www.cadanda.com Computer-Aided Design and Applications

Leveraging Advanced Design and Novel Rapid Manufacturing Solutions to Respond to the COVID19 Pandemic

Alireza D. Pasha[1], Jill Urbanic[2], Bob Hedrick[3], Hamoon Ramezani[4] and Ofelia Jianu[5]

[1]University of Windsor, davoudp@uwindsor.ca
[2]University of Windsor, jurbanic@uwindsor.ca
[3]CAMufacturing Solutions, Inc., bob.hedrick@camufacturing.com
[4]CAMufacturing Solutions, Inc., hamoon.ramezani@camufacturing.com
[5]University of Windsor, ofelia.jianu@uwindsor.ca

Corresponding author: Alireza D. Pasha, davoudp@uwindsor.ca

Abstract. The novel Coronavirus can easily be transmitted from one person to another via respiratory droplets or direct contact with infected surfaces. Human beings have several common and shared objects that they touch daily. Door handles are among the most commonly touched surfaces. In this work, novel manufacturing solutions are developed for several hands-free door handles that were designed to reduce the COVID-19 disease vectors. In tandem with the design optimization activities, a rapid and low-cost tooling solution was developed leveraging additive manufacturing, 'design for additive manufacturing', and conventional design for assembly strategies. This rapid tooling approach is capable of molding high temperature thermoplastics as well as of introducing highly complex internal channels that can aid the cooling performance of the mold and component. For the case study, the mold is built in less than one week. The part geometry varied between 1 – 3% from the CAD model. The production time for a part is reduced from 3 hours to less than 2 minutes per piece. The material price per piece was significantly dropped. This solution introduces new design and manufacturing options to the engineering community. The case study highlights the merit of these approaches.

Keywords: Additive manufacturing, Rapid tooling, Assembly, FEA, Simulation, Injection molding
DOI: https://doi.org/10.14733/cadaps.2022.755-778

1 INTRODUCTION

Coronavirus refers to a range of viruses ranging from the common cold to more severe illnesses like SARS (severe acute respiratory syndrome) and MERS (Middle-East respiratory syndrome). The disease caused by the new coronavirus has been named COVID-19 [24]. This virus was and still is very contagious and is easily transmitted via respiratory droplets, direct contact with infected persons, or by contact with contaminated objects and surfaces [6]. At the time of this research, there was no vaccine available for this virus and the main ways this virus could be stopped were:

- social distancing and proper use of personal protective equipment (PPE), such as face masks and face shields, and
- eliminating the transmission of the virus particles to your face from touching infected surfaces.

Public health officials suggested that it would be safer if people could decrease the number of times they touch their faces. The reason being, the virus could enter through the points of entry to our body, such as the mouth, nose, and eyes. One study determined students touched their faces an average of 23 times an hour [17]. Another study of office workers showed that they averaged 15.7 face touches per hour [4]. By calculating how much virus might be on each person's hands, the researchers were able to confirm that the touching posed a serious risk for disease transmission. Therefore, one of the sub-goals of this research is to reduce the disease vectors by designing, optimizing, and developing a rapid tooling solution for a parametric set of hands-free door handle product solutions.

Several hands-free door handles were developed so that the commonly touched surfaces, i.e., a door handle or knob, are not touched by a person's hands or fingers during the opening and closing of doors. The forearm is used for opening doors. Novel low-cost rapid tooling solutions are developed in tandem with the product design activities. The developed tooling design contains unique features such as complex internal channels and cavities that are fabricated by incorporating soluble patterns. By using this low-cost solution, not only a part with complex geometrical challenges was able to be manufactured but also the material cost and production time were reduced significantly. Additionally, wider range of materials, new design freedom, and the ability to create complex internal channels are made possible at a significantly lower cost compared to the conventional tool making processes. "Design for Additive Manufacturing (DfAM)" approaches to build internal channels with special soluble material [21] are developed and experimentally validated. These internal channels are created using supports materials that are usually part of the process overhead and are waste. This design and fabrication strategy provides opportunities to incorporate topology optimization solutions that have not been technically feasible.

1.1 Problem Statement and Objectives

To fabricate plastic components, injection molding (IM) and additive manufacturing (AM) technologies can be used. Even though IM is suitable for producing plastic components in large quantities, the IM molds are very expensive and require up to several weeks to be fabricated. Consequently, high production numbers are required to justify the initial investment. On the other hand, plastic AM technologies such as material extrusion can fabricate plastic components without any tooling. For this research, the fused deposition modeling (FDM) material extrusion AM process is utilized. Thermoplastic components are readily fabricated but, this process is time-consuming and the material costs are expensive compared to IM. One study conducted by Eiliat et al [9] demonstrated that the existence of voids is unavoidable in an FDM process and these voids can create failure points in FDM-built products. Additionally, using FDM technologies to directly build a tooling is not feasible due to the high pressure and temperatures involved in an IM process [11]. As a result, a new tooling method is needed to accommodate low to medium (10-5000) production volumes. This rapid tooling solution is to combine the process capabilities of IM (e.g., fast production cycle times, a wider range of materials, and structural reliability) with AM (ability to easily fabricate complex geometries) to create a low-cost rapid tool that has complex internal channels and significantly reduces tool cost and fabrication time. The specific sub-goals of the COVID-19 related research challenges are:

1. Develop a 'pull' door bracket to mount onto fixed door handles or bars (see Figure 1).
2. Develop a 'twist and pull' and a 'twist and push' bracket to mount onto commercial doorknobs, including selected rotary and lever handle models.
3. Develop parametric models (this provides a basis for a universal solution for a range of doorknob styles and rapid tooling solutions); and
4. Develop rapid tooling solutions with integrated cooling systems to readily mold replicates.

This research paper focuses on items (1) and (4). The process is further discussed in the next sections of this paper.

(a) (b)

Figure 1: (a) Original J-hook model, (b) offset-bar optimized J hook model.

2 LITERATURE REVIEW

2.1 Fused Deposition Modeling (FDM)

The FDM process is a material extrusion process. In an FDM process, the printing material is fed through a heated element in the shape of a filament. The material reaches a semi-molten state and is pushed through a nozzle. Beads are deposited side by side on a build platform to create a thin 2D geometry. These 2D layers are stacked on top of each other (layer by layer) until the desired 3D geometry is created [8]. Figure 2 shows the schematic of an FDM process.

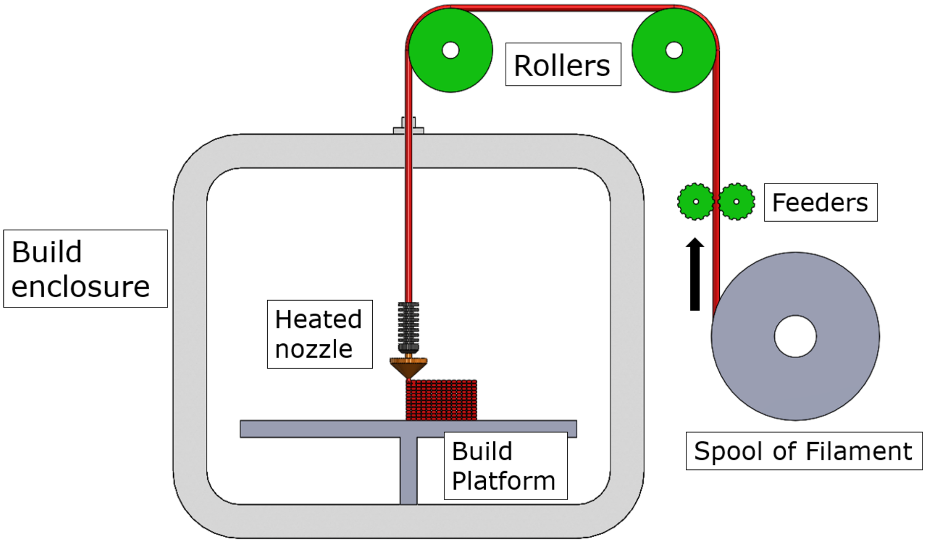


Figure 2: Fused deposition modeling (FDM) process schematic.

Since FDM technologies are capable of fabricating components without any tooling, they are best suited for prototyping or lower production volumes. To demonstrate this, using FDM to fabricate the J-hook shown in Figure 1(a), requires 3 hours, 87 cubic mm of material, and the final material cost is $36.6 (US). As a result, an FDM process is not a sensible manufacturing solution for low to medium production runs. Additionally, AM processes (including FDM) need support structures to build components with interior channels or holes, undercuts, thin, or overhanging features. Figure 3 demonstrates the necessity of support structure in an FDM process. The red lines represent model material whereas the yellow lines represent support structure. The removal of support structure is an additional process that needs to be done after the part is finished building. This will add extra processing time to the already time-consuming printing process. To facilitate post-processing operations, Stratasys Ltd. has developed a series of soluble support materials that are dissolved when exposed to a special solvent [21]. This soluble support material is leveraged to play a key role in the developed solution to build the internal channels and mold cavities.

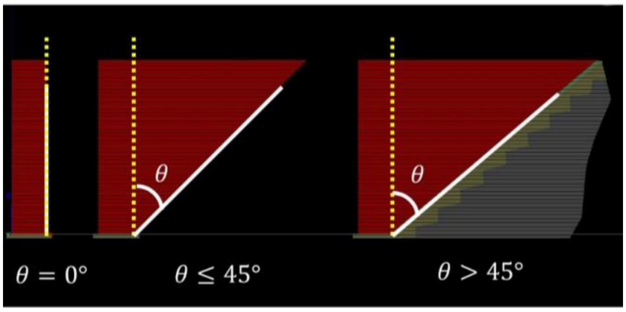


Figure 3: Necessity of support structure when the overhanging features exceeds a critical value (for example, 45 degrees).

Considering all the process capabilities and limitations of FDM, this process will not be a suitable manufacturing solution for low to medium production runs. There is a need for a tooling solution that is built relatively fast and is significantly more cost-efficient.

2.2 Literature Review on Rapid Tooling

Levy et al. [14] defined rapid tooling as a tool that can make thousands of parts before wearing out. The definition of this tooling is confined to plastic injection molding applications only. They studied different AM processes and analyzed their capabilities in creating different tooling designs. However, they stated that the breakthrough of these technologies to make an operating tool primarily depends on the cost and productivity. Karapatis et al. [12] stated that rapid prototyping technologies are moving toward rapid tooling. They believed the motive behind this move could be to reduce the time for placing an item on the market by reducing not only the development phase, but also the industrialization phase of the manufacturing process. Akula et al. [2] developed a rapid tool manufacturing process called hybrid-layer manufacturing (HLM) to manufacture metallic dies and tooling. They used metal inert gas (MIG) welding process to create a near-net shape and used CNC machining to bring the design to the final finish and dimensions. They reported that the overall cycle time to produce tools and dies was much faster via HLM compared to the existing technologies of the time. They indicated that the welding process did not achieve all the desired properties of the material. Besides, they reported that even though their tool had a lower quality in composition and tool life compared to other conventional tools, it could manufacture the final product as accurately as other conventional tools. Kalami et al. [11] designed and fabricated a low volume injection mold and followed a rapid tooling approach that was suitable for a high-temperature material. In their research, they reported that material costs are high for metallic AM technologies and plastic based AM technologies will not be suitable for a tooling solution due to thermal conductivity and material compatibility. In their studies, they used material extrusion-based AM (FDM) to create sacrificial cavity patterns. However, these patterns were not soluble and had to be removed after building the cavity. To build the mold, they used the thermally conductive Aremco 805 epoxy [3] that has been used in this research as well.

According to Dimla et al. [7] cooling can take more than 50 percent of the cycle time during an IM process. Cooling systems include a series of channels inside the mold where a coolant circulates the mold to remove the heat, and boosts solidification of the molten plastic. Like any other manufacturing process, production time and cost are strongly correlated. As a result, cooling plays an important role in an IM process. However, fabricating complex channels inside a tool is very difficult and extremely limited by conventional manufacturing constraints. As a result, the effectiveness of the cooling systems is reduced. In the next section, the effects and manufacturability of complex cooling channels is reviewed.

2.3 Literature Review on Cooling Channels

Sachs et al. [18] was one of the first to study the effect of cooling channels on IM quality. They investigated the effect of cooling channels on injection molding and reported that conformal cooling improves the control of mold temperature and part dimensions. Wu et al. [25] worked on the optimization of additive manufacturing for injection molding through simulation. In their research, they used spiral cooling channels, and in their simulations, the core and cavity were made of stainless steel and the final piece was made of polypropylene. Shinde et al. [20] carried out a case study on a rapid prototyping-assisted conformal cooling channel (CCC) that is used in the industry. They stated that a CCC improves quality and productivity. The main focus of their research was on simulation and they indicated that more research was required for the fabrication of molds with CCC. The high cost of metallic AM molds was one of the limits of this project. Jahan et al. [10] developed a numerical model to represent the thermal behavior of CCC in dies. They reported that cooling channels with rectangular cross-sections were the most effective design. Mazur et al. [15] studied the usage of conformal cooling channels made by selective laser sintering (SLM). The fabrication of cooling channels with circular sections was studied and they realized stress concentration in the SLM process can lead to compromises in dimensional accuracy. Tan et al. [23] designed an injection mold in which the cooling channels were designed in a self-supporting configuration. They used laser powder bed fusion (LPBF) to build the channels to evaluate the manufacturability of their channels. They reported that the top layers of the inner wall of a channel can cause material collapse due to high overhang angles. Besides, the residual stress introduced in a metallic AM process can lead to warpage and distortion. As a result, the maximum diameter of the cooling channels that were manufacturable without support structure was limited to 8 millimeters. To increase the diameter of the channels, support structures needed to be constructed on the inside of the channels (illustrated in Figure 4).

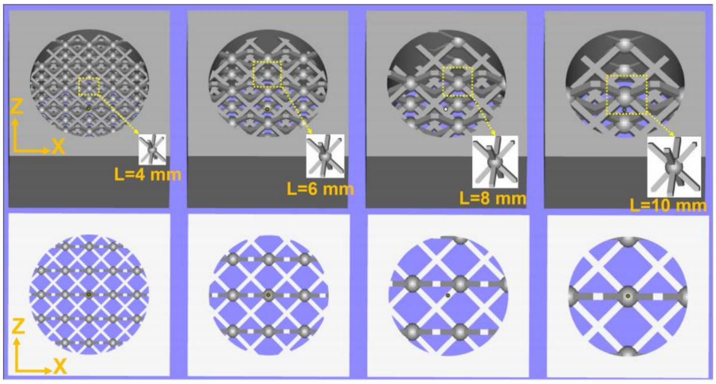


Figure 4: Optimization of support structures inside a conformal cooling channel. Courtesy of Tan et al. [23].

According to the literature reviewed, most of the research has focused on costly AM technologies such as LPBF. Moreover, metallic AM technologies require support structures to build 3D internal channels. Consequently, the state of the art is primarily based on simulations, and the scope of the experimentation is limited to the construction of a section of a tool with an internal feature. None of the reviewed literature built a complete rapid tool that is low-cost and at the same time contains internal features. The majority of the researchers reported that the high cost of metallic AM processes was a limiting factor in their studies. As a part of this research, design for manufacturing (DfM) concepts have been applied to the product design, which are very limited or missing from the reviewed literature. Therefore, in addition to developing a low-cost tooling solution, a sub-objective of the research is to develop a solution to fabricate serpentine rectangular channels with no internal support structures. The process flow for building this low-cost rapid tooling solution is discussed next.

3 METHODOLOGY

The process flow for the complete research project is presented in Figure 5. All products were designed using Solidworks and Fusion360 CAD software. For several doors, unique door handle designs were created and built using FDM, as illustrated in Figure 6. Force, moment, and motion analyses were done to determine pull and twist forces, and comfortable engagement.

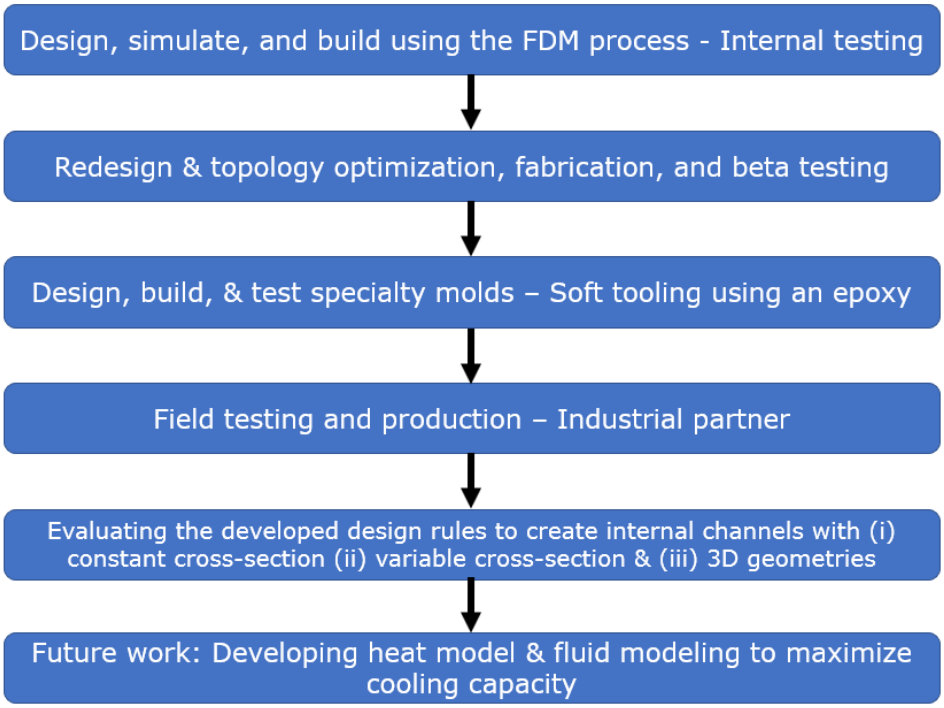


Figure 5: Research process flow.

To develop the rapid tooling concept, the original J-hook (see Figure 1(a)) was selected due to its thick-wall thin-wall geometry. Internal testing highlighted issues related to comfort and usability. Finite element analysis (FEA) was conducted on the beta version to make sure that the revised J-hook is capable of withstanding the loads applied.

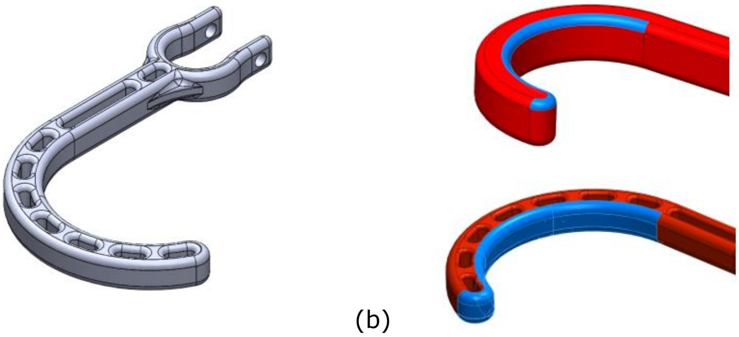
(a) Pull | (b) Twist and pull (heavy doors) | (c) Twist and pull (office and residential)

Figure 6: (a) J-hook type I for pull only doors, (b) J-hook type II for twist and pull level style doorhandles, (c) J-hook type III, for spherical and tapered residential and office doorknobs.

Once the design was finalized, injection molding simulation studies were conducted in Autodesk Moldflow to evaluate the design compatibility for an IM process. The Fortus 400 MC FDM process was employed to fabricate the alpha and beta prototypes using ABS-M30 (acrylonitrile butadiene styrene) material [22]. The build accuracy for this production FDM machine is 0.0015 mm per mm [1]. However, distortion and warpage can occur due to heating and cooling variations within a component, similar to geometric variations observed in castings [19]. The observed variations for the components fabricated using the FDM process dimensional are ± 0.1 mm. The design to product realization period is compressed, but this process is too expensive and time-consuming for leveraging it for general public/commercial purposes. Therefore, the product design and 'design for manufacturing' strategies were addressed in tandem to developing the molding solution.

3.1 Design for Manufacturing and Virtual Validation

The beta version of the J-hook has been demonstrated in Figure 7(a). Initially, the edge fillets were increased to create a bigger and consistent contact area for the user's hand to improve comfort (see Figure 7(b)). Additionally, unique pockets were cut in the middle of the part to maintain a more consistent wall-thickness throughout the part (see Figure 7(a)). A uniform wall thickness is better suited for an IM process. Having inconsistent wall thicknesses in a product can lead to warpage, sink marks, and potential scrap issues during an injection process [13].



(a) (b)

Figure 7: (a) Optimized J-hook type I design, (b) contact area of the original and new designs highlighted in blue.

To virtually test the new design on the performance of the new J-hook, a finite element analysis in CATIA V5 was conducted. The primary purpose of conducting an FEA study was to ensure that the added design features (the middle pockets and fillets) would not create any areas of high stress concentration and also predict the behavior of the J-hook under excessive loading.

The pulling forces required to open several doors were measured and the pulling force was calculated (average 70 N). To make the simulation more representative of the real use of the handle, a vertical downward force of 50 N was added to the handle. The material in all cases was assumed to be linear and elastic with Young's modulus E = 2.18 GPa, and Poisson's ratio υ = 0.38. The material density is taken to be ρ = 1200 Kg/m^3. The detailed application of the forces is demonstrated in Figure 8.

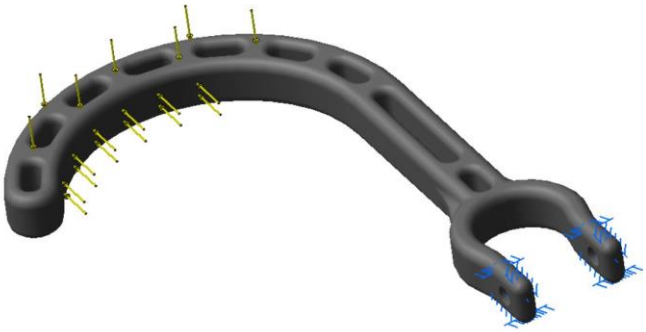


Figure 8: FEA analysis of beta prototype J-hook.

The part was meshed with a 1 mm parabolic octree tetrahedron solid mesh. This mesh size was selected by conducting a mesh convergence study. As ABS behaves in a more brittle than ductile manner at its failure mode at room temperature, the simulated maximum principal stress is plotted in Figure 9. The maximum principal stress reached 30.9 MPa. The result is still satisfactory as the material tensile strength is equal to 31 MPa. It is noted that the forces applied are higher than a common force applied to a part by the end-user.

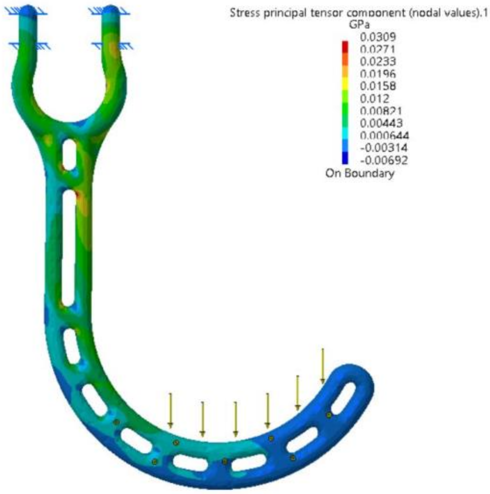


Figure 9: The maximum principal stress component plot for the beta version.

The FEA results were validated by an in-field experimental study on selected door handles. The J-hook was first objected to the forces simulated in the FEA study (70 N horizontal and 50 N vertical). Due to the low safety factor of the simulations, once the virtual results were validated, the vertical loading was increased to study the behavior of J-hook under excessive loading. The excessive loading test was done five times and each time the vertical load was increased incrementally until it reached the maximum of 91.5 N in the last trial. Each time the loading was maintained for 60 seconds and then, the horizonal loading was applied to open the door. The experiments were successful, and the J-hook did not fail under any of the excessive loads.

Another virtual study was conducted in Autodesk Moldflow to evaluate the injection molding process of the Beta version. The runner system (direct sprue), draft angles (2 deg), and parting line (symmetry plane) were added to the Beta version. Figure 10 shows the added features. Technomelt-PA 7846 black, a high melting temperature plastic, was utilized for the molding material. The properties of Technomelt can be found in Table 1. Technomelt is a durable material that is more resilient and can withstand moisture and a variety of environmental conditions. ABS is prone to moisture absorption and products built by ABS will degrade over time. To conduct the injection simulation, the injection temperature (200 ℃), initial mold temperature (18 ℃), and material properties were selected (Technomelt-PA 7846).

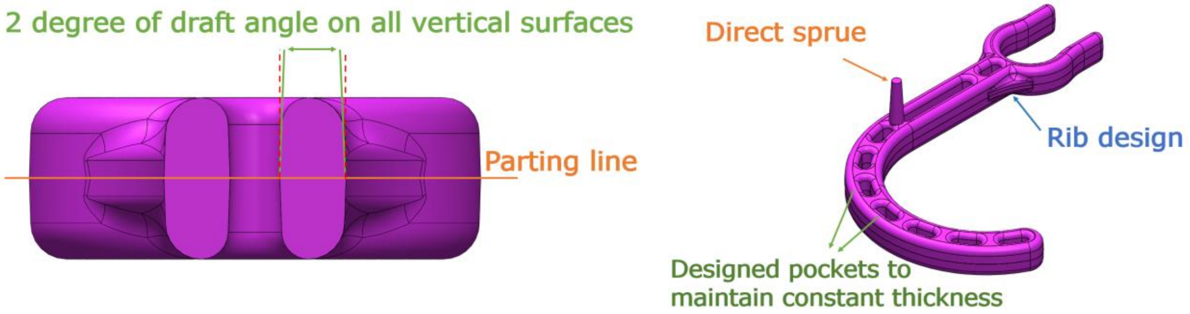


Figure 10: Design for manufacturing features in the Beta version of “J-hook”.

Mechanical property	*Value*
Density, g/cm³	0.98
Softening point °C ASTM E28 (in glycerine)	170 - 180
Melting Viscosity at 210 °C, mPas	6,500
Yield Strength, N/mm ISO 527 Specimen no. 5, cross-head speed: 50 mm/min	5.0
Break Strength, N/mm ISO 527 Specimen no. 5, cross-head speed: 50 mm/min	9.0
Glass Transition, °C	-30
Working Temperature, °C	-40 to 130
Softening point, °C	170 to 180

Table 1: Properties of Technomelt-PA 7846 [11].

To study the effect of additional cooling features in the mold, a complex 2D channel was designed inside the Moldflow software to compare the results. As can be seen in Figure 11, adding cooling features to the mold can reduce the “time to eject” parameter in the simulations. By activating the cooling channels, the ‘time to eject’ parameter was reduced from 121.2 seconds to almost 90 seconds for each injection. This will not only aid part quality by improving the cooling effect but also will reduce the cooling cycle of each injection by almost 25 percent.

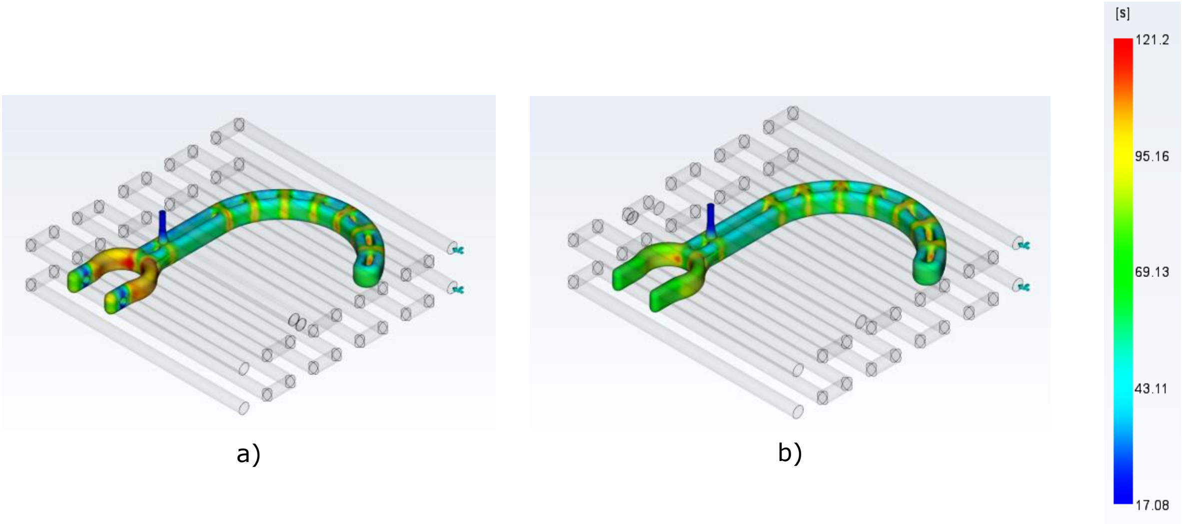


Figure 11: Preliminary study of cooling channels. (a) Cooling is deactivated, (b) cooling is activated. The time to eject graph has been demonstrated on the side.

3.2 Manufacturing Constraints and Limitations

Drilling a network of internal cooling channels inside a tool is limited by the linear nature of the machining process. Additionally, the final cooling channel has low cooling capacity due to geometrical limitations. Consequently, it is very difficult to manufacture complicated three-dimensional channels, especially close to the wall of the mold (see Figure 12). This will lead to an ineffective cooling system because the heat cannot be removed uniformly from the mold, and varying temperatures can cause warpage, distortion, and long cooling cycles. Conformal cooling channels can lead to major improvements and a general reduction of the cycle time while improving the heat transfer [7]. Even though AM technologies are capable of fabricating these complex conformal cooling channels inside a mold, they are very expensive and have their own limitations [23]. Therefore, a new development strategy needs to be established so that any complex cooling channel can be built without any additional support structures on the inside. Proof of concept strategies are explored to validate the feasibility of developing an epoxy-based IM mold with a complex cooling line strategy. Since design recommendations related to draft angles, pocket designs, surface finishing, and part ejection were not available, manufacturability concepts of curved cooling channels also needed to be validated.

3.3 Proof of Concept Strategies

To evaluate the manufacturability of the cooling channels and test required draft angles for an epoxy tooling material (Aremco 805) two proof of concept tests were developed. In the first test, a soluble spiral cooling channel was embedded within the epoxy in an ABS enclosure (Figure 13). To ensure that the part can be released conveniently after injection with the included draft angles, a section of the beta J-hook was built with the soluble SR-30. Figure 14 shows the detail of the second proof of concept test. To ease the ejection process, a layer of silicone-free mold release agent (Demolub [16]) was sprayed on the surface cavity.

In this tooling solution, soluble support material SR-30 is used to build the cooling channels via the FDM process. SR-30 is dissolved when it is exposed to a special solvent. To build rectangular cooling channels, the channels were split into two sections.

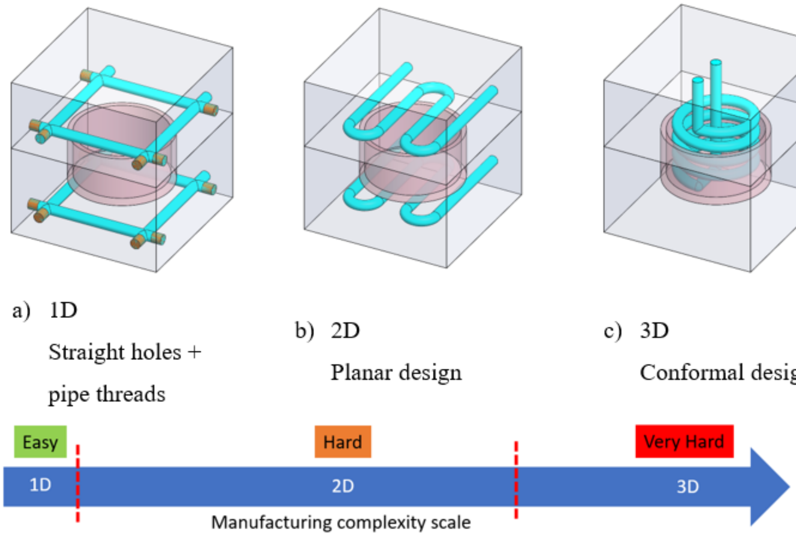


Figure 12: Manufacturing complexity of building internal features in a mold.

By using the "split rule", any complex cross-section can be divided into simpler geometries that require no support material to be built. Once all the pieces have been fabricated via FDM, the components can be assembled with acetone to create the desired channel geometry, as shown in Figure 15. Once these soluble cooling channels were built, they were submerged into Aremco 805 epoxy. Aremco 805, a high-temperature thermally conductive epoxy, is used to make the soft tooling [2].

Figure 13: (a) CAD design of the cooling channel experiment – the red section is made of soluble support material, (b) embedding the soluble support material, (c) Pouring Epoxy Aremco 805, (d) After dissolving the support structure and testing the channel.

Initially, the cooling channels were designed with a constant cross-section inside the tool. Once the methodology was established and the channels were able to be manufactured, other designs such as planar cooling channels with variable cross-sections and non-planar cooling channels with 3D-geometries are built to evaluate the design rules and build strategies that are developed in this research. Fabrication of these complex cooling channels will examine the expandability of this methodology.

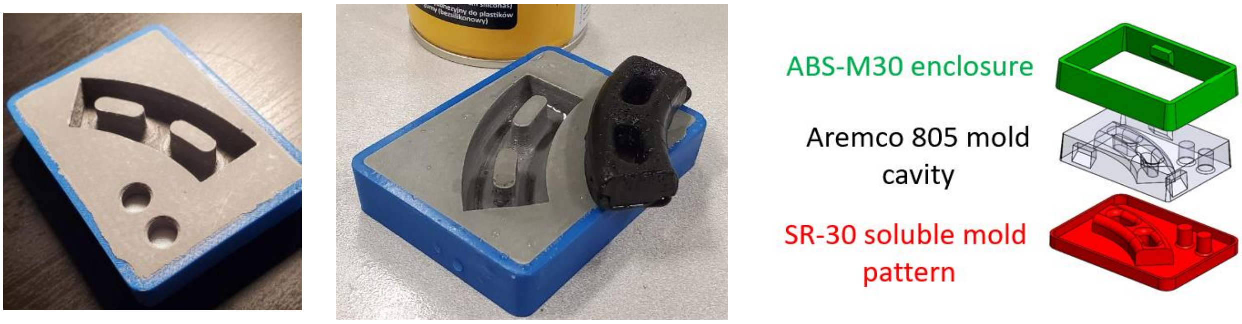


Figure 14: Ejection test and CAD design of the release experiment.

a) b)

Figure 15: (a) Cooling channel designs as one-piece design, (b) Split design to avoid using support structure for overhang surfaces.

3.4 Final Mold Design and Fabrication

To build a mold with the Aremco 805 epoxy, a boundary box and a soluble sacrificial pattern were designed. This soluble pattern contained the cavity with draft angles and the sprue for the feeding system. Figure 14 shows the exploded view of each mold cavity.

For building the cavity blocks, a soluble sacrificial pattern from each side of the J-hook was built by the FDM process. An ABS-M30 enclosure was placed on the soluble pattern to make sure that epoxy would not leak after casting. To further seal the edges, plumber's putty was applied on the edges. The soluble internal features were placed in their designated locations and two sets of stands were printed out of ABS to make sure that the distance of these channels to the cavity surface is constant (10mm) throughout the mold. Once the baseline mold package was assembled, the epoxy was cast into the mold enclosure (Figure 17)

After casting the epoxy, the Aremco 805 needed to be cured (24 hrs.). The same process was done at the same time to build the other side of the mold. Once the epoxy was cured, the parts were then transferred to the support removing tank and were submerged for 48 hours to dissolve the soluble SR-30. Table 2 shows the manufacturing time to build this low-cost set-up.

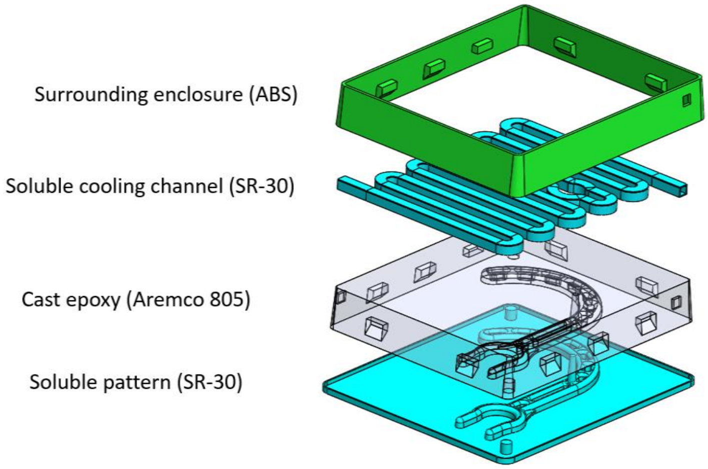


Figure 16: Exploded view of the top mold cavity showing the mold box or surrounding enclosure, the cooling channels, which are embedded in the cast epoxy, and the soluble pattern which is mounted on top if the cast epoxy.

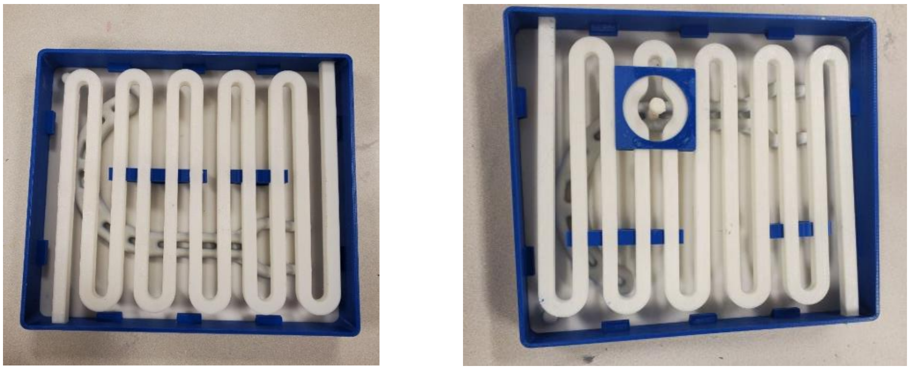


Figure 17: The top view of the components including cooling channels and cavity pattern.

Process	*Time*
Printing the soluble top Pattern (SR-30)	3 hrs. 31 min. (211 min)
Printing the soluble bottom pattern (SR-30)	3 hrs. 50 min. (230 min)
Printing two surrounding enclosures (ABS)	12 hr. 00 min. (720 min)
Printing two internal soluble patterns (SR-30)	4 hrs. 52 min. (292 min)
* Epoxy casting and cure time (both made at the same time)	24 hrs. (1440 min.)
Dissolving the soluble support	48 hrs. (2880 min.)
Preparing the surfaces	2 hrs. (120 min.)
Total	**4 days 8 hrs.**

Table 2: Build time information on manufacturing the low-cost tooling set-up (*Curing time for epoxy can be reduced from 24 hrs. to 4 hrs. by using an oven).

In this unique setup, an in-house developed injection machine [11] is directly mounted on the mold, the top mold box was designed in a way so that it could adapt the injection bushing in addition to the flange which holds the injection machine (Figure 18). To prepare the experimental setup, a centrifugal pump and a temperature control unit are required to complete the mold setup. Additionally, to provide a flow of fluid inside the internal channels, a Mastercraft ¼ hp dual-function pump was used [5]. This pump can provide 101 lit/min in flow rate. The schematic of the fluid circuit is provided in Figure 19.

4 RESULTS AND DISCUSSION

4.1 Dissolving the Soluble Patterns

Figure 20 shows the cured, dissolved, and assembled version of the cavity blocks. To ensure that the cavity blocks would fit into the mold blocks, the outer sidewalls of the cavity blocks were sanded to a smooth finish. This operation could be eliminated by coating the sacrificial patterns with silicone.

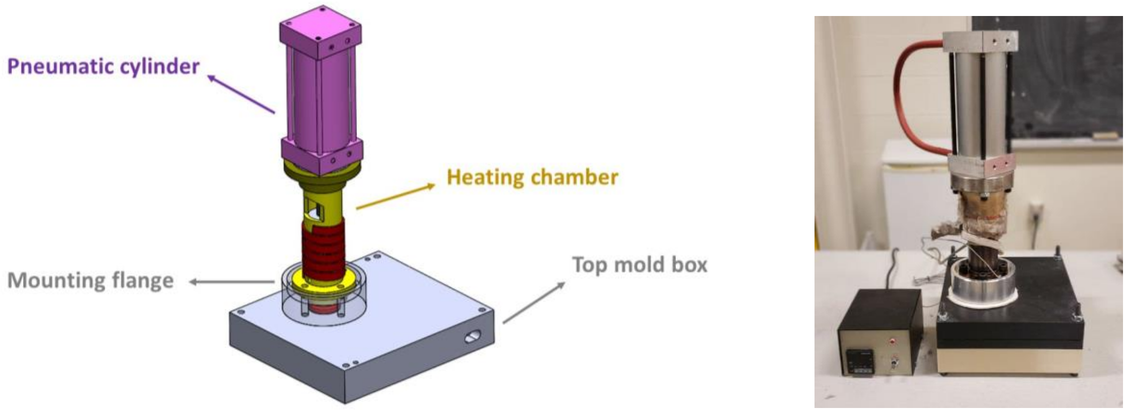


Figure 18: Components of the top mold box (left) and the experimental injection setup (right).

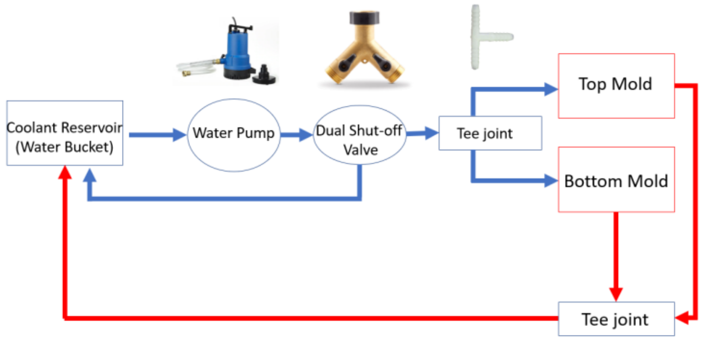


Figure 19: Fluid circuit design for the developed injection setup.

4.2 Injection Molding Results

Prior to assembling the mold sets, mold release was applied on the cavity surfaces. Pellets of Technomelt were heated to 200 ℃, and the material was injected. The part was cooled down for 1.5 minutes while the fluid was circulating inside the internal channels. Figure 21 shows the component inside the mold cavity. After the removal of the part, the excess material (flash) was removed, and the final product was successfully manufactured.

(a) (b) (c)

Figure 20: (a) Cured epoxy, (b) after dissolving the patterns, (b) assembled into the mold box.

(a) (b)

Figure 21: (a) The injected J-hook right after opening the mold package. (Red areas show the excess material "flash" that is inevitable an injection molding process), (b) final J-hook.

4.3 Visual Assessment of the Injected Product

It was clear that the cavity was completely filled, and no underfilled area was observed. This validated the results of the injection simulation that stated the part was able to be filled completely and the component had fill-confidence of 100%. The draft angles for the cavities (2 deg) are effective. The part was effortlessly removed, and no scratch marks or surface defects were found on either the component or the mold surfaces. After closely observing the surfaces of the J-hook under direct light, no sink mark was found on the surface of the product. This implies that the part was solidified uniformly. Weld-lines are another common defect in injection molded components that are easily visible by a standard visual test. No weld-lines are evident.

Air bubbles are among the standard defects in an injection molding process. The existence of air bubbles, especially on the surfaces of a component would suggest that the air bubbles that might be formed during the melting stage of the pellets have not been able to escape the mold cavity. As shown in Figure 22, tiny air bubbles were formed on the upper end of the product surfaces. These air bubbles can be easily avoided by introducing air vents on the surface of the mold cavities. Adding air vents is a standard practice in injection molding and these air vents would enable the air bubbles to easily escape from the mold cavity. Figure 23 shows the suggested design of the air vents.

Figure 22: Formation of air bubbles at both ends of J-hook.

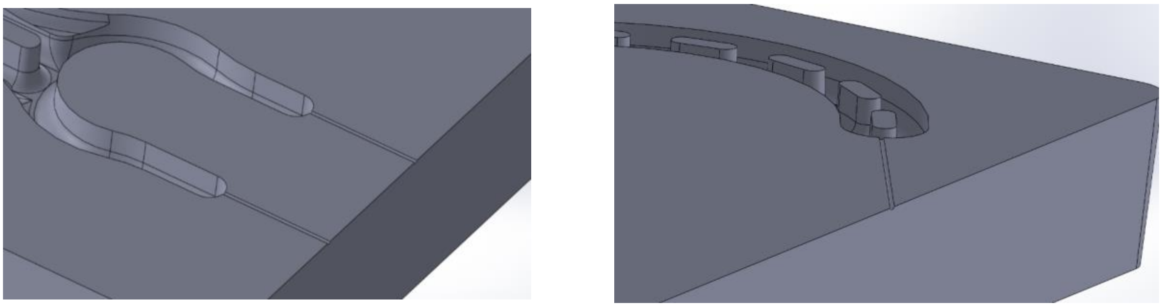


Figure 23: The new design of the mold cavities with incorporated air vents.

4.4 Geometric Quality Assessment

To calculate the flatness and warpage of the injected J-hook, it was placed on a relatively flat surface and light was reflected in the background. As shown in Figure 24, the light between the J-hook and the surface shows the warpage along the length of the part. By using a scale, the warpage was measured to be approximately 1mm across the length of the J-hook.

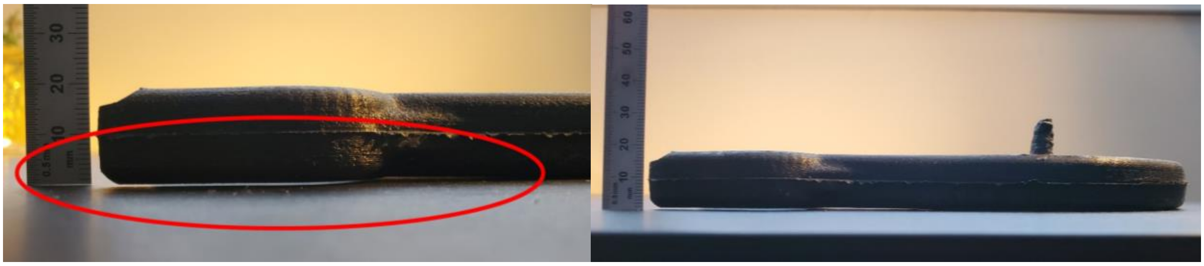


Figure 24: Flatness measurement of the injection-molded J-hook.

In addition to the flatness, the width, height, and thickness of the mounting were analyzed as well. Three measurement regions were selected and from each region, three measurements were taken in close proximity. Figure 25 shows the measurement regions.

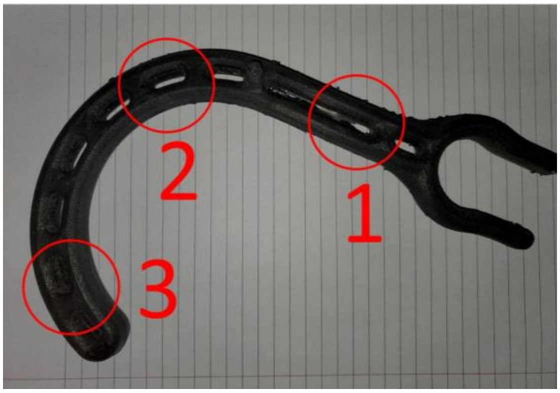
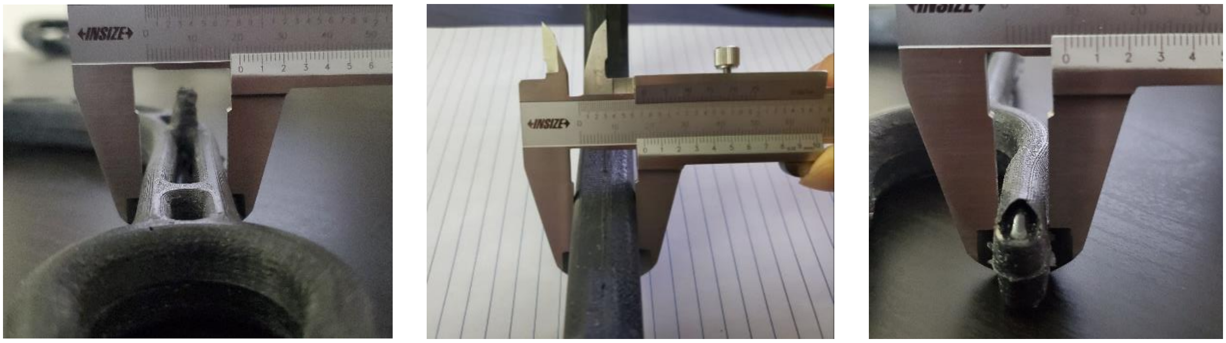


Figure 25: Selected areas for dimensional measurements.

The measurements were taken by a Vernier caliper and were compared to the original dimension in the CAD design (see Figure 26). To measure the dimensional accuracy of the mounting points, three measurements were taken from each side. Table 3 demonstrates that the average dimensional error in different orientations of the J-hook is around ±1%. The dimensional accuracy of the final prepared mold was measured to be within ±1.08 % of the original CAD designs. The measurement regions are shown in Figure 25. Even though the dimensional error of the soluble patterns were not measured, based on closed observations and the accuracy of the final mold, it can be deduced that the soluble patterns were well within the acceptable tolerances.



(a) (b) (c)

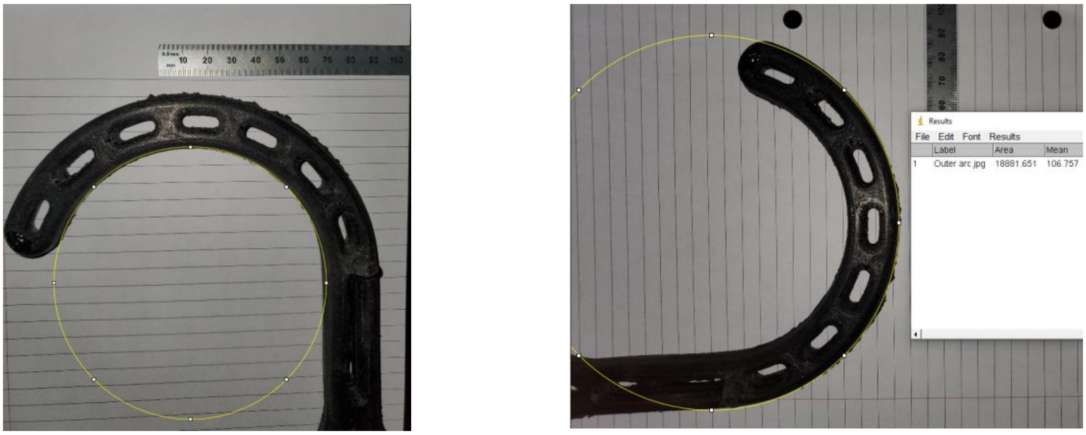
Figure 26: Measurements of (a) width, (b) height, and (d) thickness of mounting points.

Parameter	*Region*	*Measurements (mm)*	*Ave. (mm)*	*Original CAD (mm)*	*Error (± %)*	*Ave. error (± %)*
Width	1	20.60, 20.65, 20.45	20.56	20.87	1.48	1.16
	2	20.80, 20.65, 20.80	20.75	20.87	0.57	
	3	20.45, 20.45, 20.80	20.57	20.87	1.43	
Height	1	18.20, 18.20, 18.20	18.2	18	1.11	0.61

	2	17.90, 18.00, 18.00	17.96	18	0.22	
	3	17.85, 18.00, 17.90	17.91	18	0.5	
Thickness	1	8.70, 8.90, 8.75	8.83	8.87	0.97	1.11
	2	8.90, 9.05, 9.00	8.98	8.87	1.24	

Table 3: Width, height, and thickness measurement of error in the J-hook.

To analyze the dimensional accuracy of the arc section of the J-hook, image processing software ImageJ was utilized. The inner and outer arcs were measured three times via the software and the average radius and perimeter were compared to the original CAD design. Figure 27 shows the image processing method. Table 4 shows that the average dimensional error in the inner and outer arc were 2.82% and 2.71%, respectively. Even though the dimensional accuracy of the injected J-hook is within the desired tolerances, shape complexity and also the angle of the captured images might be a contributing factor to the higher error percentage around the arcs.



(a) (b)

Figure 27: Fitted circle to the (a) inner and (b) outer arc by ImageJ software.

Area	*Fit*	*Dimensions (mm)*	*CAD dimensions (mm)*	*Error (± %)*	*Ave. error (± %)*
Inner arc	First fit	Area: 9888.20 mm2 Dia.: 112.2 Per.: 352.50	Dia.: 109.13 Per.: 342.83	Dia.: 2.81 Per.: 2.82	Dia.: 2.82 Per.: 2.83
	Second fit	Area: 9849.00 mm2 Dia.: 111.98 Per.: 351.80	Dia.: 109.13 Per.: 342.83	Dia.: 2.61 Per.: 2.61	

	Third fit	Area: 9837.86 mm2 Dia.: 112.48 Per.: 353.38	Dia.: 109.13 Per.: 342.83	Dia.: 3.06 Per.: 3.07	
	First fit	Area: 18860.21 mm2 Dia.: 154.96 Per.: 486.82	Dia.: 150.87 Per.: 473.99	Dia.:2.71 Per.: 2.70	
Outer arc	Second fit	Area: 18843.68 mm2 Dia.: 154.89 Per.: 486.61	Dia.: 150.87 Per.: 473.99	Dia.: 2.66 Per.: 2.66	Dia.: 2.71 Per.: 2.71
	Third fit	Area: 18881.65 mm2 Dia.: 155.05 Per.: 487.10	Dia.: 150.87 Per.: 473.99	Dia.: 2.77 Per.: 2.77	

Table 4: Calculation of error percentage around the inner and outer arcs of the J-hook.

4.5 Cost and Time Analysis

The total fabrication cost of the developed rapid tooling in this research was less than $500.00 (US), as itemized in Table 5. The developed tooling was built in less than 5 days whereas a machined mold would have taken several weeks to be completed. In addition, the internal channels would not have been able to be machined to the extent they were fabricated in this research. The durability and tool life of this developed tooling solution have not been established. More injections are required to evaluate tool life and calculate final piece price. However, to date it is known that the Aremco 805 epoxy mold can withstand 100 cycles when molding the Technomelt.

The final piece price was also reduced from $36.60 (US) for an ABS part built from the FDM process to less than $6.00 (US) for injection molding using the Technomelt. Other materials could be molded – the Technomelt is a high temperature material. Table 5 shows the cost and time analysis of building this low-cost tooling setup.

Component	*Build time*	*Cost*
Epoxy molds	~ 4 days & 8 hours	*$330 (US)
Ancillary hardware	-	Less than $50 (US)
Mold boxes	~18 hours	(Built from waste material)
Sacrificial patterns	~ 10 hours	Less than $100 (US)
		Total: $480 (US)

Table 5: Cost and time summary of the experiment set-up (*for low to medium and medium production, extra epoxy molds might be needed to be built).

To further compare the FDM and the developed solution in this study, a scenario of fabricating 100 products is considered. Table 6 estimates the cost and time that would be required to fulfill this production number. Based on the calculations provided in Table 6, the low-cost rapid tooling solution may reduce the manufacturing time to almost a third of the FDM process. Additionally, the production cost may also be reduced by almost $2700 (US), which is a significant amount for a relatively low production number. Even though, the numbers show the promising prospects of this low-cost tooling solution, more injection tests are required to establish the real tool life and study the mold degradation effects. The tool life can provide a deeper insight on real production costs and capabilities of this solution.

Process	*Setup cost*	*Setup fabrication time*	*Estimated Production time*	*Estimated material cost*	*Estimated production time*	*Estimated production cost*
FDM	*$150 (US)	-	100 x 3 hr.	100 x $36.6 (US)	300 hr.	$3,810 (US)
IM	$480 (US)	104 hr.	100x 1.5 min	100 x $6 (US)	106 hr. 30 mins	$1,080 (US)

Table 6: Production time and cost analysis to fabricate 100 J-hooks by FDM and the developed IM solution (*Substrate sheets and nozzle tips are needed for FDM process).

For the development of this low-cost setup, all the components were built by the FDM process. By machining a set of permanents mold boxes e.g., aluminum mold boxes, the lead time can be reduced for future experimental setups. One advantage of using permanent mold boxes is that for other products, only epoxy inserts need to be fabricated and these inserts can be swapped very fast. Having swappable inserts can reduce the ‘tool change time’ significantly. This not only reduces the tool fabrication time for other products, but also reduces the tool fabrication costs in long runs.

4.6 Design Rules

In this research, these design for additive manufacturing (DfAM) rules were created and leveraged:

I. 2° draft rule: this shallow draft angle was experimentally validated to be suitable for the Aremco epoxy molds and will aid part release after injection (refer to Figure 14).

II. 45-degree rule: enabling the possibility of creating channels with variable cross-sections without additional support structures. By not exceeding the 45-degree limit in designing the overhanging features, no additional support structure was needed (see Figure 28).

III. Split rule: enabling fabricating soluble channels with complex geometries by splitting the complex cross section into less complex sections and then assembling the pieces with acetone. As demonstrated in Figure 29, a spiral internal channel (non-planar) was built without any additional support material on the inside.

IV. Soluble air vents: similar to any other tooling solutions, air vents are also required for the Aremco epoxy. As a result, the air particles can escape form the cavity and no air bubbles can be formed on the component (refer to Figure 22 and Figure 23). The air vent features can be added to the soluble sacrificial cavity patterns.

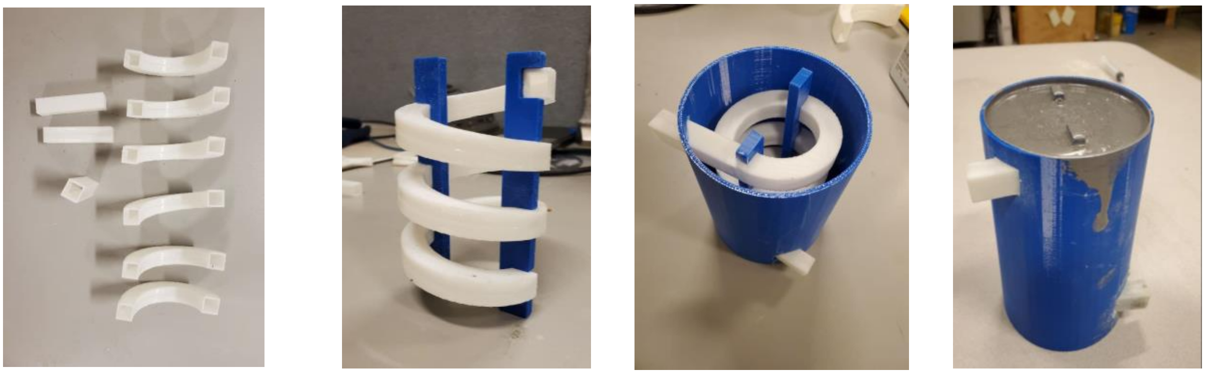
V. Designing soluble feeding systems: The available simulation tools for the conventional injection molding such as Autodesk Moldflow can be used to design and optimize feeding systems for Aremco epoxy molds. By leveraging the soluble approach, any complex feeding system can be created without any significant manufacturing restrictions.

VI. Additional stands to maintain a constant distance between the channels and the cavity surface: since the soluble internal channels are flexible, in some cases (see Figure 29(a)) additional stands need to be incorporated in the channels to maintain the desired distance to the cavity surface. In future, the possibility of coating the channels with heat conductive metals will be explored which will no longer require additional stands to maintain rigidity.

VII. Using silicone to improve surface finish: in some cases where a high surface quality is needed, the soluble cavity patterns can be coated by silicone so that the final mold cavity is created with a high surface finish. The application of silicone was adopted from Kalami et al [11] research.

(a) (b) (c) (d)

Figure 28: (a) Soluble channel with variable cross section without any support material, (b) assembling the test piece, (c) casting Aremco 805, (d) successfully testing fluid flow.



(a) (b) (c) (d)

Figure 29: (a) Nonplanar cooling channel design with modular design, (b) assembling the modules and creating a spiral channel, (c) assembling the test components, (c) casting Aremco 805.

5 CONCLUSION

Advances in developing rapid tooling are continuing to progress. The urgency for specialty products is heightened during this COVID-19 pandemic, but a rapid tooling solution needed to be developed as well as the products. Several hands-free door handles variants were designed. The FDM process helped quickly validate design ideas, but it could not be effectively used for higher production volumes and the available material is limited. Using epoxy and the FDM AM process in an unconventional manner, a mold with a moderately complex shape and intricate conformal cooling channels was manufactured without introducing any support structures and was experimentally proven to be effective. This technology solution opens up opportunities to manufacture molds that could reduce the cooling cycle significantly compared to conventional injection molding processes, where introducing conformal cooling channels with the desired geometry currently is not feasible.

By using the rapid tooling solution and leveraging 'waste materials' in this work, the build time for the J-hook was significantly reduced from 3 hours (FDM) to less than 2 minutes (IM). Additionally, by using the IM process, the quality of the final part is more consistent throughout the production. As demonstrated in Table 3 and Table 4, the dimensional error of the injection-molded J-hook is less than 3 % and the warpage is almost 1 mm across the length of the component. Even though machining a mold with conventional mold-making methods would cost thousands of dollars, from the cost analysis conducted, less than $500 (US) was used to build this tooling setup and the material piece price of the J-hook was reduced from 36.60 (US) to less than $6 (US). To calculate the final price of the product, more injections need to be done to test the durability of this developed tooling, then a final price per piece can be estimated. Additionally, by using a rapid tooling IM process, a wider range of material is available that can reduce the final material per piece even further.

It is experimentally demonstrated that the developed methodology is extendable, and any complex internal channel design can be fabricated and incorporated into a mold without any significant design and build limitations. These solutions have the potential to help maximize the cooling capacity, the efficiency, and to balance the heat flow to reduce product distortion and warpage. The design rules developed in this research open up opportunities to build extremely complex tools with internal channels that have been expensive (or impossible) to manufacture before.

One of the challenges during this research was the limitations of Autodesk Moldflow software where only existing build solutions (circular and semi-circular cooling channels) could be generated in the software. The Moldflow software needs to be able to readily incorporate novel cooling channels similar to the ones designed and built in this research. To leverage alternative and novel designs, the tools available for manufacturers need to be upgraded.

6 FUTURE WORK

To test the durability of this low-cost rapid tooling solution, more injection shots are required to predict and establish a tool life for the epoxy molds. Once the tool life of the epoxy molds was established, the molds could be then used in an industrial setup to evaluate the performance of the molds in a more conventional injection setup.

One of the advantages of the injection molding process is that a wide range of materials is available. Thus, other material options could be explored so that the final material price of each J-hook can be further reduced. Since the fabrication cost and time of this new mold-making technique are significantly lower than conventional mold-making methods, larger and more complex case studies that were previously limited by high cost and manufacturing constraints, will be fabricated to further test the capabilities of this new tooling method.

Additionally, different epoxies and other production ideas such as using metallic chills or sensors that are embedded inside the tools, can be easily incorporated in this tooling solution. This will help derive great experimental data sets that can help optimize alternative cooling designs. Additionally, topology optimization studies could be conducted to reduce the amount of epoxy that is used in building the molds. This can also affect the heat transfer of the mold blocks. Finally, the possibility of coating the soluble channels with heat conductive metals such as copper will be investigated. This will further increase the cooling capacity of the cooling channels.

Jill Urbanic, https://orcid.org/0000-0002-2906-7618
Bob Hedrick, https://orcid.org/0000-0003-2708-6943
Hamoon Ramezani, https://orcid.org/0000-0002-8866-966X
Ofelia Jianu, https://orcid.org/0000-0002-7194-9366

7 REFERENCES

[1] 3D Printers Canada: The Fortus 400mc Production 3D Printer, Stratasys, [Online]. Available: http://www.3dprinterscanada.com/fdm-production-series-fortus-400mc.php.

[2] Akula, S.; Karunakaran, K. -P.: Hybrid adaptive layer manufacturing: An Intelligent art of direct metal rapid tooling process, Robotics and Computer-Integrated Manufacturing, vol. 22, no. 2, pp. 113-123, 2006. DOI: https://doi.org/10.1016/j.rcim.2005.02.006

[3] Aremco: 25 October 2013. [Online]. Available: https://www.aremco.com/news-item/aremco-bond-805-high-temp-thermally-conductive-epoxy-now-available/. [Accessed 15 Jan 2021].

[4] Best, D.; Nicas, M.: A study quantifying the hand-to-face contact rate and its potential application to predicting respiratory tract infection, Journal of Occupational and Environmental Hygiene, vol. 6, no. 5, pp. 347-352, 2008. DOI: 10.1080/15459620802003896

[5] Canadian Tire: Mastercraft 1/4-HP Duel Function Pump, [Online]. Available: https://www.canadiantire.ca/en/pdp/mastercraft-1-4-hp-duel-function-pump-0623408p.html. [Accessed 15 March 2021].

[6] Centers for Disease Control and Prevention: How COVID-19 Spreads, 28 October 2020. [Online]. Available: https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html. [Accessed 5 February 2021].

[7] Dimla, D.-E.; Camilotto, M.; Miani, F.: Design and optimisation of conformal cooling channels in injection moulding tools, Journal of Materials Processing Technology, vol. 164, no. 165, pp. 1294-1300, 2005. https://doi.org/10.1016/j.jmatprotec.2005.02.162

[8] Dudek, P.: FDM 3D printing technology in manufacturing composite elements, Archives of Metallurgy and Materials, vol. 58, no. 4, pp. 1415-1418, 2013. DOI: 10.2478/amm-2013-0186

[9] Eiliat, H.; Urbanic, J.: Minimizing voids for a material extrusion-based process, Rapid Prototyping Journal, vol. 24, no. 2, pp. 485-500, 2018. https://doi.org/10.1108/RPJ-05-2017-0092

[10] Jahan, S.-A.; El-Mounayri, H.: Optimal Conformal Cooling Channels in 3D Printed Dies for Plastic Injection Molding, Procedia Manufacturing, vol. 5, pp. 888-900, 2016. https://doi.org/10.1016/j.promfg.2016.08.076

[11] Kalami, H.; Urbanic, R.-J.: Design and Fabrication of a Low Volume, High Temperature Injection Mould Leveraging a Rapid Tooling Approach, Int. Journal of Advanced Manufacturing Technology, Special Issue - Digital Manufacturing & Assembly Systems, 2019. https://doi.org/10.1007/s00170-019-03799-8

[12] Karapatis, N.-P.; van Griethuysen, J.-P.-S.; Glardon, R.: Direct rapid tooling: a review of current research, Rapid prototyping Journal, vol. 4, no. 2, pp. 77-89, 1998. https://doi.org/10.1108/13552549810210248

[13] Kazmer, D.: Injection mold design engineering, Munich, Germany; Cincinnati, Ohio: Hanser Publications, 2016.

[14] Levy, G.-N.; Schnidel, R.; Kruth, J.-P.: RAPID MANUFACTURING AND RAPID TOOLING WITH LAYER MANUFACTURING (LM) TECHNOLOGIES, STATE OF THE ART AND FUTURE PERSPECTIVES, CIRP Annals, vol. 52, no. 2, pp. 589-609, 2003. https://doi.org/10.1016/S0007-8506(07)60206-6

[15] Mazur, M.; Leary, M.; McMillan, M.; Elambasseril, J; Brandt, M.: SLM additive manufacture of H13 tool steel with conformal cooling and structural lattices, Rapid Prototyping Journal, vol. 22, no. 3, pp. 504-5018, 2016. https://doi.org/10.1108/RPJ-06-2014-0075

[16] Molydal: Silicone-free mould release agent, [Online]. Available: https://www.molydal.com/en/products/lubricants/plastic-injection/mould-release-agents/silicone-free-mould-release-agent/demolub.html. [Accessed 7 February 2021].

[17] Mueller, S.-M.; Martin, S.; Grunwald, M.: Self-touch: Contact durations and point of touch of spontaneous facial self-touches differ depending on cognitive and emotional load, PLos One, vol. 14, no. 3, 2019. https://doi.org/10.1371/journal.pone.0213677

[18] Sachs, E.; Wylonis, E.; Allen, S.; Cima, M.; Guo, H.: Production of injection molding tooling with conformal cooling channels using the three-dimensional printing process, Polymer Engineering & Science, vol. 40, pp. 1232-1247, 2000. https://doi.org/10.1002/pen.11251

[19] Saqib, S.; Urbanic, J.: An Experimental Study to Determine Geometric and Dimensional Accuracy Impact Factors for Fused Deposition Modelled Parts, in Enabling Manufacturing Competitiveness and Economic Sustainability, Berlin, Heidelberg, Springer Berlin Heidelberg, 2012, pp. 293-298. DOI: https://doi.org/10.1007/978-3-642-23860-4_48

[20] Shinde, M.-S.; Ashtankar, K.-M.: Additive manufacturing–assisted conformal cooling channels in mold manufacturing processes, Advances in Mechanical Engineering, 2017. DOI: 10.1177/1687814017699764

[21] Stratasys: FDM Support Materials, [Online]. Available: https://support.stratasys.com/en/materials/fdm/fdm-support-materials. [Accessed 8 1 2021].

[22] Stratasys: FDM Materials, [Online]. Available: https://www.stratasys.com/materials/search?technologies=ff37d7b8297c4e43977c155d765f3305&sortIndex=0. [Accessed 29 12 2020].

[23] Tan, C.; Wang, D.; Ma, W.; Chen, Y.; Chen, S.; Yang, Y.; Zhou, K.: Design and additive manufacturing of novel conformal cooling molds, Materials & Design, vol. 196, 2020. https://doi.org/10.1016/j.matdes.2020.109147

[24] World Health Organization: Coronavirus disease 2019 (COVID-19) situation report -73, 2 April 2020. [Online]. Available: https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200402-sitrep-73-covid-19.pdf?sfvrsn=5ae25bc7_6. [Accessed 15 Jan 2021].

[25] Wu, T.; Jahan, S.-A.; Kumaar, P.; Tovar, A.; El-Mounayri, H.; Zhang, y.; Zhang, J.; Acheson, D.; Brand, K.; Nalim, R.: A Framework for optimizing the design of injection molds with conformal cooling for additive manufacturing, Procedia Manufacturing, vol. 1, pp. 404-415, 2015. https://doi.org/10.1016/j.promfg.2015.09.049