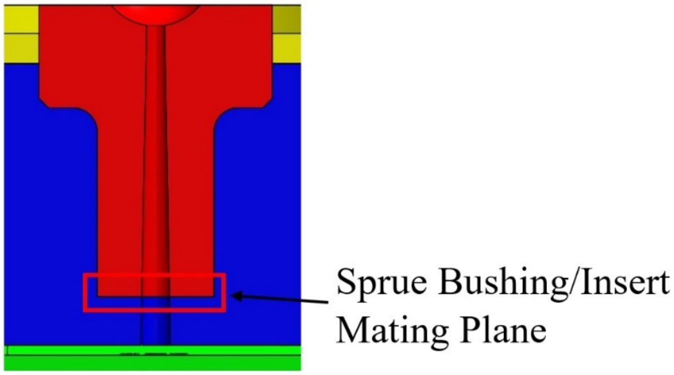

Figure 3-10: Sprue Bushing Flash Issues

This issue made it impossible for parts to be removed unless the A-side assembly was disassembled, and the flash removed and then reassembled. This was not an acceptable process, so a solution was needed. Different methods were tried out but the method that worked best was applying a layer of high temp flash tape to the end of the sprue bushing, and then applying high temp epoxy to the taped end of the sprue bushing and to the inside of the mold. Then more epoxy was applied to the inside of the sprue, where the parts interfaced. After the epoxy cured, the sprue was then reamed out with a taper ream to remove the excess epoxy and create a smooth seamless transition from the sprue bushing to the insert. This method worked quite well and allowed testing to continue. Also, during initial trials during preparation, the base of the insert was fractured while trying to disassemble the molds to remove the sprue bushing flash. This was repaired and did not affect the testing as it was the base of the insert and did not affect the core of the insert. After these issues were resolved, the mold was ready for testing as shown in Figures 3-11 and 3-12.

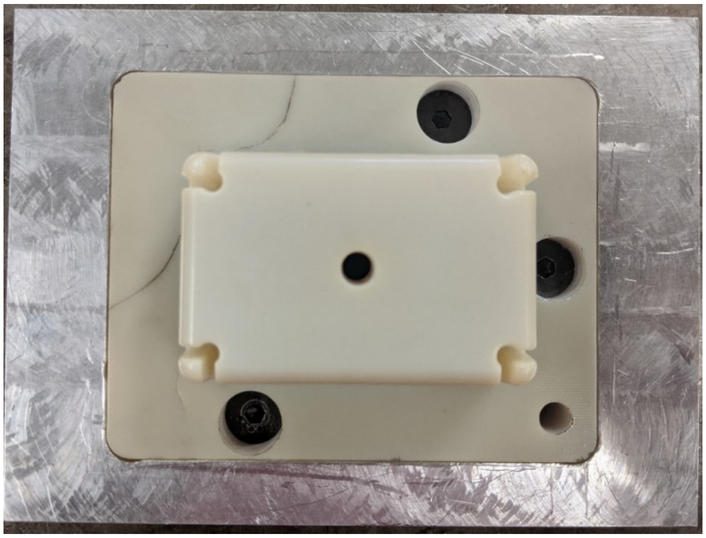

Figure 3-11: Digital ABS A-Side Mold Prepped for Testing

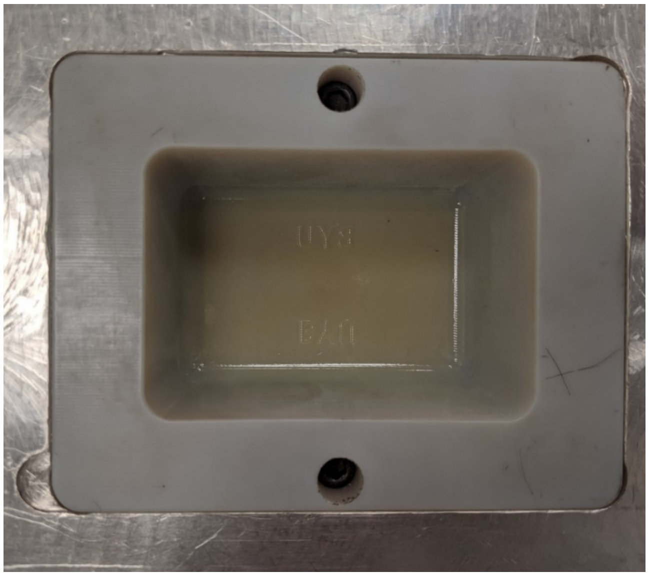

Figure 3-12: Digital ABS B-Side Mold Prepped for Testing

The High Temp Resin insert followed a slightly different method of preparation. After the print was complete, the insert went through a series of cleaning and curing processes. The part was put in an isopropyl bath to remove excess resin. It then was put in a heated UV cure at 80°C for 120 minutes and then additionally post cured in an oven for 3 hours at 160°C. This was done to achieve the highest heat deflection temperature (HDT) of 238°C @ .45 MPa. The hope was that this higher temp cure would help the insert to last longer in the molding process. After curing, the support material was removed mechanically by breaking off the supports and then sanding the supported surfaces smooth.

After support removal, the A-side insert was sanded for proper fit of the sprue bushing, similar to the Digital ABS insert, and then was epoxied in place as well. After the oven curing process, some warping and cracking occurred to the inserts (Figure 3-13). It is likely that was due to the print orientation and the large size of the part. The layers of the print likely caused the part to cure unevenly and cause cracking and warpage. It also likely that removing the support material before curing caused cracking and warpage. Later parts were cured before support material removal and warping, and cracking was minimal. The A-side had some internal cracking and some warpage, so it was sanded to remove the warpage and allow for proper installation in the support frame. The B-side has cracking but it did not propagate through into to the cavity. This half was also sanded for proper fit into the support frame as well.

Figure 3-13: High Temp Resin A-Side Curing Damage

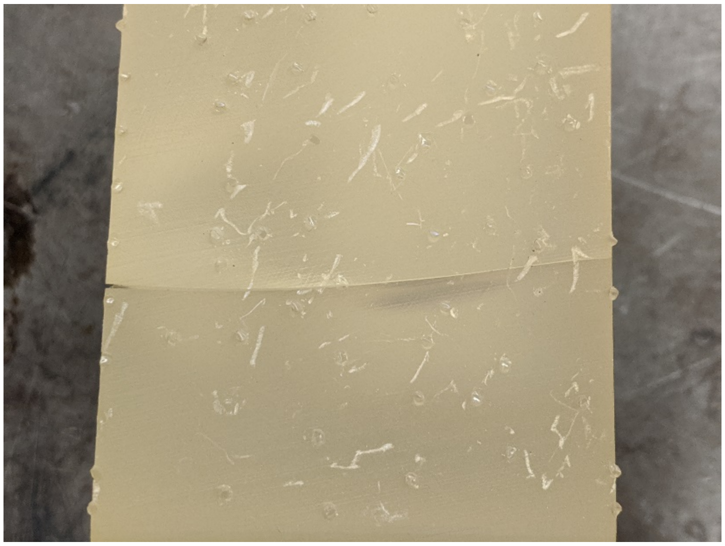

Figure 3-14: High Temp Resin B-Side Curing Damage

After initial testing to ensure proper function of the High Temp Resin inserts, the part very quickly failed. The results of the test will be discussed in more detail later but, in brief, the surface finish of the High Temp Resin was very poor in comparison to the Digital ABS insert which made the molded part removal very difficult. While attempting to remove the part, the gusset features broke off and rendered the A-side insert unusable. This same gusset feature on the Digital ABS mold also proved to be a failure mode. Although the Digital ABS mold features did not break. They would bend outward due to the heat and pressure of injection. Because this was a common failure mode, it was decided that this feature would be removed for future inserts as it was not the focus of the study and could potentially cause premature failure of the insert. Despite it being removed for future testing, it is worth noting the capabilities of the Digital ABS material for being able to mold so many parts with this feature still present. After this initial part failure, the A-side insert was re-printed without the gusset features and then prepared for test in the same manner as described above but this time, the surface of the A-side core insert was sanded to a smooth finish for easier part removal.

The Digital ABS inserts with conformal cooling channels were then printed. They were printed with the same Digital ABS materials as mentioned above. The Rev 1 inserts were printed first. The support material on the exterior of the inserts were removed first and then the internal support material that created the cooling channels was then attempted to be removed. What could be removed with a water jet, was easily removed but deep inside the channels, the water jet was not strong enough to remove the material. The main issue with this was that when the parts were requested to be printed, the assumption was that the soluble support material, SUP 706 was going to be used for the print and that the support material removal would be a simple process. It was, however, printed with SUP 705 which only slightly softens when soaked in a sodium hydroxide solution unlike SUP 706 which is much easier to remove after being soaked in a similar solution. Because of the design of the channels, there was no way that the support material could be removed without damaging the mold. The manifold type design made it extremely difficult.

After it was determined that the support material could not be removed, the Rev 2 mold was designed and then printed. The printing supplier did not have SUP 706 so the hope was that with the single channel printed with the same SUP 705 that the material could be removed with a long wire or cable by pushing it through the channel. The Rev 2 mold was then printed, and the support material was attempted to be removed. Because the channel was a single channel and much longer than the Rev 1 mold, a wire could not be pushed all the way through the channel to remove the support material. Other attempts at soaking the part in a heated sodium hydroxide bath for extended periods of time with good circulation helped to soften the support material but the material was still not able to be removed.

With limited resources, it was resolved that getting at least the B-side of the mold to have channels would be sufficient to get data for testing. The B-side insert had an exterior wall that could be drilled into and allow for easier access to the channel so that the support material could be removed. A series of holes were drilled on the outside of the B-side insert, the support material was removed, and then the holes were blocked up with set screws and RTV silicone. Although this was not the ideal setup for the tests to be conducted, it would still allow for data to be collected on the effectiveness of the channels at controlling the temperature of the insert and could give a good indication at how it could potentially improve the life of the tool. It can be said with a high degree of confidence that the support material could be removed with much more ease if it were originally printed with SUP 706.

3.4 Molding Process

A BOY 22A injection molding machine was used for all experimentation. For all experiments ran, the molder was run on a semi-automatic cycle (the machine would stop after opening the mold so that the injected part could be removed manually and once the safety gate was closed, the machine would continue its cycle). As recommended by Stratasys, the machine was run on lower settings for temperatures, pressures, and speeds [13]. The following process parameters were used for all experimentation (Table 3-2).

Table 3-2: Molding Machine Process Parameters

Process Parameter	*Setting*
Injection Speed	5% of max
Injection Pressure	200 PSI
Injection Time	5 sec
Holding Time	5 sec
Holding Pressure	80 PSI
Screw Retraction Distance	3.1 in
Screw Rotation Speed	14.8 % of max
Screw Plasticizing Pressure	50 PSI
Cooling Time	90 sec
Nozzle Temperature	405°F
Front Barrel Temperature	401°F
Front Middle Barrel Temperature	393°F
Rear Middle Barrel Temperature	375°F
Rear Barrel Temperature	365°F
Mold Clamping Pressure	200 PSI

The ABS polymer was placed in a dryer at 170°F and then vacuum fed into the hopper. The cooling system was run through a MOKON temperature control unit. The unit was set to cool to 62°F. The inlet coolant was hooked up to the bottom line that was closest to the bottom of the cavity so that the coolest water would contact the hottest part of the mold. The basic steps that were followed while running the molding machine was as follows: spray the mold surface with mold release, close the safety gate, press start, mold closes, screw advances and injects the polymer melt, the screw rotates and retracts, the part cools, the mold opens, the safety gate is opened, and the part is removed. This process was followed for all tests. At times, there was some difficulties with the molds and there were occasional pauses between cycles to address issues and therefore, the average cycle time was 210 seconds.

3.5 Insert Test Method and Analysis Method

The method used to test the inserts was simple and straight forward. The first benchmark Digital ABS mold was run until failure while collecting temperature data from the insert. Due to time constraints, this first test was done in 3 separate runs. The purpose of this test was to set a baseline from which all other tests could be compared. The High Temp Resin inserts were run until failure as well. The final tests that were run were also until failure, but the number of shots run on the insert was not a metric for performance of the insert. This was not a metric for performance since only one half of the mold was being tested. The A-side insert was not cooled and therefore failed faster than if it had been cooled. The intent of the final cooling tests was to collect data on how the conformal cooling channels performed and to determine the actual cycle-averaged mold temperature of the insert being tested [30, 31, 32].

The definition of insert failure was the point at which no more parts could be made with the insert. This was quite obvious in all cases and was not difficult to determine. The number of shots that any insert could produce was not a metric that determined success or failure of the insert but provided a quick and simple way to compare between materials. It was not used as a metric to determine the results of this study.

The method used for testing the inserts was modeled after work done by Natti [32], Sachs [12], and Davoudinejad [6]. The models that were used to design the cooling channels were the key metric of performance of the inserts and the main insight into how well the conformal cooling channels improved the life of the insert. The intent was to create a design based off of a model and then to test the model and determine how well the model can inform the design process. The hope was that the model would give a close representation of how the insert would actually perform.

Another key metric was the cycle-averaged temperature of the mold. As stated previously in this paper, a key metric to measure cooling channel performance is how well the insert can stay at or below 120°F, which has been shown to significantly improve the life of an AM IM tool [5, 6, 13]. When the mold stays at a cooler temperature, there is less risk of the mold being damaged and less risk of a flexural failure [5].

4 RESULTS AND DISCUSSION

4.1 Insert Failure

As mentioned earlier, insert failure is a common metric used for the performance of an AM IM tooling. This method will be used for demonstrating the performance of the benchmark Digital ABS mold and the High Temp Resin molds. The number of shots that the insert was able to successfully receive before catastrophic failure was the metric used to compare the initial molds. The first mold, made from Digital ABS, performed well and was able to produce 66 shots before catastrophic failure. The High Temp Resin mold was able to produce 3 shots before catastrophic failure.

The mold ran at an average temperature of 138°F with a peak temperature of 185°F. The mold took approximately 30 minutes to heat up to a more stable temperature. Once heated up, the mold had an average temperature of about 155°F. Because of design flaws with the sprue bushing, there were interruptions in the molding process and the recorded data was somewhat lacking. Much more consistent and accurate data could potentially be recorded with a different sprue/runner/gate design as it would allow for more consistent molding and the part would be much easier to remove. There are breaks in the cycles because issues had to be addressed while operating (mostly issues with the sprue bushing) which caused long cycle times and allowed the mold to cool more than desired. Below is the data from the 3 runs of the temperature of the insert over time (Figures 4-1, 4-2, and 4-3).

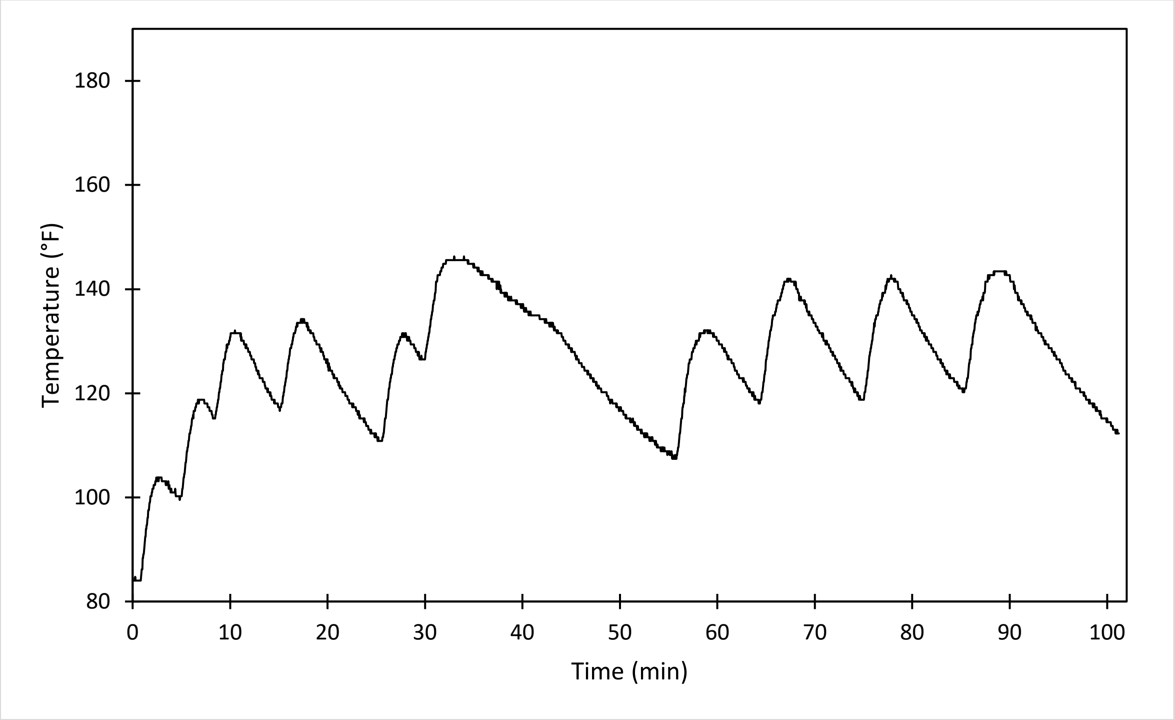

Figure 4-1: Digital ABS Benchmark Mold – Run 1

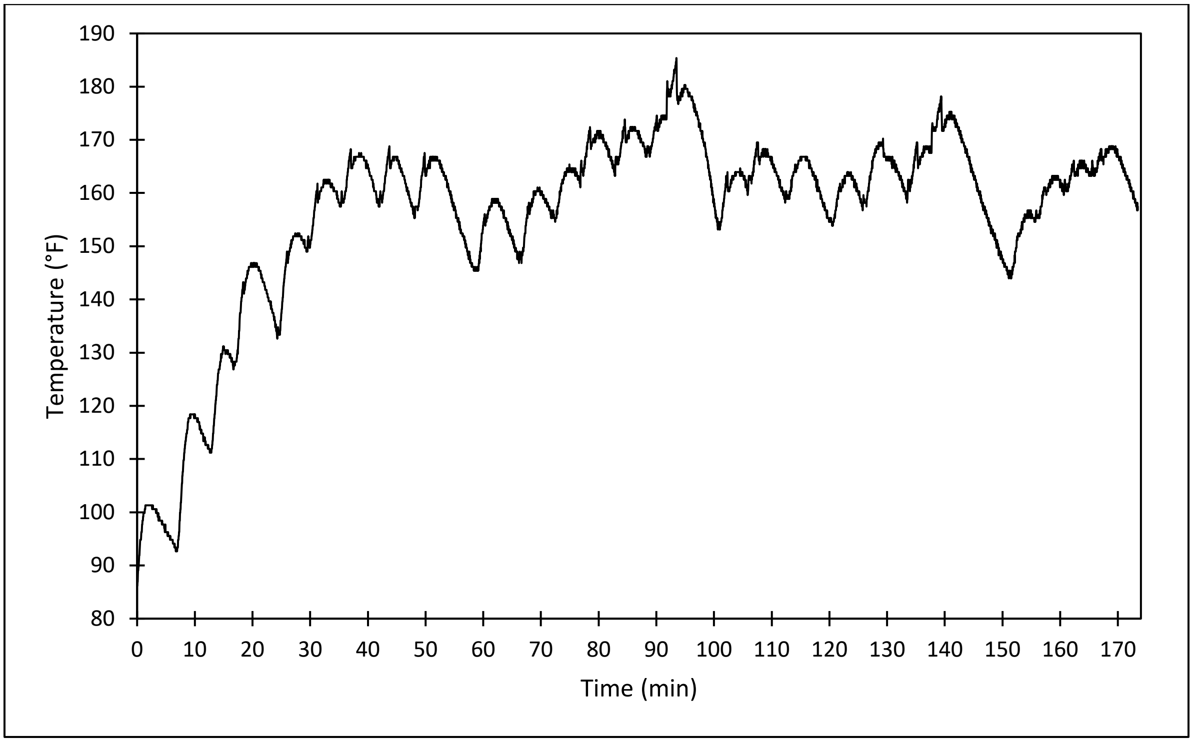

Figure 4-2: Digital ABS Benchmark Mold – Run 2

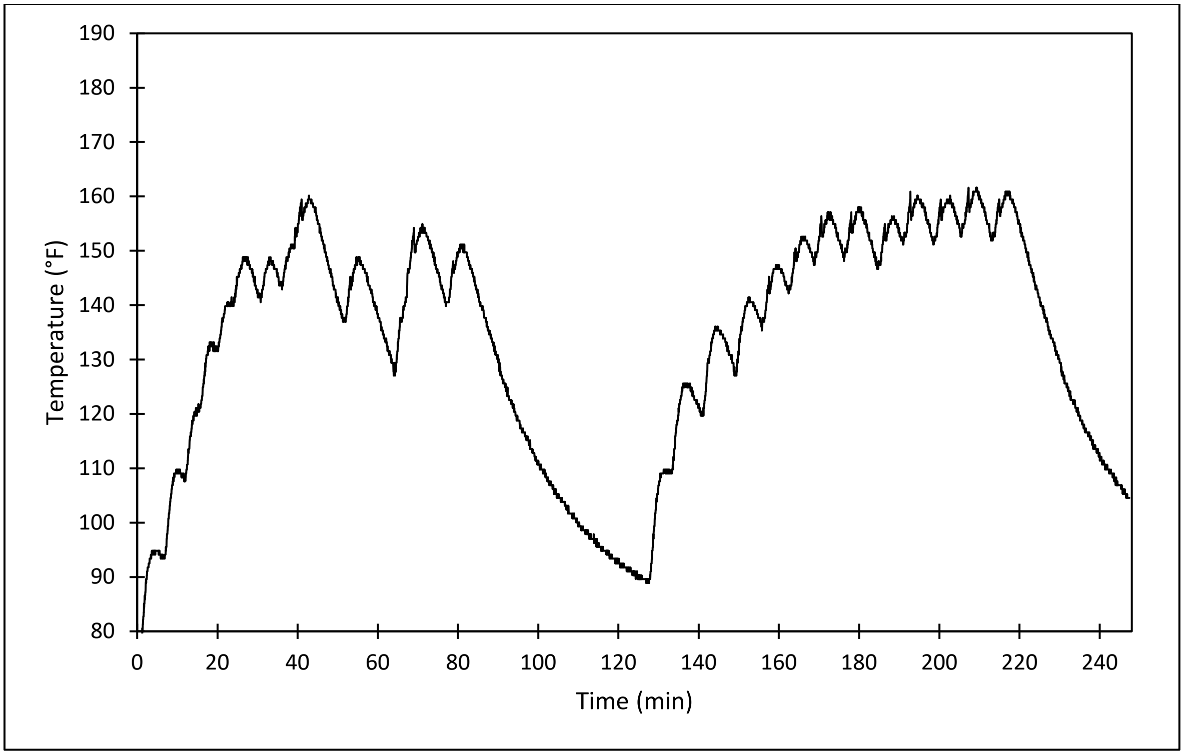

Figure 4-3: Digital ABS Benchmark Mold – Run 3

The final failure of the mold was a large crack that developed starting at the sprue and propagated outward from there. The crack became so long and deep that the polymer that entered the crack could no longer be removed. The crack initiated on the 31st shot during the 3rd run and continued to grow from there until the 66th shot and complete failure. It is believed that because of the design of the mold, the injection molding machine nozzle was pushing on the sprue bushing with enough force that the mold material between the end of the sprue bushing and the surface of the core fractured during injection when the pressure and heat were greatest (Figures 4-4, 4-5, and 4-6).

This issue is one of the main issues with the sprue gate design of this insert. Evidence suggests that the poor design was the main cause of the insert failure. It also was the cause for poor data collection because of the flash that would develop between the end of the sprue bushing and the insert. It is believed that if the sprue bushing was to the side of the core, and the polymer melt was injected through the sprue, to a runner, and into the part through an edge gate, the insert would have had much better success. This is an issue that could be researched further, the best sprue, runner, and gate design for AM IM tooling.

Figure 4-4: Digital ABS Benchmark Mold Initial Cracking

Figure 4-5: Digital ABS Benchmark Mold Cracking Just Prior to Failure

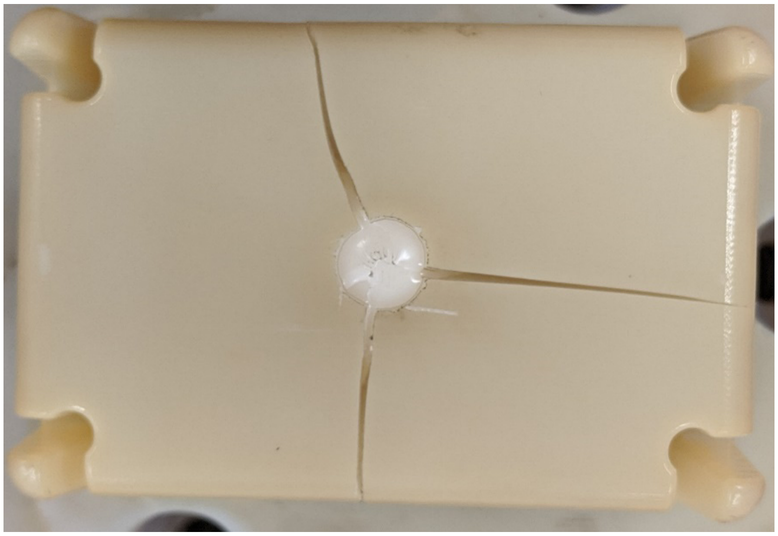

Figure 4-6: Digital ABS Benchmark Mold Final Failure

Another failure mode for the insert was the gusset features on the corners. These features started to deform under the heat and pressure of injection after the 21st shot. The corner feature deformed enough to touch the cavity surface on the B-side insert and create a hole in the produced part. This is likely due to the large aspect ratio of the feature and being right in the path of the melt flow. The melt likely pushed these features outward during injection (Figure 4-7). It likely wasn't seen until the 21st shot because the mold had not heated up enough for the material to get beyond its heat deflection temperature. Some research has been done on the effect of the aspect ratio on feature durability and shows that this is a common issue with AM IM tooling [5]. It is not recommended that large aspect ratio features be used on AM IM tooling unless it positioned in such a way that the melt flow will not directly collide with the feature and potentially cause failure or deformation. The B-side insert suffered no observable damage. There was some discoloration to the surface of the insert as shown in Figure 4-8 (likely from heat or the mold release), but the insert was intact and could potentially run much longer.

Figure 4-7: Digital ABS Benchmark Mold Gusset Feature Deformation

Figure 4-8: Digital ABS Benchmark Mold B-Side After Failure

The High Temp Resin inserts had much lower performance than the Digital ABS inserts. The High Temp Resin inserts experienced the same basic failure modes as the Digital ABS inserts but failed much faster due to the material properties of the inserts. The High Temp Resin is much more brittle and a less tough material. The first High Temp Resin mold was the same design as the Digital ABS benchmark mold with the same gusset features and sprue bushing design. The sprue bushing issue was resolved in the same way as the Digital ABS mold. The High Temp Resin mold failed on the first shot. The part could not be removed from the mold. The poor surface finish of the mold made it impossible to remove the part without breaking the gusset features on the mold (Figures 4-9 and 4-10).

Figure 4-9: High Temp Resin With Molded Part

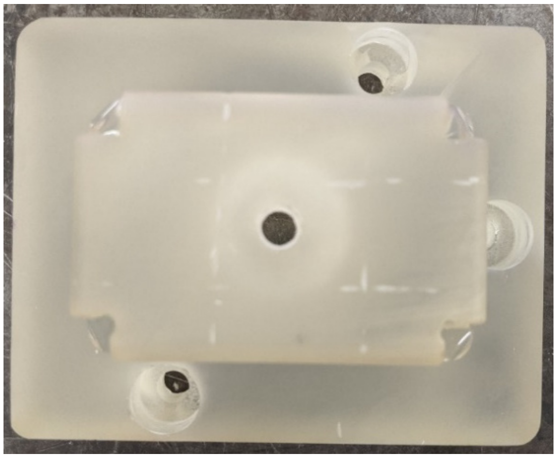

Figure 4-10:High Temp Resin Gusset Feature Failure

After removing the part and reviewing the damage to the mold, it was decided that because the gusset feature was a known failure mode for both molds, the feature would be removed in the design, the mold reprinted and the test would be run again. The second mold was printed and prepped, and the test was run. The mold failed after 3 shots due to the pressure of the nozzle pressing against the sprue bushing. The top of the insert fractured all the way through (Figures 4-11 and 4-12). This failure solidified the theory of the cause of the Digital ABS mold failure as well. It also solidified the idea of a better sprue, runner, gate design that would prevent the nozzle form transferring its closing pressure against the mold material, and instead, the sprue bushing should be positioned in such a way that it is supported by the frame of the mold.

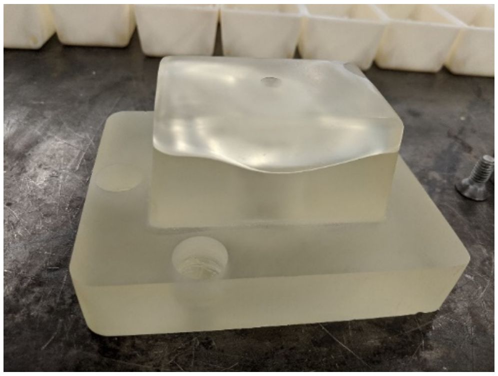

Figure 4-11: High Temp Resin A-Side Insert Crack

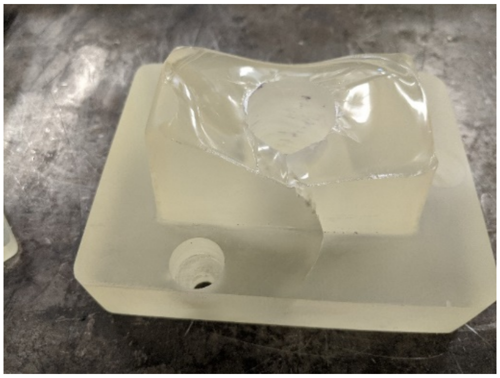

Figure 4-12: High Temp Resin A-Side Insert Failure

It is believed that if a mold made from High Temp Resin were properly designed and properly supported, this material could have great potential for success. A disadvantage of this is that it could only be used for simple parts that don't have features with large aspect ratios. These features would very likely break simply from the injection pressure. But for the small use case of simple parts and a well-designed mold, this material could be a suitable option. Further research is needed on the actual potential of this material. Another material from Formlabs that could be researched further is their Clear Resin which has similar properties to Stratasys' Digital ABS.

4.2 Conformal Cooling Channel Performance

The data collected from the tests on the Digital ABS molds with conformal cooling channels showed a lower temperature of the inserts and did so to a level that, according to research, suggests great potential to significantly improve the life of the AM IM tool. On average, the insert temperature was 111°F which is about 44°F cooler than the mold without cooling channels (see Figures 4-13, 4-14, and 4-15). Research has shown that AM IM tooling that can be kept below 120°F will significantly improve the life of the tool [5, 6, 13]. This test was not done until failure, nor was a large sample size of inserts printed and tested, but with more resources, this would be further research that would help confirm these findings, especially for the Digital ABS material. Had there not been issues with the incorrect support material in the cooling channels as discussed in the methodology, this mold would have been run to failure. The temperature of the coolant entering the mold and exiting the mold was also recorded but didn't give consistent enough data for analysis. The coolant data is still displayed in the graph. It is interesting to note how much the exiting coolant fluctuates during the molding process.

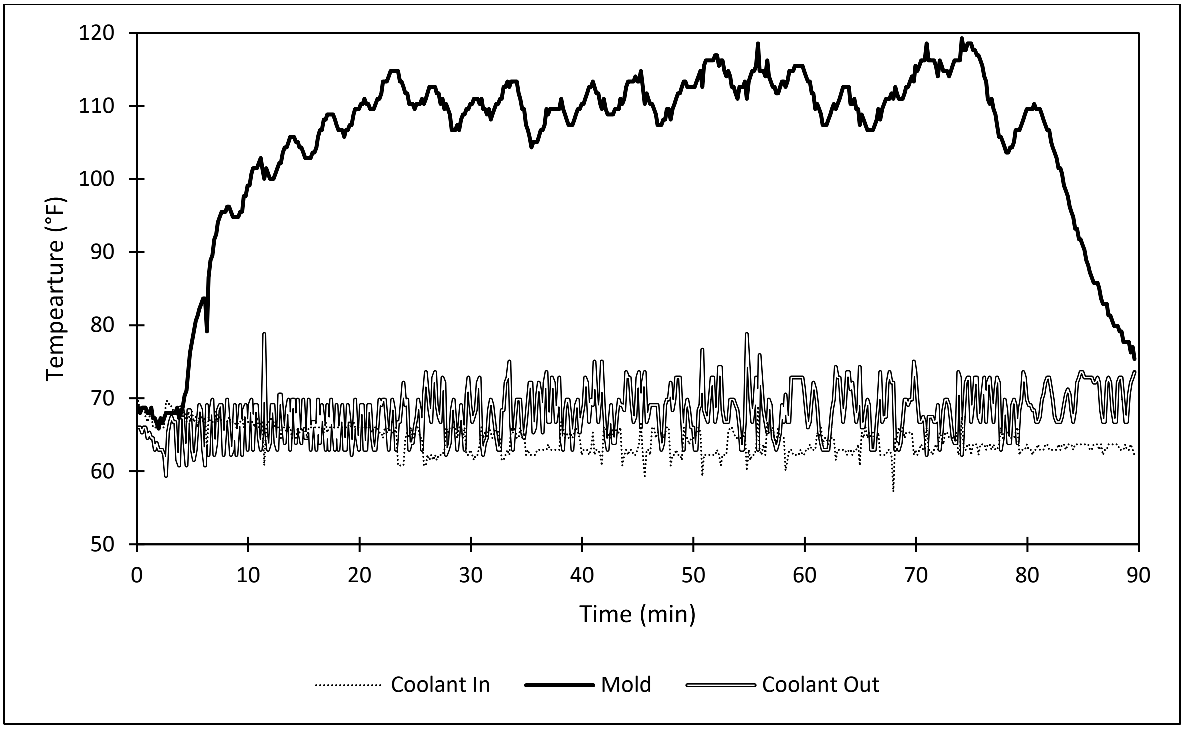

Figure 4-13: Digital ABS Mold With Conformal Cooling Channels Run 1

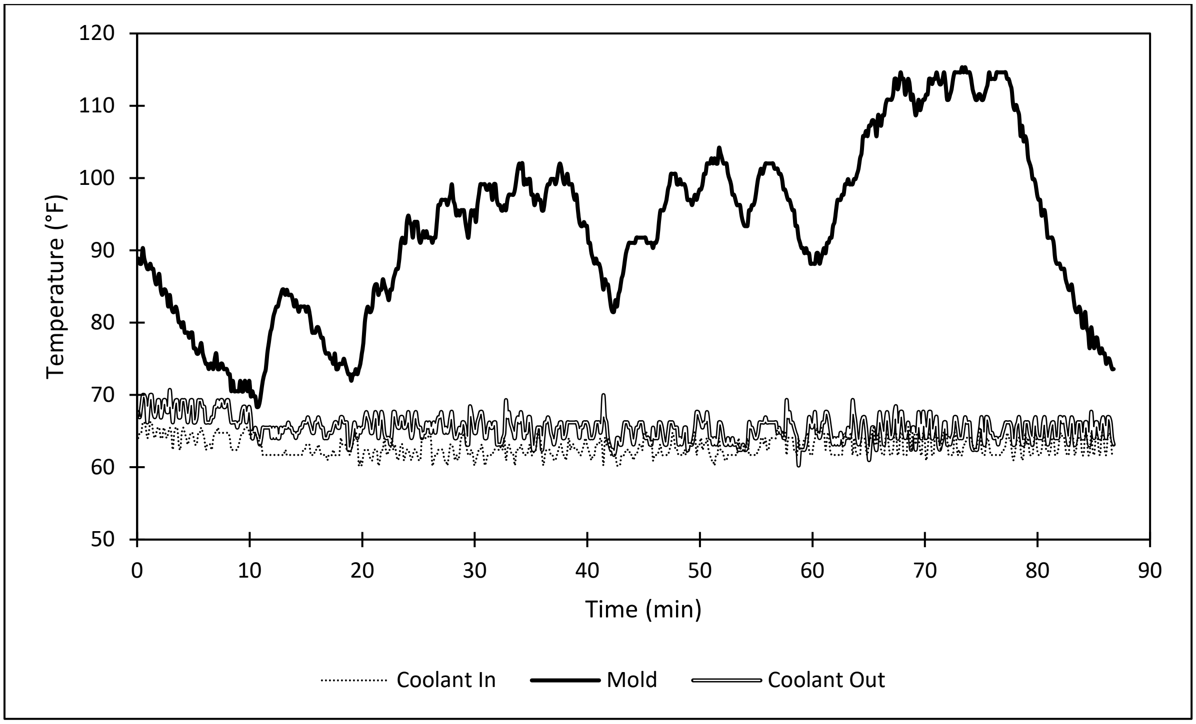

Figure 4-14: Digital ABS Mold With Conformal Cooling Channels Run 2

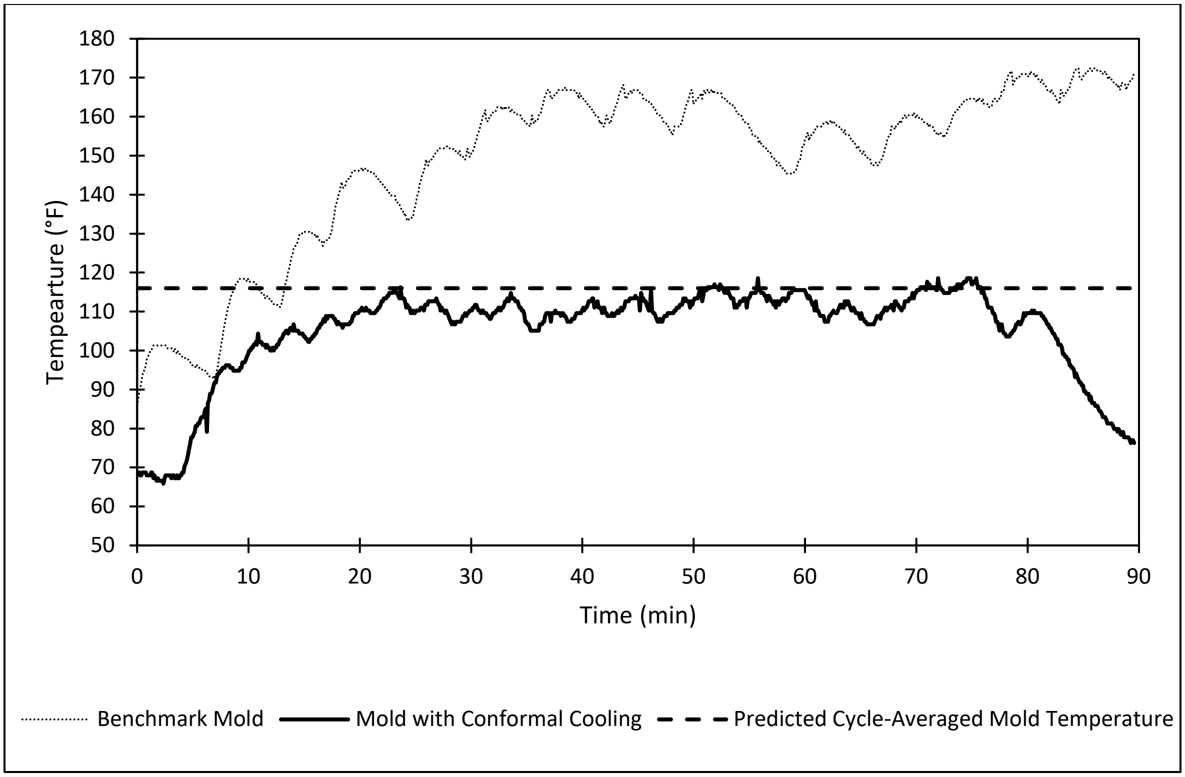

Figure 4-15: Mold With vs Mold Without Cooling Channels

In order to better understand the performance of the conformal cooling channels, the models introduced in the methodology section will be discussed further here. The simple model used by Sachs [12] was a very good model for the depth that the channels need to be in order for them to perform properly (equations 4-1, and 4-2). With an average cycle time of 210 sec, and the channel depth of .21", the channels performed just as the simple model predicted, which, as explained by Sachs, "this result is essentially the same as the result for the distance that a heat pulse can travel by conduction to a solid in a given time… we can calculate … the requirement for a channel to behave as a conformal channel" [12]. This model can be used as a rule of thumb or a quick estimation in design and give a general idea of how deep to place channels.

$$\boldsymbol{a} = \frac{\boldsymbol{k}}{\boldsymbol{\rho_m c_{pm}}} \tag{4-1}$$

$$\boldsymbol{l < \sqrt{a t_k}} \qquad (4\text{-}2)$$

In this study, the complex model (equations 4-3, 4-4, and 4-5) was used after experimentation with the intent to validate the model so that it can be used in future studies or in industry applications. When the model is used with more unknown data, some more work is required to find unknown values, such as cycle time. Kanbur and Rao go into great detail on how this model can be iterated to find the optimal value for any unknown variable [30, 32]. These values were found experimentally in this study. The values that were discovered experimentally that were used in this model were the ejection temperature and the cycle time. Below are the same equations and values used as shown in the methodology section but are presented again here for quicker reference.

$$\boldsymbol{T_m = T_c + \frac{\rho_p \cdot c_{pp} \cdot \frac{s}{2} \cdot (2 \cdot k \cdot x + \alpha \cdot 4 \cdot d \cdot l) \cdot (T_p - T_e)}{\alpha \cdot 4 \cdot d \cdot k \cdot t_k}} \qquad (4\text{-}3)$$

$$\boldsymbol{\alpha = \frac{.031395}{d} \cdot Re^{0.8}} \qquad (4\text{-}4)$$

$$\boldsymbol{Re = u \cdot \frac{d_h}{v}} \qquad (4\text{-}5)$$

Table 4-1:Values Used for Calculation [3, 4, 6, 36, 37]

Property	*Value*
Thermal Conductivity of Insert $(k)\ \frac{W}{mK}$	0.17
Density of Insert $(\rho_m)\ \frac{kg}{m^3}$	1170
Specific Heat of Insert $(c_{pm})\ \frac{J}{kgK}$	1030
Thermal Diffusivity of Insert $(a)\ \frac{m^2}{s}$	8.3×10^{-7}
Cooling Channel Depth $(l)\ m, in$	5.33×10^{-3}, .21
Temperature of Coolant $(T_c)\ K, °F$	291, 64
Melt Polymer Density $(\rho_p)\ \frac{kg}{m^3}$	1040

Table 4-1 Continued

Property	*Value*
Specific Heat of Polymer $(c_{pp})\,\frac{J}{kgK}$	1700
Part Wall Thickness $(s)\ m, in$	2.16 x 10^{-3}, .085
Cooling Channel Pitch $(x)\ m, in$	1.69 x 10^{-2}, .665
Heat Transfer Coefficient $(\alpha)\,\frac{W}{m^2K}$	19114
Cooling Channel Height/Width $(d)\ m, in$	5.84 x 10^{-3}, .23
Polymer Melt Temperature $(T_p)\ K, °F$	480, 405
Ejection Temperature $(T_e) K, °F$	379, 223
Cycle Time $(t_k)\ sec$	210
Cycle-Averaged Mold Temperature $(T_m) K, °F$	319, 116
Reynolds Number (Re)	27455
Coolant Velocity $(u)\,\frac{m}{s}$	2.36
Hydraulic Diameter of Channel $(d_h)\ m$	1.17 x 10^{-2}
Kinematic Viscosity of Coolant $(v)\,\frac{m^2}{s}$	1.004 x 10^{-6}

With more detail into what is happening with the mold and how the cooling channels control the temperature, the more complex model can predict the cycle-averaged mold temperature. Which was 116°F as shown in Figure 4-15. The experimental cycle-averaged mold temperature was 111°F. It is believed that if the cooling channel experiment could have continued longer, the cycle-average mold temperature would be closer to the predicted 116°F. It is also a possibility that the thermal properties of the mold could have been slightly off from the actual properties of the mold used. Further experimentation would be needed to validate the properties found in other studies [3, 4, 6, 36, 37]. The data strongly suggests that the more complex model that was used can accurately predict the cycle-averaged mold temperature and is a good tool to be used when designing conformal cooling channels for AM IM tooling.

5 CONCLUSIONS

Digital ABS and High Temp Resin AM IM tooling were produced using polymer jetting and SLA processes, respectively. They were tested until failure which resulted in producing 66 shots for Digital ABS and 3 shots for High Temp Resin. The mold design was then modified to include conformal cooling channels and was produced in Digital ABS using polymer jetting. The temperature of the mold was logged during the injection molding process and compared to the temperature of the benchmark mold. On average, the temperature of the mold with cooling channels was 44°F cooler than the mold without. The mold with conformal cooling channels had a cycle-averaged mold temperature of 111°F. Studies show that AM IM tooling life is significantly improved when the cycle-averaged temperature remains below 120°F [5, 6, 13]. Furthermore, the experimental data was compared to a conformal cooling channel model to see how well the model could predict the cycle-averaged mold temperature. The model predicted a cycle-averaged mold temperature of 116°F.

The results of this study strongly suggest that the addition of conformal cooling channels to AM IM tooling will reduce the cycle-averaged mold temperature to a level that research has shown to improve tooling life significantly. This study also validated the cooling channel model and its use for the Digital ABS material. Because the cooling channel test was only performed with one half of the inserts cooled, one could only expect better results as far as cooling time and overall cycle time. Using the cooling channels in the AM IM tooling will help lengthen the life of the tool and help reduce the cycle time of part production. This solution has the potential to expand the use case for AM IM tooling by allowing for a higher volume of parts produced whether it be for production parts, for prototyping and testing, or for mold design validation.

The major focus of this study was the effect that the conformal cooling channels had on the cycle-averaged mold temperature. More research could be done with conformal cooling channels to see how it effects the life of the tooling over a complete tool life cycle. Other, more cost effective, materials should be studied as well, and the addition of conformal cooling channels may expand the number of materials able to be used for IM tooling.

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