NASA-Missouri Space Grant Consortium

Apr 21st, 3:15 PM - 4:15 PM

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Abstract

Polymer injection molding processes have been used for over 100 years to create high-volume parts quickly and efficiently. Injection molding uses mold plates that are traditionally made of very hard tool steels, such as P20 steel, which is extremely heavy and has very long lead times to build new molds. In this study, composite-based additive manufacturing (CBAM) was used to create mold plates using long-fiber carbon fiber and polyether ether ketone (PEEK). These mold plates were installed in an injection molding machine, and rectangular flat plates were produced using Lustran 348 acrylonitrile butadiene styrene (ABS). Tensile testing was performed on these parts as well as parts produced using traditional P20 steel mold plates with the same geometry to compare the performance of the different mold plates. The parts produced using the carbon fiber mold plates were within 5% of the tensile strength. However, the parts produced using the carbon fiber mold plates required additional cooling time due to the lower conductivity of the carbon fiber composite compared to the P20 steel. This allows additively manufactured composite molds to be a good substitute for conventional molds in low-volume injection molding production.

Introduction

In 2021, the plastics industry produced nearly $400 billion in global shipments and accounted for 1 million jobs in the United States alone [1]. Over 30% of this market is made up of injection molding alone. Injection molding is used in many high-volume, high-speed applications of thermoplastic, elastomer, and thermoset materials. Additives such as colorants or fillers can also be added to improve mechanical or cosmetic properties. The injection molding process is very robust and provides many advantages such as high dimensional control over complex geometries, high repeatability, low labor, and low scrap [2]. The injection molding process begins with small pellets of the base material and subjects them to 5 basic steps: plasticizing, injection, filling, cooling, and release [3]. Plasticizing intakes the raw pellets and uses conduction from a series of heaters along with friction from a rotating screw pushing the pellets along the wall of the barrel to fully melt the polymer to the required injection temperature. During injection, a clamping unit closes the mold. Then, a ram forces a pre-set volume of molten polymer into the mold cavity at high pressure. During filling, the screw is held in a forward position to force more polymer into the mold to account for shrinkage due to cooling or small displacements in the machinery. The fourth step, cooling, conducts thermal energy out of the polymer to allow it to solidify in the mold. This step is usually the longest in the process, but also the most important because without uniform cooling, thermal stresses and warping can be introduced to the part. Finally, in ejection, the mold is opened, and pins eject the finished part from the mold. The screw retracts to measure a new shot of polymer for the next cycle, and the process can be repeated [4].

One of the biggest drawbacks though is that it requires extremely high upfront tooling costs. Due to the high precision, complex CNC manufacturing required, simple, small molds often cost $5000

with larger, more complex molds costing up to $100,000 [5]. In addition, traditional steel molds often have lead times of multiple months and are difficult to repair if the initial design is found to be inferior during first article testing, which hampers the economic viability of the injection molding process [6]. Due to these drawbacks, new rapid tooling production methods using additive manufacturing are being considered to produce customized parts with complex geometries, reducing mold production costs and cycle times [7]. Given the reduction in lead times as well, the additively manufactured parts are better suited for prototyping and certification of the mold design.

In this study, composite-based additive manufacturing (CBAM) was used to create injection mold plates. Composites are primarily composed of a fiber material surrounded by a matrix. The fibers provide high strength and stiffness to the part necessary to overcome the high clamping and injection pressures. The matrix serves to transfer the load to the fibers, assist in maintaining the part's geometry, and is responsible for the surface finish of the composite mold plates [8]. CBAM creates parts with very low void content and can use a wide range of high-performance long-fiber materials to create an extremely high mechanical performance. Furthermore, CBAM takes advantage of additive manufacturing in which highly complex geometries can be quickly created at an affordable cost. In addition, CBAM mold plates can be designed and adapted to be used in existing dies, thereby creating additional time and cost reductions [9].

Manufacturing and Installation of Mold Plates

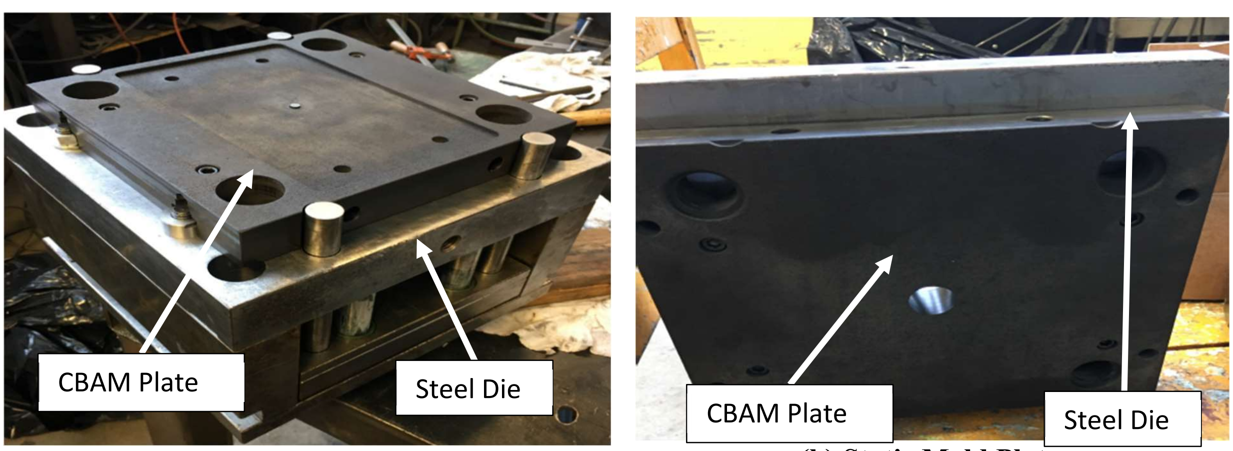
CBAM Mold Plates

The CBAM mold plates used in this study were developed using the CBAM 2 printer, which is manufactured and managed by Impossible Objects Inc. in Northbrook, IL. This process utilizes three main steps in order to produce final parts from an initial CAD model. First, long-strand carbon fiber veils are taken into the machine. Then a thermal inkjet is used to lay an aqueous adhesive solution on the veils in locations where the final part will be produced. The veils are then passed under a flow of thermoset polymer powder followed by a vacuum. The polymer powder sticks to the veils where the solution was placed and is removed from all other locations. Each veil is then stacked to create a full build block. This build block is then pressed and cured which crosslinks the polymer surrounding the fiber veils and fuses the sheets into a solid mass. Finally, a mechanical blasting process is used to abrade the carbon material that is not bound to the PEEK matrix [10]. The material properties of the final CBAM/PEEK composite are shown in **Error! Reference source not found.** below [11,12].

Table 1. Carbon Fiber/PEEK CBAM Properties

Carbon Fiber/PEEK CBAM Properties		
Nominal Fiber Volume Fraction	0.22	-
Density	0.0506	lb/in^3
Tensile Strength	19.1	ksi
Compressive Strength	23.5	ksi
Elastic Modulus	1848	ksi
CTE, xy-linear	7.0	µin/(in-°F)
CTE, z-linear	36.4	µin/(in-°F)
Thermal Conductivity	0.16	BTU/(hr-ft-°F)
Poisson's Ratio	0.32	-

In this study, a set of mold plates were created using this process such that the final injection molded part's shape is a rectangular prism with dimensions of 9.8125 inches in length, 5.1875 inches in width, and 0.125 inches in depth with a 0.25 inch fillet on each corner. After the CBAM process was complete, standard mechanical subtractive methods were used to finish creating the composite molds. Two holes were drilled through the mold to allow for cooling lines, along with five holes for ejector pins within the mold cavity. Due to the compression stage of the CBAM process, creating long, straight, internal voids is quite difficult with current technologies, hence the need for modifications. The mold plates were installed on the dies using the same screws and holes as the steel molds. The final CBAM mold plates mounted to the dies are shown in Figure 1.



(a) Dynamic Mold Plate **(b) Static Mold Plate**

Figure 1. CBAM Mold Plates attached to Injection Die

The CBAM process has a number of advantages over other methods of creating injection molding plates. First, mold plates can be made extremely quickly with the CBAM method. These molds took a total of 26 hours to produce: 12 hours to print, 12 hours to bake, and a final 2 hours of post-processing time. In part due to this time reduction, the CBAM mold plates are significantly cheaper to fabricate than comparable steel molds. These molds made with the CBAM process cost a total of $1,730, less than 15% of the cost of a comparable steel mold. This reduction in price makes a significant difference to the final cost of products running with a small production cycle.

There is a wide range of materials available for the CBAM process. Currently, long-fiber (fiber length ≥ 12mm) glass and carbon fibers are available with a range of thermoset polymer materials. These materials allow for the customization of material characteristics to the application. In this study, the carbon fiber/PEEK was used due to its high strength and thermal stability. This also created significant weight savings over the steel molds. The CBAM-produced molds have a density of 0.0506 lb/in^3 while P20 steel has a density of 0.284 lb/in^3. This equated to a weight savings of over 80%.

P20 Steel Mold Plates

As a control group, standard steel mold plates with the same geometry were procured. These mold plates were produced using CNC milling of AISI P20 steel. Due to its strong resistance and ability to maintain hardness and strength at high temperatures, AISI P20 steel is one of the most widely used types of tool steel used in the plastics injection molding industry [13]. The material properties for the steel mold are in Table 2 below [14].

Table 2: P20 Steel Properties

P20 Steel Properties		
Density	0.284	lb/in^3
Brinell Hardness	300	
Tensile Strength	125	ksi
Compressive Strength	125	ksi
Elastic Modulus	29700	ksi
CTE, linear	7.1	μin/(in-°F)
Thermal Conductivity	24	BTU/(hr-ft-°F)
Poisson's Ratio	0.3	-

One of the most important things about the P20 steel molds is a comparison in the thermal conductivity of the steel compared to the carbon fiber/PEEK. The steel has a very high thermal conductivity of 24 BTU/(hr-ft-°F) as shown in multiple data sheets from tool steel corporations [15]. The thermal conductivity for the carbon fiber/PEEK mold material is significantly lower coming in at only 0.16 BTU/(hr-ft-°F). This means that heat is transferred to the steel molds

roughly 150x faster than the composite molds. The ultimate result of this is that cooling times will be significantly longer for the composite molds.

Although in many cases, this is a considerable drawback due to injection molds often being used for years and millions of cycles, there are still opportunities for low-volume production in which creating a steel mold is prohibitively expensive [16]. In this case, where one would desire custom molds for low-volume demands, a higher cycle time would become acceptable due to the initial cost savings on tooling.

ABS Manufacturing and Modifications

The injection molding process uses thermal processes to melt a thermoplastic polymer, inject the molten polymer at a high pressure into a mold, cool the polymer to a hard solid, and then eject the completed part from the mold.

Injection Molding Material

For this study, Lustran 348 Acrylonitrile Butadiene Styrene (ABS) was selected as the material of interest for injection molding. The material used in this study was supplied by Avient in Avon Lake, OH. Its material specifications can be found in Table 3 [17]. ABS is a nontoxic amorphous polymer consisting of three monomers: acrylonitrile, butadiene, and styrene. It is known for its high rigidity and impact resistance along with high dimensional stability. It was chosen for this study due to its availability and being a widely-used polymer in injection molding that traditionally does not pose any material-related special considerations.

Table 3. Lustran 348 ABS Material Properties

Lustran 348 ABS Material Properties		
Density	1060	kg/m^3
Melt Temperature	475-525	°F
Shrinkage	4.0E-3 to 6.0E-3	in/in
Drying Temperature	175	°F
Drying Time	At least 2 hours	
Mold Temperature	85-140	°F

Setup and Process Modifications

The tonnage in injection molding refers to the amount of force applied by the machine to the mold plates when they are clamped together. The clamping pressure multiplied by the part area in the mold must not exceed the tonnage of the injection molding clamp in order to not damage the molds and to maintain dimensional control of the plastic parts [18]. If the tonnage is too low, plastic can creep out of the crack between the two molds and create sharp edges. The maximum allowable tonnage is a function of the mold's compressive strength and surface area of the mold as shown in

$$P_{max} = \frac{\sigma_C \cdot SA}{2000lbs} \quad (1)$$

Applying this to the CBAM mold, it is found that the maximum allowable tonnage is 483 tons which, although lower than the steel mold, is still vastly higher than the injection molding machine's maximum of 165 tons. The minimum tonnage required for a mold is estimated by the following equation where K_P is the clamping force constant based on the material being injected, SA is the surface area of the part, and SF is a safety factor.

$$P_{min} = K_P \cdot SA \cdot SF \quad (2)$$

Lustran ABS was used for this study which has a K_P of 1.2. This results in a minimum tonnage of 55 tons. Therefore, the CBAM mold and injection molding machine are strong enough to withstand the required tonnage for this mold.

Cooling Systems and Times

Cooling is a critical step in the injection molding process. Traditionally, over half of the cycle time is spent in the cooling stage. The cooling time gives the molten part time to transfer thermal energy to the mold, thus solidifying the final geometry and mechanical properties before it is ejected from the mold [19].

Traditionally, cooling systems for injection molding utilize a cooling fluid that flows through pipes to the mold, and then back to a thermal processing unit. Usually, this cooling fluid is water that is piped through the mold which allows for direct conduction of heat from the mold into the water. This water is maintained at a temperature between 100-120°F depending on a variety of factors to avoid warpage due to high thermal gradients [20]. Unlike steel, CBAM products have a slightly porous surface finish. Due to this, they cannot be directly exposed to the cooling fluid, or else the finished part quality would be diminished. In this study, Type K copper tubing was run through the molds to carry the water. Type K copper was chosen due to its high thermal conductivity (400 BTU/(hr-ft-°F), high melting point, and low thermal expansion. Furthermore, graphite and copper have very similar electropotentials meaning that galvanic corrosion is unlikely.

Cooling time is also an important factor to consider in the process. Without enough cooling time, the part will not be solidified when it is ejected from the mold, thus leading to warpage and other problems. On the contrary, cooling too fast can lead to amorphous solidification of the polymer, leaving a weak, brittle part. Traditionally, the following equation is used to estimate the required cooling time using a steel mold:

$$T_{Cooling} = \frac{d_{sprue}^2}{\pi^2 \alpha} ln\left(\frac{4(T_M - \bar{T}_W)}{\pi(\hat{T}_E - \bar{T}_W)}\right) \quad (3)$$

Where d_{sprue} is the sprue diameter, α is the coefficient of thermal diffusivity of the molten polymer, T_M is the injection temperature of the molten plastic, $\bar{T}_W$ is the average temperature of the mold plate surface, and $\hat{T}_E$ is the average temperature of the part when it is ejected from the mold [21]. When applied to the steel mold, this results in approximately 10 seconds of cooling time. However, the CBAM material has far lower thermal conductivity than the steel does, and as such, the mold surface temperature absorbs heat from the polymer slower. Through experimentation performed in [22], it was found that 60-90 seconds of cooling time is necessary to fully transition the part to a crystalline solid both of which were applied to this study.

Modifications to CBAM Mold Plate

As a further result of the porous surface of the mold plate, an impervious coating had to be applied to the surface of the mold. Initially, a conventional two-part mold sealant/release system was attempted. After the first part was made, it was found that this system was insufficient to properly prevent the liquid polymer from filling internal voids in the CBAM mold as shown in Figure 2. The black splotches are areas where the plastic had adhered so much to the mold that in order to remove the part, it tore off parts of the CBAM mold.

Figure 2. Injection Molded Part Using Mold Release

The mold had to be repaired by using a float to spread a thin layer of J-B Weld steel-reinforced epoxy to restore a smooth surface finish. This material was selected due to its similar thermal conductivity to the CBAM material, as well as its ability to withstand the high temperatures and pressures encountered in the injection molding process. Once the mold was repaired, a new system to protect the mold plates was proposed. In this system, a high-temperature, metallic-backed tape was applied to all surfaces the plastic would come in contact with. Parts made with the improved mold can be seen in Figure 4. Upon visual inspection, these parts looked to be geometrically sound and removed cleanly from the mold, so this tape system was used for all remaining trials with the CBAM manufactured mold plates.

Figure 3. First series of parts made using protected CBAM mold plates

Injection Molding

For this study, a Cincinnati Milacron VT-165 165-ton injection molding machine at the Missouri University of Science and Technology's Composite Manufacturing Laboratory. Parts were manufactured with both the steel mold and the CBAM mold before cutting out test articles for tensile and flexural testing. Due to the hygroscopic nature of ABS, before inserting the pellets, they were dried in an industrial dryer at 180°F for at least 9 hours per the technical datasheet. The injection molding machine used has a three-banded heater screw along with a heated sprue. The rear band was set to 465°F, the mid to 475°F, and front was set to 485°F. The sprue was also set to 485°F which maintained the temperature of the molten plastic in the mold. Once reaching the designated operating temperature, the machine was allowed to "soak" at this temperature for 30 minutes before parts began being manufactured. For all parts made in the steel mold, the cooling time was set to 10 seconds. Parts for tensile testing specimens made in the CBAM mold were cooled for 90 seconds. Flexural testing specimens were cooled for either 30, 60, or 90 seconds to compare the effect of cooling time on the material performance and to find a cooling time at which the CBAM-produced part performed most similarly to the traditional steel mold-produced part. The input specifications for manufacturing are summarized in Table 4 below.

Table 4. Summary of Injection Molding Input Parameters

Parameter	Steel Mold	CBAM Mold	Unit
Tonnage	165	165	tons
Injection Pressure	1800	1800	psi
Rear Heater Temperature	465	465	°F
Mid Heater Temperature	475	475	°F
Front Heater Temperature	485	485	°F
Sprue Temperature	485	485	°F
Injection Time	6	6	s
Packing Time	3	3	s
Cooling Time	10	30-90	s

It was found that with 30 seconds of cooling time, the parts were still pliable when ejected from the composite mold. These parts were placed between two heavy plates immediately after ejection to remove warpage induced by the ejection process. These parts were still tested through the remainder of the study, however more cooling time is necessary to produce solid parts upon ejection.

Tensile Testing

Tensile testing was conducted according to ASTM D638 [23]. Tensile specimens 6.5 inches long with a test section 0.5 inches wide (see Figure 5 and **Error! Reference source not found.** below) were removed from the injection molded parts and prepared for testing by drawing one tracking dot on each side of the test section. Each specimen's test section geometry was measured with calipers to the nearest 0.001 of an inch and recorded prior to testing.

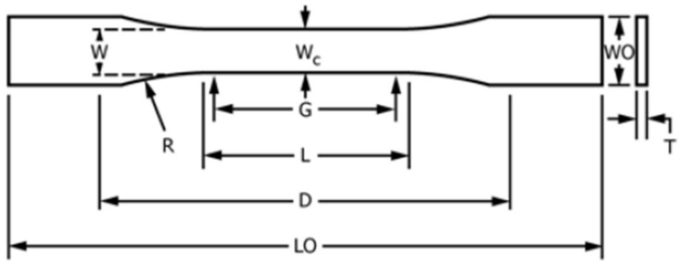


Figure 4. ASTM D638 Tensile Test Specimen

Table 5. ASTM D638 Tensile Test Specimen Dimensions

Label	Dimension, mm (in)
W—Width of narrow section	13 (0.50)
L—Length of narrow section	57 (2.25)
WO—Width overall	19 (0.75)
LO—Length overall	165 (6.5)
G—Gage length	50 (2.00)
D—Distance between grips	115 (4.5)
R—Radius of fillet	76 (3.00)

These test samples were then selected at random and loaded into an Instron 5985 universal testbed fitted with a 250kN load cell, video extensometer, and standard wedge style tensile grips from Wyoming Test Fixtures as shown in Figure 5. Five samples of each set were tested until failure. The extension rate was set at 25.4 mm/min and data was collected at a rate of 20 Hz once the preload value of 50 N was reached. Specimens that did not break within the ASTM allowable failure methods were discarded and not replaced.

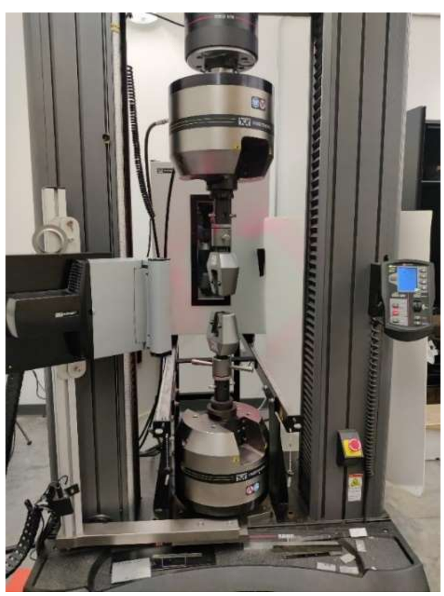


Figure 5. Instron 5985 with Tensile Grips and Video Extensometer

Results

Tensile Testing

During the test, data was collected at a rate of 20 Hz. This data included time, load, mechanical extension, stress, and strain as measured by the video extensometer. From this, stress-strain curves were plotted and shown in Figure 7 below. The data shows a very high correlation between the samples built in the steel mold and the CBAM mold. The difference in average ultimate tensile strength ($\overline{\sigma}_{ULT}$) is 3.74% and the difference in average elastic modulus (E) is 1.27%. These differences are minuscule and can very easily be attributed to experimental variation, thus it can be concluded that parts made in a CBAM injection mold have similar tensile properties to those made in traditional steel molds.

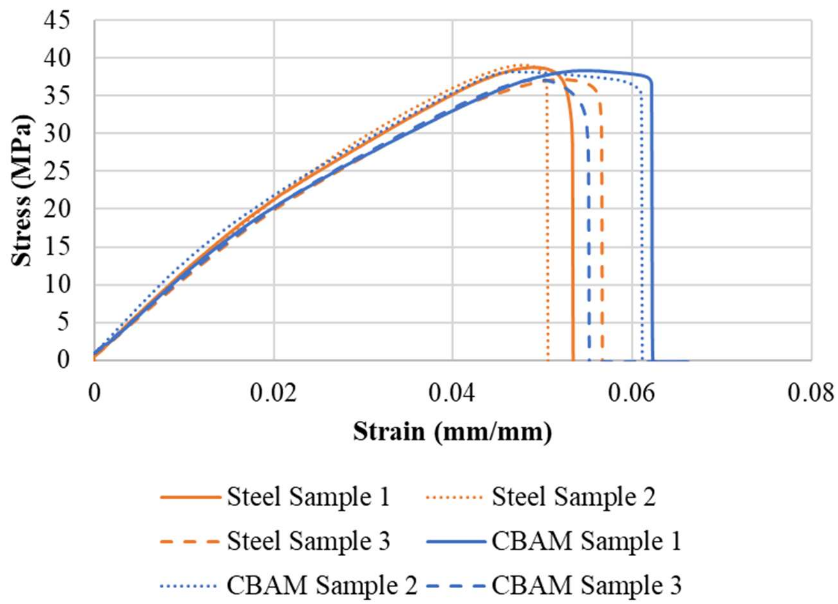


Figure 6. Tensile Stress-Strain Curves

Summary

The purpose of this project was to test the feasibility of injection molding using CBAM molds versus standard P20 steel molds. The parts manufactured using both methods were tested and found to have fairly similar properties, suggesting that carbon fiber molds are a feasible alternative. Further research will be conducted on CBAM mold modifications such as nickel plating and mold lubrication, as well as different injection materials and process time.

Acknowledgements

The author would like to thank the NASA-Missouri Space Grant Consortium Grant Award number 80NSSC20M0100, which sponsored this work. The author would also like to thank his advisor, Dr. K Chandrashekhara, without whose guidance and support this would not be possible. Support from Impossible Objects through the Center for Aerospace Manufacturing Technologies (CAMT) at Missouri University of Science and Technology is gratefully acknowledged. Finally, the author would like to thank S. Dasari, M. Rangapuram, H. Haffner, and M. Heskin for their support, insight, and experience throughout this project.

Biography

John Mitchell is from St. Louis, Missouri, and is a 4th-year Aerospace Engineering student, attending the Missouri University of Science and Technology. John also serves as the Chief Technology Officer of Miner Aviation, a Student Design Team at Missouri S&T. He has worked as a Laboratory Teaching Assistant for the Sophomore Aircraft Design Class at Missouri S&T. John plans to begin his career as a Model-Based Systems Engineer for Government Training Systems at Boeing St. Louis.

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