

Reusable Conformable Workholding



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Abstract

Often times milled parts are designed around their ability to be fixtured within a machine tool. This paper looks at the plausibility of developing work holding methods for parts with abnormal geometry. A process was developed for three parts of increasing complexity with each part representing a grade of part that one might encounter. A 3D printed negative mold of the part with vacuum ports was developed and examined for feasibility in workholding. The process includes coatings to better seal the fixture and adapt an additively manufactured part for the purpose of workholding. The process was tested and conclusions were drawn based upon the quality of the finished part, the ease of the process, and visual keys during machining.

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Introduction

Objective

Our objective is to develop work holding methods for parts with abnormal geometry for milling operations.

Rationale

Any part manufactured in a mill needs to be fixtured in some form or fashion. Fixturing a part primarily does two things. First, it holds the part while the forces associated with cutting the material attempt to move it. Second, it serves to locate the part within a mill's operating envelope, thus allowing accurate measurements to be made. Even with the large range of fixturing methods, parts still need to be designed with fixturing in mind. Parts with abnormal geometry have no fixturing method that is practical for their machining and often need to be adjusted or abandoned. In some instances, parts with abnormal geometry can be fixtured with traditional fixturing methods, but often times the process of adapting traditional fixturing to abnormal geometry ends up being time consuming and costly. With this in mind, a method for fixturing abnormal geometry would improve the versatility and capability of milling operations.

State of the Art

In order to better understand the role our fixturing needs to play, it is important to explore the current methods of fixturing typically used in milling operations. Each fixturing method has its own applications, strengths, and weaknesses, and together cover a large range of possible parts that would be used in milling.

In a general sense, a fixturing method accomplishes two primary tasks, location and clamping of the workpiece. Location depends upon the positioning and orientation of the piece within the machine. In this respect, there are 12 total degrees of freedom that need to be fixed in order to secure the location of a workpiece. This can be done using one of several different methods, one of the most common being a flat locator. A flat locator is a flat surface which the workpiece rests upon that is calibrated to the axis of the machine and then limits a part's movement. A vise is a common example which utilizes this method for the Z and one other axis though the usage of tramming. Clamping is the physical action of holding the workpiece in place while the machining operations take place. This process is a balancing act between rigidly holding the workpiece and resisting deformation due to overapplication of clamping pressure. It also needs to resist vibrations generating during milling operations. [1]

Clamping

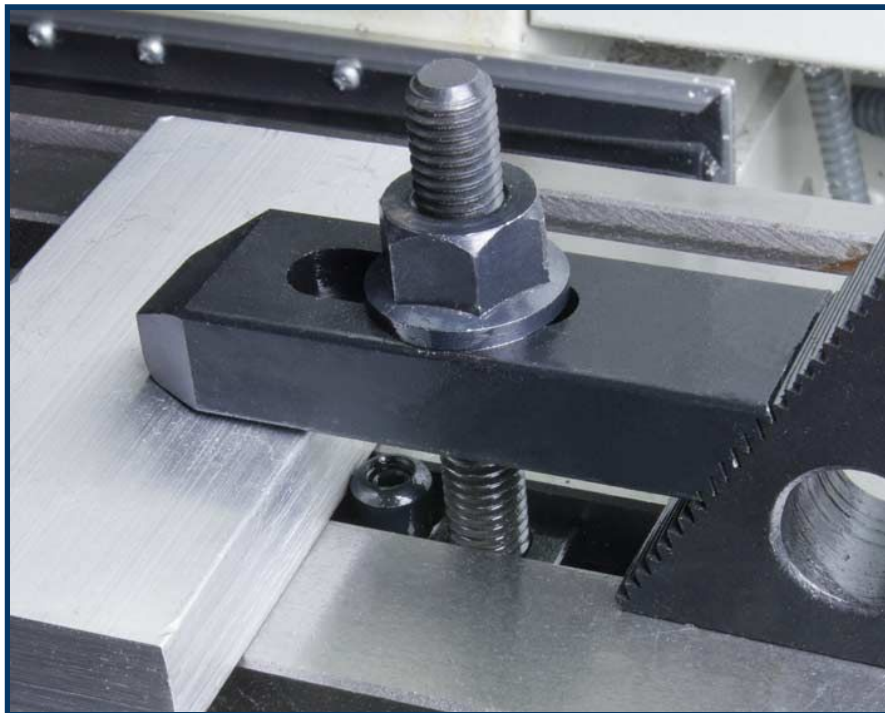


Figure 1: T-track Clamps^[2]

A common and versatile method of fixturing is using T-track clamps. T-track clamps use T-nuts that slide along the grooves of the mills bed and a set of clamps that mate with them to hold a workpiece down to the table. T-track clamps can be used in a wide range of applications and are extremely versatile given that they have no bound geometry and can be moved and adapted to the specific part. They provide an extremely strong clamping force that is extremely reliable when machining. The downside to T-track clamps is that they can be difficult to write programs for, as the placement of the clamps can vary, do not provide a referenceable geometry, and hold the part right on the table, which should not be machined.^[3]

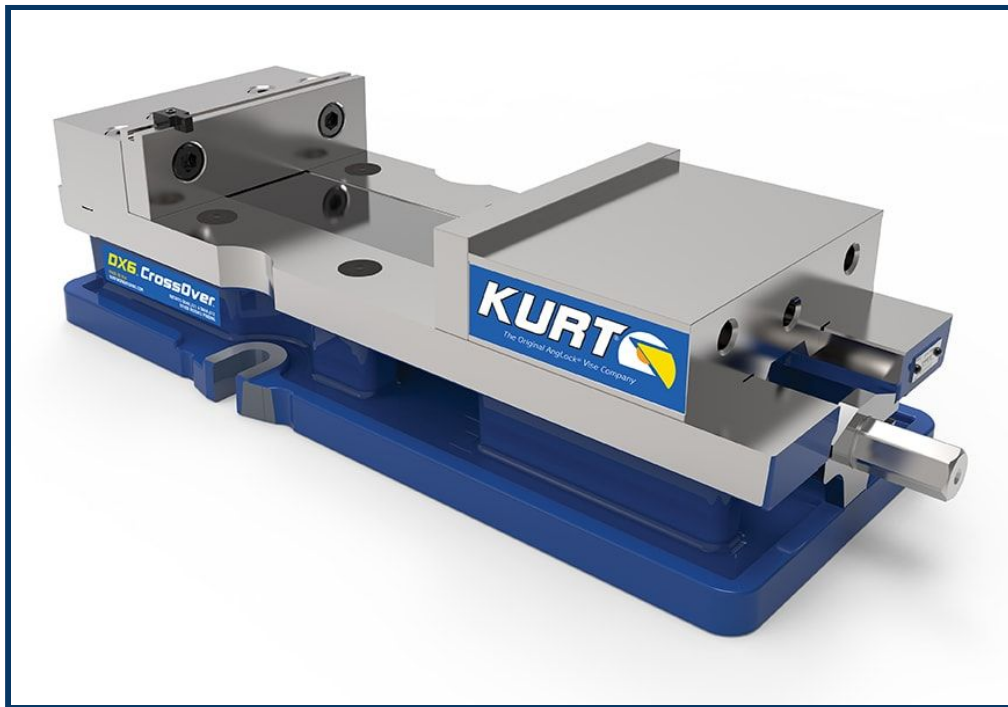


Figure 2: Machining Vise^[4]

Another common fixturing method is to use a vise. A vise is a set of two jaws with one jaw moving along a set screw. When a part is placed between the jaws the set screw is tightened to hold it in place. Vises are a secure method for holding parts and only apply

clamping force along a singular axis. In addition to the standard jaws, a machinist can create a set of soft jaws for more specific and complex applications. Soft jaws are machined to fit a specific parts geometry to increase the surface area being clamped to make the operation safer and stabler. The downside to using a vise is that parts fixtured in the vice usually need to have a flat bottom surface and a predominantly flat side surface to properly hold the part for milling.



Figure 3: Four Different Styles of Collets^[5]

Similar to vises, collets are also one of the most standard fixturing methods. Collets utilize pneumatic jaws to clamp cylindrical stock. The clamping forces of a collet are strong enough to securely hold any stock placed into it. The issue with collets is that the jaws are sized based on standard stock sizes and are completely cylindrical. Any stock that is too deviated from standard stock size or is not entirely cylindrical often times cannot be fixtured in a collet.^[6]

Magnetic Holding

One of the primary applications of magnets in workholding is through the direct application of electro-permanent magnets to the underside of the workpiece. These magnets can have their field's turned on or off with the application of an electric current. This method of workholding offers the benefit of having no external parts or clamps rising above the sides of the workpiece allowing for more applications. However, it is not functional for smaller parts due to a lack of magnetic force which could be superseded by the cutting forces. It is also limited to strong ferromagnetic materials that can be attracted to magnets.^[7]

An adaptation of the vise used in few applications is the magnetic vise. This fixturing method uses the stabilization of vise jaws and the holding force of magnets to hold workpieces. Typical vise jaws are used to guide the workpiece and keep it stable while electromagnets are used to provide a strong holding force so the part can be machined. This method minimizes deformation while providing the same benefits that a typical vise has. The issue with this method of fixturing is that it is limited by material selection and abnormal geometry. If a material used to make the part is not magnetic enough to be help by the electromagnet, then the clamping force will not be enough to safely machine. If the part has abnormal geometry it is possible that the magnet does not have enough surface area to exert force on and ends up becoming a pivot point or not holding the part at all.^[8]

Adhesive Holding (Typically does not offer location finding)



Figure 4: Double-sided Tape^[9]

A non standard fixturing method that is most often used for low-impact one off parts is double-sided tape. Double-sided tape is a quick and simple fixturing method that excels in situations where cutting forces are not exceedingly large, allowing the tape to hold the part steady with ease. Double-sided tapes can be made for manufacturing purposes with both a force rating and a pressure activation. When a part is fixtured with manufacturing tape a force must be applied to activate the tape and hold the part securely. The issue with double-sided tape is that it is often hard to remove your part after milling operation, since there is no release method for the tape. In addition, double-sided tape only works effectively with flat surfaces to

mate to. Double-sided tape also creates difficulty when calculating the actual holding force on a part, since it isn't applying force in an easily measurable way.

Similar to double-sided tape, cyanoacrylate, often abbreviated CA, can also be used to stick parts down for milling operation. CA can be applied to a part to adhere it to another board or material to keep it in place. This allows CA to be used for many different applications provided the cutting forces are not excessive. Unfortunately, CA can be extremely brittle and can break during manufacturing, especially with metal parts that may expand when heated. CA can also leave a residue behind that can be a nuisance to remove after.

Another fixturing method, though not widely used, is wax fixturing. Wax is typically used in one of two ways. The first is coating a part in wax to prevent marking or deformation from a different fixturing method. This allows delicate parts or soft materials to be machined without worrying about final dimensions or surface roughness. The other typical way wax is used is to prevent drill deflection in hollow parts. A hollow part can be filled with wax to prevent the material from deflecting and snapping the drill or making the hole off center. Wax can also be used to fully fixture parts, but fixturing in this method is often avoided. Fixturing with wax is only really applicable for operations with extremely low impact with parts that have no other possible way to be fixtured. Wax does not provide much holding force, so any operation that puts force on the part being machined can possibly throw something held with just wax.

Vacuum Holding (Typically does not offer location finding)

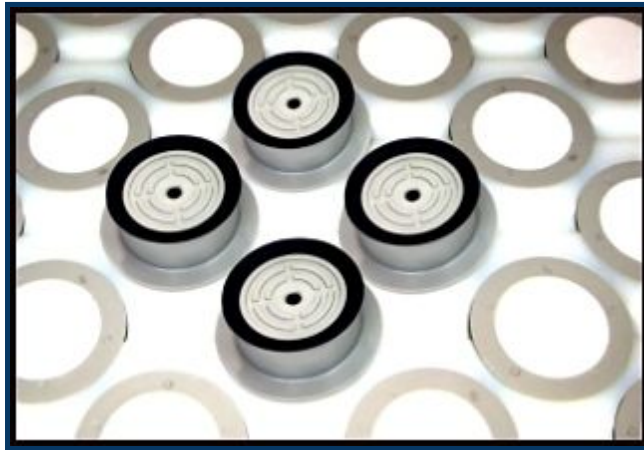


Figure 5: 2D Vacuum Clamps^[10]

Fixturing can also be done using vacuum forces. One of the simplest vacuum fixturing methods is the 2D vacuum clamp. The 2D vacuum clamp is a pod or cup that applies vacuum forces to the bottom of a part. 2D vacuum clamps are extremely easy to set up as they just need to be attached to the table, but are quite expensive to purchase and maintain. 2D vacuum clamps are also limited in their fixturing abilities, as any part to be fixtured in a 2D vacuum clamp must have a flat bottom for the vacuum to seal to.^[11]



Figure 6: 3D Vacuum Clamp^[12]

Another method of vacuum clamping is the 3D vacuum clamp. The 3D vacuum clamp is more versatile than the 2D vacuum clamp as it can be used to fixture parts without flat bottoms and can be adjusted to hold the part in different orientations in the 3D space. The clamps can be moved around the table as needed and the heads can be adjusted to match the contours of the piece that's to be machined. 3D vacuum clamps, like 2D vacuum clamps, are extremely expensive. The clamps are also difficult to set up and write programs for. The problem with being able to be adjusted as needed in 3D space is that there is no way to guarantee that the part to be machined is in the right spot in the right orientation without taking excessive amounts of time to measure and gauge everything. In addition, 3D vacuum clamps could require any operation to be done in 4 or 5 axes to ensure the part is machined properly. This added level of complexity can make 3D vacuum clamps an undesirable fixturing method for most applications.^[13]

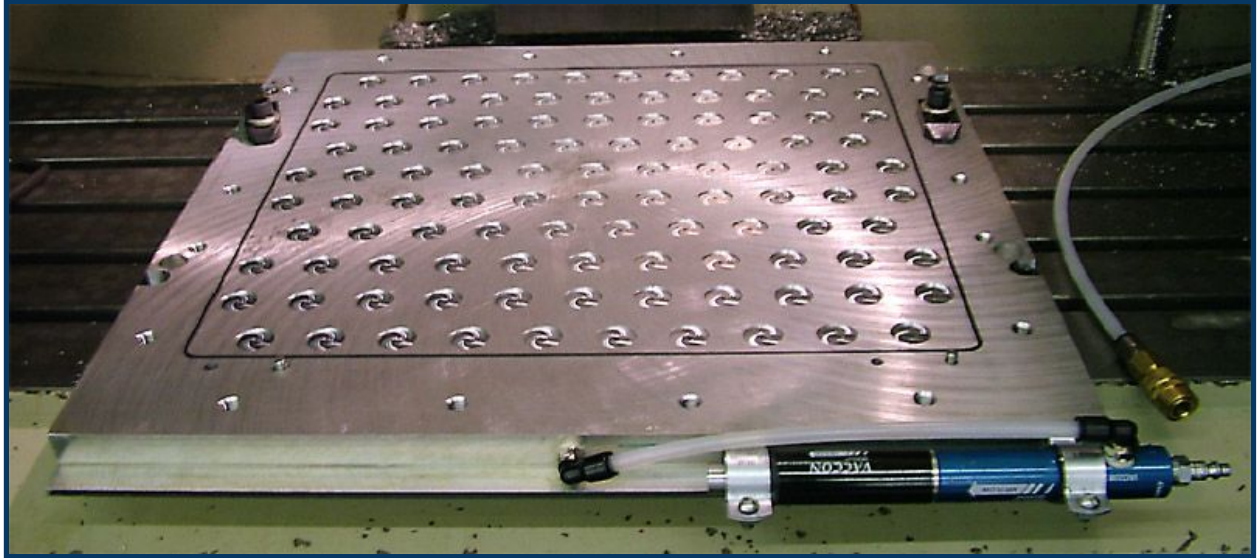


Figure 7: Vacuum Table^[14]

In the same vein as 2D and 3D vacuum clamping, a universal vacuum, or a vacuum table, can be used to fixture parts using a vacuum. The vacuum table is much simpler than the 2D and 3D vacuum clamps, as it doesn't require suction heads and instead uses a plate to hold parts. The parts rest on a plate with many small holes that create a vacuum seal between the part and the plate. This force is enough to hold the part for manufacturing. A vacuum table is often easy to set up but can only be used for parts with flat bottoms. In addition, a vacuum table requires a constant vacuum to hold parts down, as the table provides no additional holding force. If the vacuum is lost for a moment the part will shift.

Approach

Traditional workholding for CNC manufacturing has relied primarily upon parts designed with parallel sides, two-dimensional contours, or flat faces. Abnormal geometry, including three dimensional contours, are difficult and impractical to fixture with traditional work holding techniques, while more advanced methods can achieve these ends, they are often out of reach of hobbyists and small scale production facilities. As such, it became important to identify a method of reusable work-holding that could not only conform to these complex geometries, but also withstand significant machining forces and the harsh environments found in machine tools. Additionally, due to the nature of CNC manufacturing, we decided that a fixture must demonstrate reasonable repeatability and durability over several machining cycles.

In order to be a successful workholding solution, the two factors of location and holding must be addressed. Location consists primarily of holding the part in a position that can be known to the machine. This can be done through adjustability within the solution itself; a common example of this is the tramming of a vise to ensure that the jaws are inline with the axis of the machine. The factor of holding consists of the forces put on the piece and its ability to withstand movement laterally and lifting off of the fixture.^[15]

After reviewing existing conformable workholding methods, we decided that existing technologies could be used to create fixtures. We determined that additive manufacturing is cost effective, highly versatile and accessible making it suitable for conformable fixture design. We hypothesized that a custom fixture coupled with a vacuum to hold the workpiece could serve as a sufficient fixture. The fixture, manufactured on a 3D printer, would be designed to mirror an abnormal part's geometry in a way that soft jaws or other traditionally machined fixtures could not due to the limitations of tool geometry. The workholding devices must be rigid, durable in corrosive environments and reusable, allowing them to produce a uniform part over many

machining cycles. We determined that testing would be done to determine the most appropriate and readily available additive manufacturing materials. Additionally, additive Fused Deposition Modeling (FDM) was explored and was ultimately selected as the category of 3D printer due to the low entry price point and availability.

A 2015 study by Gartner, predicted that by 2019 FDM printers will account for 97.5% of all printers sold. Additionally FDM printers are versatile with the ability to print materials including ABS, PLA, PVA, PET, PET, HIPS and Nylon. We decided that the selection of material could be narrowed to ABS, PLA and Nylon. This selection was made by disregarding those materials designed for specific applications such as food-safe containers or 3D printed support materials. Such filaments were designed to be overly flexible, brittle, or soluble. ABS was selected due to its higher melting point, PLA for its strength, and Nylon for its wear resistance.^[16] We started with extensive testing to select the material of which our fixture would be made of. These preliminary tests would include air permeability testing to determine if the plastic would hold vacuum or if a coating is necessary. Additionally, due to the layered construction of FDM prints, various print coatings were explored with the intention of limiting the loss of pressure through print permeability.

After selecting materials, parts with geometry that limited or eliminated traditional workholding techniques as methods for their manufacturing were selected. The successful manufacturing of these parts through the method detailed in the report determined the feasibility of additive manufacturing for workholding devices.

Methods

The first test of the system consisted of a fully 3D printed fixture for an aluminum hemisphere. From there, to address several issues that arose in the proof of concept, we developed a fixture plate which prints could be positioned in. With that, we began testing materials for our 3D prints. After visual inspection of the prints, coatings were selected and tested to improve the seal and friction. A vacuum test was conducted with sample parts to establish what coating seals the prints most effectively. From there, measurements were taken to find how thick each coating is. With that, the coefficient of static friction was found for each coating. With this data we moved into machining tests starting with an engraving operation utilizing various types of seals. From there we moved into a slotting operation that was slightly more rigorous. Our final test consisted of facing off the underside of a pyramid.

Hemisphere Proof of Concept

As a proof of concept, we devised a test of a hemisphere in a 3D printed vacuum mold. A 2.5" diameter hemisphere was machined and placed into a 3D printed mold of 2.5" diameter which had holes placed in an octagonal pattern inside the mold. The holes were connected to a ¼ hp 1 stage vacuum pump via .2" interior diameter tubing as a member of the team attempted to remove the hemisphere from the mold.



Figure 8: Hemisphere Proof of Concept

Fixture Plate

To address the issues that became apparent in the first proof of concept, a universal fixture plate was designed. The plate was designed to be fixturable using t-slots or a vice and was constructed with 1" thick walls and 4130 steel. A pocket was placed in the center of the plate where the 3D printed fixture would sit on a .5" lip. Beneath the lip was placed another small pocket connected via a hole in the side of the fixture to a vacuum. This pocket was designed to disperse the vacuum to the through holes in the bottom of the 3D printed fixture. The 3D printed fixtures themselves were printed with both ABS and PLA.

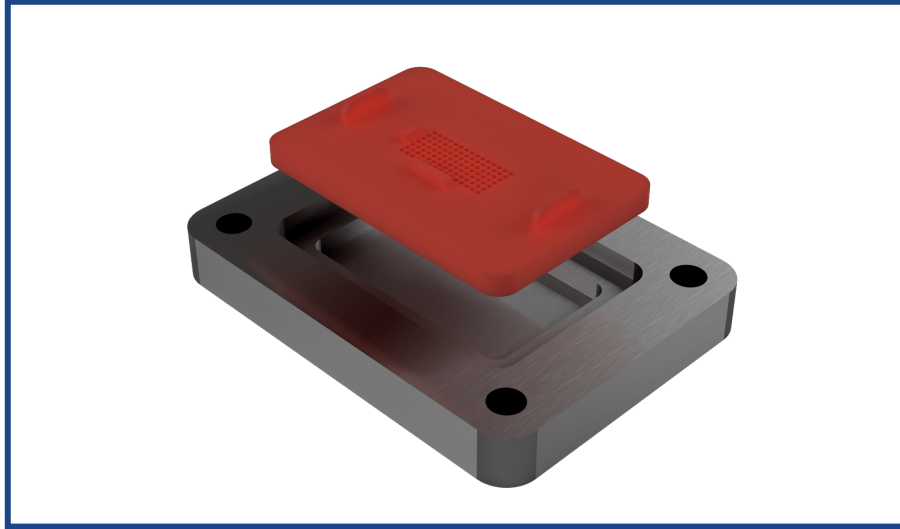


Figure 9: Fixture Plate - Initial Design

3D Printing Materials Testing

We decided to compare two common FDM 3D printing filaments to determine which had attributes that were most beneficial for the application of 3D printed workholding. PLA and ABS samples were printed.

Two test prints of the business card fixture were printed in both PLA and ABS. infill was set to 80% and layer height was set to 0.2mm. Both parts were fitted to the base plate and a vacuum was applied.

Part Coating Materials Testing

Following the initial proof of concept, several test were conducted to determine if a material existed that could potentially seal the print to the plate and seal the print itself. Three easily accessible and affordable substances were selected: spray paint, XTC 3D (A commercially available 3D print epoxy coating), and spray on Plastidip. A test of each materials effect on the permeability of the 3D printed part and its ability to hold a vacuum was conducted.

Additionally the coefficient of friction for each coating when applied to a 3D printed sample was calculated as well as the thickness of the coating. These three properties were measure to determine which material most effectively increased the 3D printed fixtures ability to hold a part.

Vacuum Test

Five 2" OD hollow cylinders with wall thickness of 1/4" and 1/4"-20 threaded ports at one end were printed out of PLA at a resolution of 0.2 mm layer height and 80% infill. The ports were attached to a vacuum pump, via a 1/4 barb in series with 1/4 ID pneumatic tubing. Also in series were a vacuum pressure gauge and a ball valve. Each sample corresponded to one of the 3 coatings mentioned earlier as well as an uncoated sample as control. Additionally one sample was coated in Plastidip while negatively pressurized in order to draw the coating into the pores of the print. Each of the five samples was brought to a pressure of at least -28 in Hg or when the reading on the pressure gauge stabilized. The initial gauge reading was recorded. Once the pressure was stable, the ball valve was closed, separating the vacuum from the system. Pressure could at this point only escape from the printed part. The threaded port in the sample was fully sealed so that a only negligible amount of air could escape at the connection. A timer was set to record the time for each sample from the time that the ball valved closed to the time at which the gauge read 5 in.-Hg. Figure 20 shows a summary of the results of that test.

Print Material	Coating Material	Number of Tests
PLA	None (Control)	1
PLA	Plastidip	1
PLA	Spray paint	1

PLA	XTC3D	1
PLA	Plastidip (Under Vacuum)	1

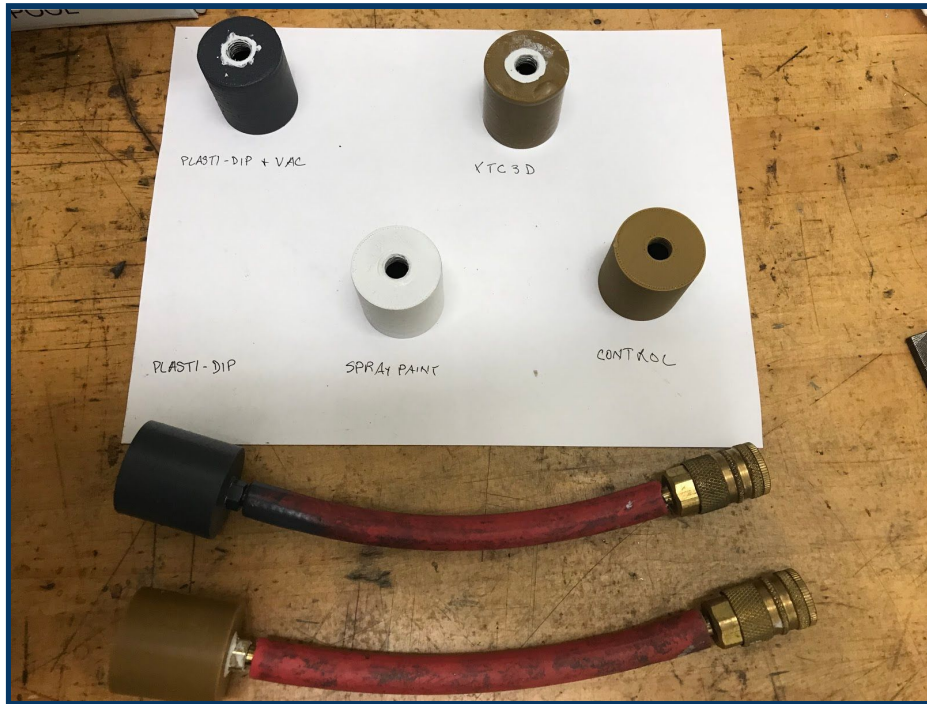


Figure 10: Vacuum Test Pieces

Coating Thickness Test

It was decided that the thickness of each coating should be measured to ensure a tight part fit. Four test samples were printed of rectangular geometry. The samples were designed such that they could be connected to a weight via a string for a test of static friction. Each test piece was measured 5 times with calipers to get an average control measurement for the part. Due to the inherent nature of FDM printing, faces printed horizontally and vertically have significantly different surface finishes. As such, measurements were taken between two parallel

faces on two adjacent sides of the samples as indicated in Figure 4. Each test piece was coated on 1 side on either the top or bottom with a single coating. After allowing the coatings to set for 24 hours, dimensions were measured and recorded. The samples coated in spray paint and Plastidip were then coated again to ensure a complete coating. After drying the test pieces were measured again in the same manner as before. The change in dimension between each step was used to calculate the average layer thickness for each material.

Print Material	Coating Material	Number of Tests	Number of Measurements
PLA	Plastidip	1	5
PLA	Spray Paint	1	5
PLA	XTC3D	1	5

Coefficient of Static Friction Test

It was decided that the coefficient of static friction would be important for a vacuum workholding device. A greater coefficient of friction would correspond to a fixtures ability to withstand larger forces in the x and y axis. Samples from the previous layer thickness tests were placed on horizontal aluminum surface. A 500g mass was placed on the back of each sample as a way of increasing the normal force for a more accurate result. The sample was then connected to a hanging mass via a pulley and string. The mass on the string was increased until the sample moved across the surface. The values of the mass at the moment when the sample began to move was used to calculate the coefficient of static friction ($F_s = \mu_s N$) for each of the coated samples as well as a control sample with no coating.

Print Material	Coating Material	Number of Tests
PLA	Plastidip	1
PLA	Spray Paint	1
PLA	XTC3D	1

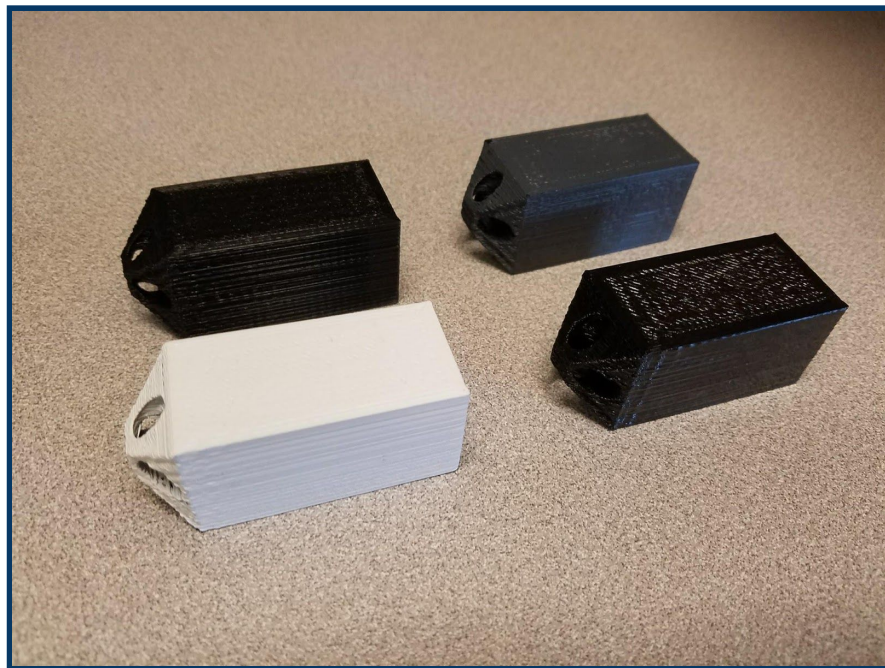


Figure 11: Layer Thickness/Coefficient of Static Friction Test Pieces



Figure 12: Coefficient of Static Friction Test Setup

Final Observations

Based on the results of each test, the team was able to select Plastidip as the coating with the most promising properties for vacuum workholding. Plastidip has an average static coefficient of friction of each measured side of .615 compared to the next best of .345 with spray paint. Additionally plastidip received a relatively high score for the times vacuum trials of 21.32 seconds without a vacuum while the coating was applied and 129.35 seconds with a vacuum when the coating was applied. It was noted after the coating layer thickness tests, that the change in the geometry of any part was negligible.

Machine Testing

Using the results from our prior tests, we moved into the machine testing stage which consisted of testing real world scenarios and the usage of the workholding method. The first test consisted of a small 1" x 2" stamping blank engraved with the letters "MQP". The second test was a pocketing operation through the stamping blank. The final test was facing off the bottom side of a pyramid. These tests increased in rigour with each new test being an increase in difficulty.

Business Card - Proof of Concept Engraving



Figure 13: Finished Engraving Operation

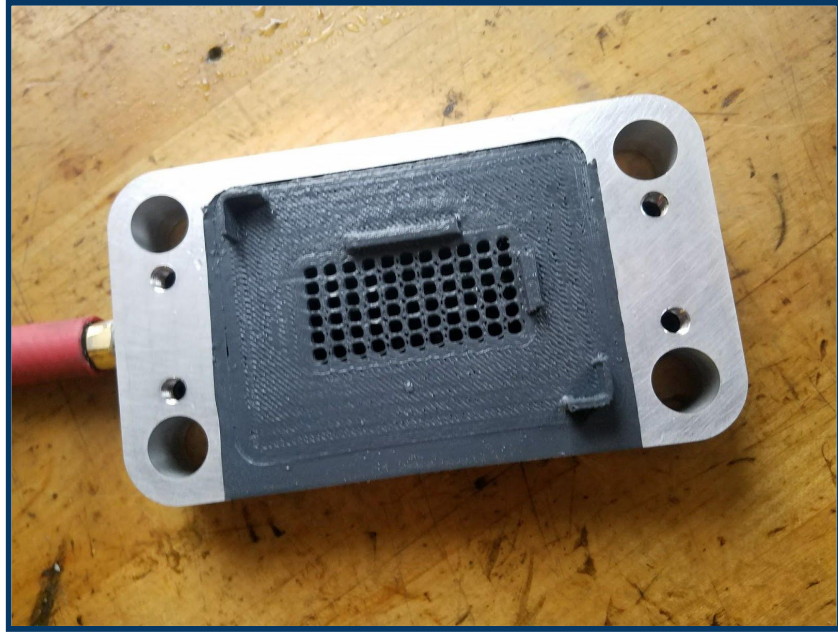


Figure 14: Business Card - Proof of Concept Engraving - First Design

The business card part was tested with a standard engraving operation as seen in Figure 13. This part could already be fixtured using a traditional vacuum table, however, it provides a proof of concept for the method itself. The first trial would consist of a solid fill PLA print, which was coated in plastidip while in the fixture plate. The engraving operation was a standard 0.005" engraving at 40 inches per minute with an engraving tool.

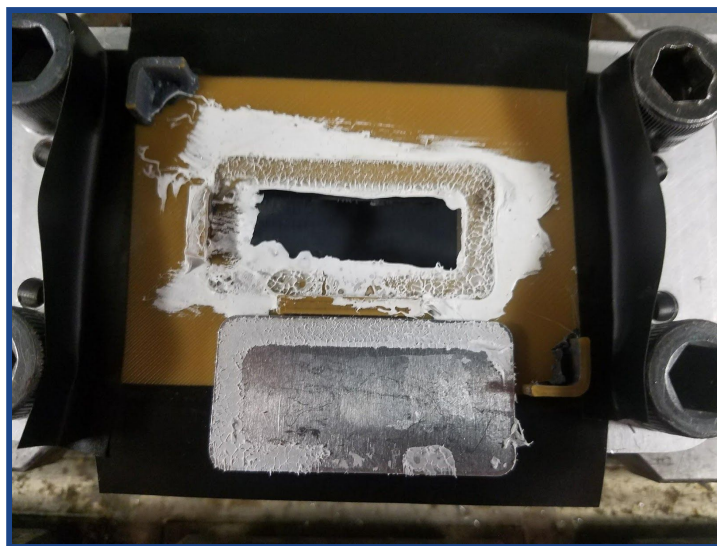


Figure 15: Business Card - Proof of Concept Engraving - Second Design

The second test consisted of a strict focus on generating a tight seal to see if under ideal circumstances, the part would hold. The first step in this process was redesigning the fixture plate so that there was a larger overlap between the print and the part. The next change made was to use liquid teflon as our sealing agent between the blank and the fixture.. Liquid teflon was applied between the bottom and edges of the part and the fixture. The agent was allowed to set for at least 12 hours.

The third test consisted of using duct tape across the overlap between the print and the part to create a seal, This method worked rather well, achieving a similar standard of vacuum and was used to engrave a part.

After developing a method to create a gasket using Plastidip, test were reconducted.

Business Card - Pocket Through Test

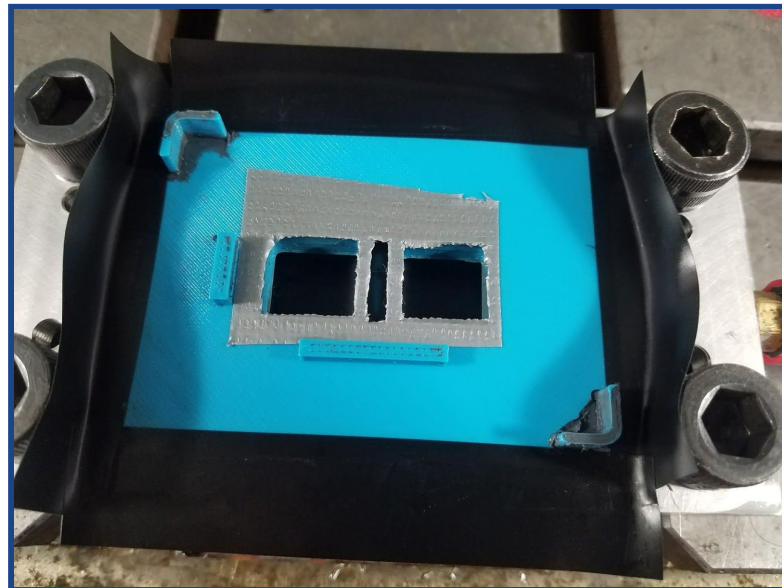


Figure 16: Business Card - Pocket Through Fixture

This test consisted of making a small slot in the workpiece using an $\frac{1}{8}$ " endmill. A number of test samples were collected, including pocketing at reduced cutting rates, and step down settings. Additionally a number of coolants were compared including air coolant, flood coolant, and denatured alcohol. An in line filter was also added between the fixture and vacuum pump in order to prevent coolant from entering the pump.

Pyramid - Facing Test

After success with the engraving parts, the final test was of the more complex pyramid part. An inverse pyramid fixture was designed with four pocket holes and a center hole. The center hole, for the very tip of the pyramid, allowed for the part to sit on the sides rather than having a contact point at the tip. The 3D printed fixture was placed into the fixture plate and was coated with Plastidip. The pyramid part was then placed into the fixture and the whole assembly was then sprayed again, creating a gasket and edges around the part. Figures 17 and 18 show the fixture as well as the assembly.

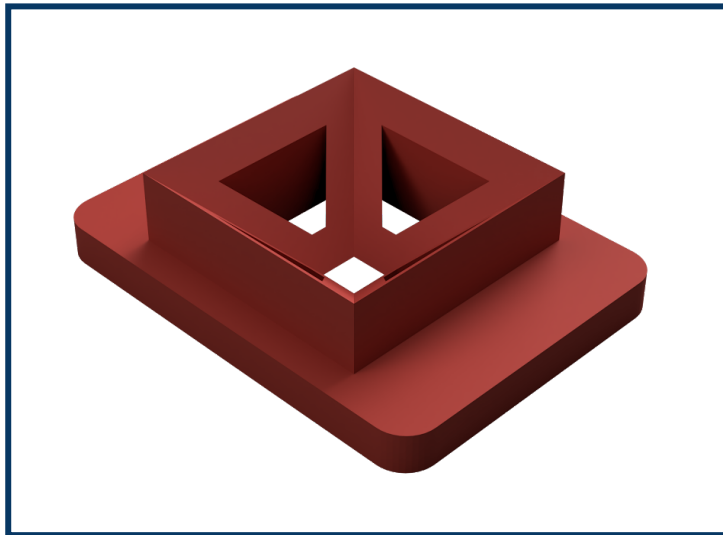


Figure 17: Pyramid - Facing Fixture

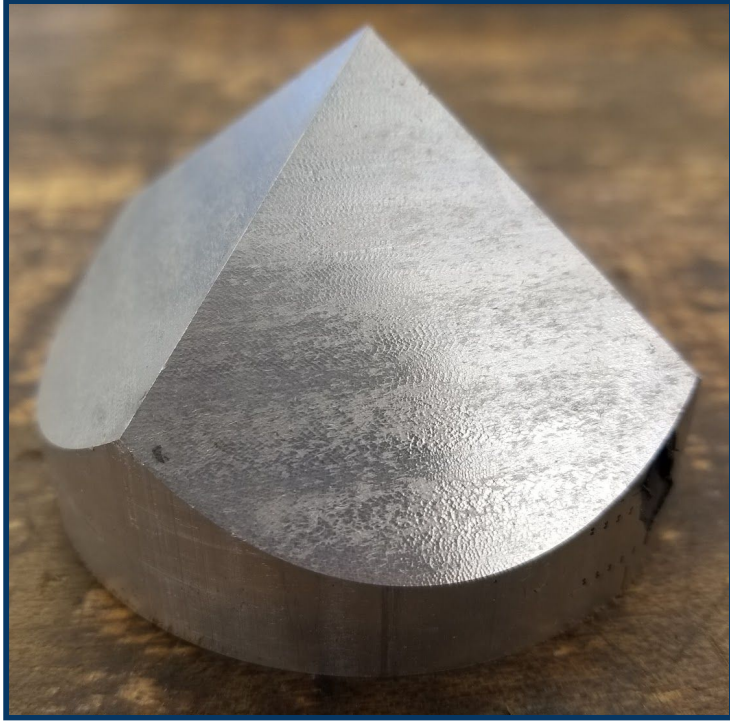


Figure 18: Pyramid Facing Test - Finished Part

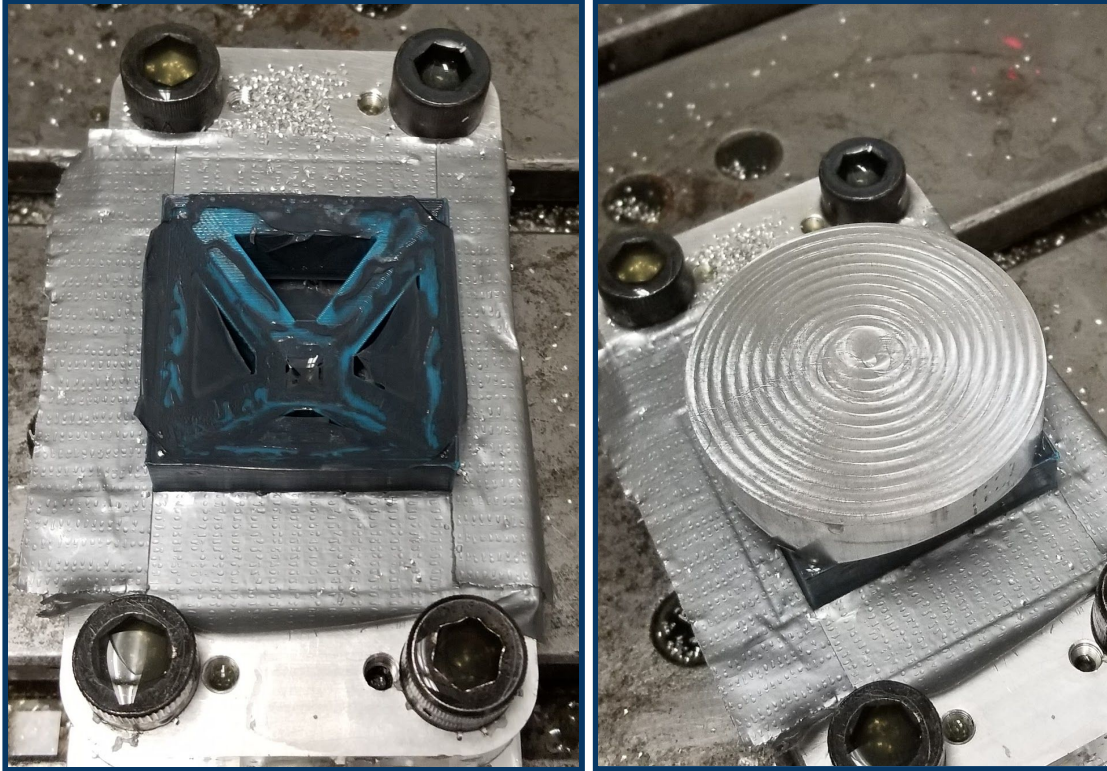


Figure 19: Pyramid Facing Test - Fixture Assembly

A concentric in cylindrical facing operation was done at standard speeds and feeds for a .125 inch step down. A cylindrical pattern tested the fixtures ability to withstand rotational forces as well as forces along the z axis of the machine. This test was conducted multiple times to ensure the fixtures durability.

Results

Hemisphere Proof of Concept

The observational data from this test showed that the print was easily removed or moved out of alignment with minimal force. Considering that movement during machining would result in a failed part, this method was deemed a failure.

Fixture Plate

The introduction of the fixture plate eliminated some of the issues we were encountering in a fully 3D printed fixture. Potential areas of concern were more readily visible and could be managed and dealt with while within the machine.

3D Printing Materials Testing

Visual observation of the print revealed that both nylon and ABS had warped significantly more than PLA under the same print conditions. Additionally both materials required higher heat and, on the printer available to the team, nylon prints commonly had layer separation.

After applying the business card it was observed that neither print was able to hold vacuum. Examination revealed that the seal between the printed part and the fixture plate along with the inherent permeability of 3D printed parts was to blame. Two observational experiments were conducted to determine if a method of sealing the print existed. ABS is soluble in acetone. The ABS print was submerged into a container of Acetone for approximately 2 seconds. The ABS print was then allowed to dry and then placed into the fixture plate. Duct Tape was placed

around the outside edges to seal the two parts, allowing air to only pass through the holes in the 3D printed part. When the business card blank was placed onto the fixture a vacuum was observed, however warping as a result of the acetone treatment was observed. When the PLA print without the acetone treatment was placed into the fixture plate under the same condition, no vacuum was observed and the fixture was unable to hold the part.

Part Coating Materials Testing

Vacuum Test

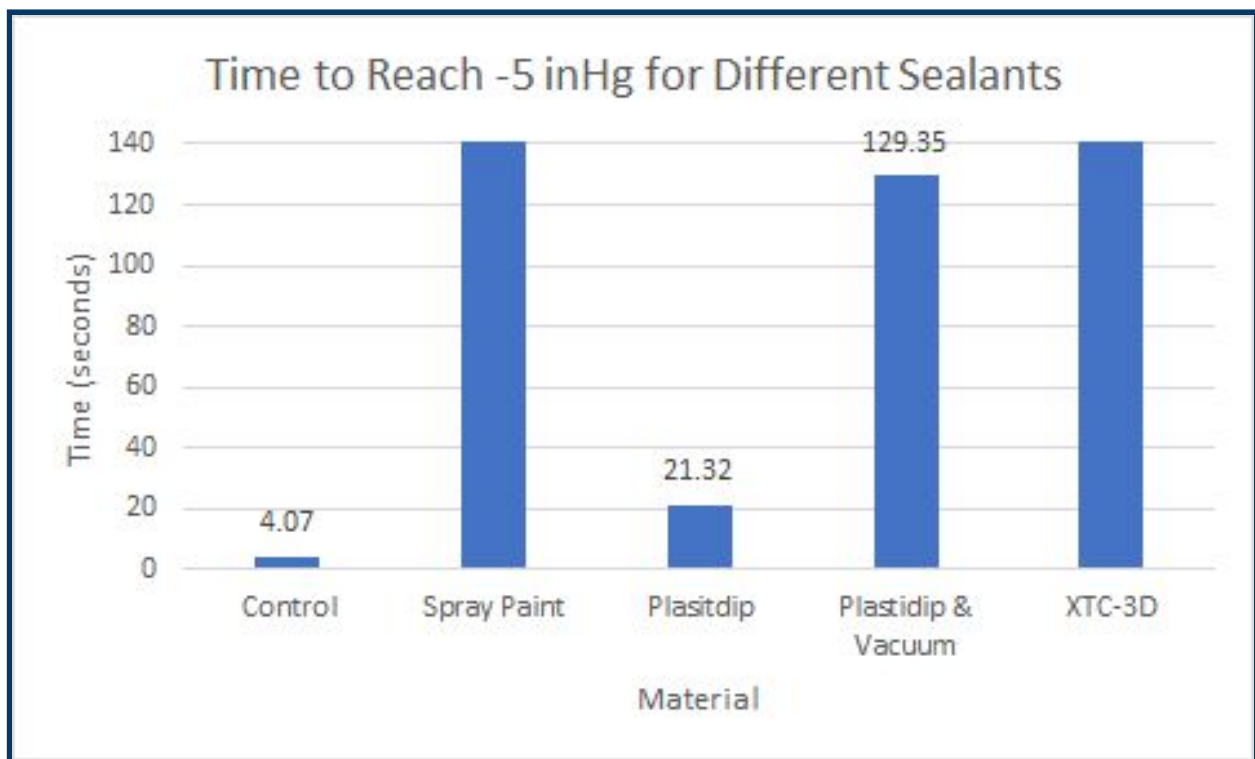


Figure 20: Vacuum Test - Experimental Results

From our vacuum test we wanted to identify which available coating would provide the largest improvement in sealing our part to hold a vacuum. Coating our material would fill the pores of the part in such a way that a vacuum could be held longer than with the bare, porous 3D printed part. For this test we tested a control 3D printed part, spray paint, Plastidip, Plastidip applied while holding a vacuum, and XTC-3D. The control piece we tested took only 4.07 seconds to reach -5 inHg. This result was in line with our expectations, considering PLA is naturally porous. The test piece coated in Plastidip took 21.32 seconds to reach -5 inHg. When applied while holding a vacuum, Plastidip took 129.35 seconds to reach -5 inHg. These results show that Plastidip is a reasonably effective coating for our application. Plastidip on its own improves the effectiveness of the printed part in regards to holding a vacuum by a factor of 4. If applied while holding a vacuum the Plastidip will be able to fill the printed parts pores even more effectively, improving the effectiveness of the printed part in regards to holding a vacuum by a factor of 32. The results for spray paint and XTC-3D were inconclusive due to their effectiveness in improving the vacuum hold of our test parts. For both spray paint and XTC-3D, the vacuum being held by our test parts was not significantly lost over an extended period of time. The needle on the vacuum gauge did not significantly move from the maximum value over a period of 10 minutes. It was concluded that spray paint and XTC-3D were effective enough that they would hold a sufficient vacuum.

Coating Thickness Test

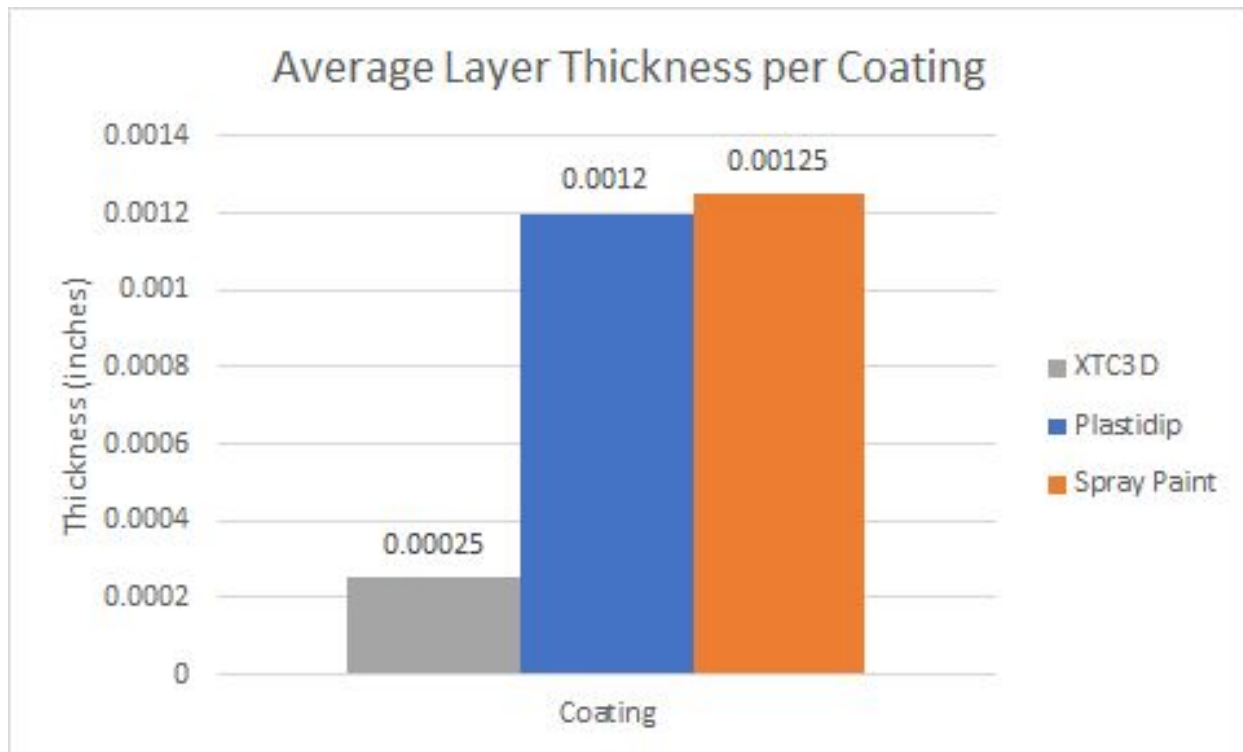


Figure 21: Coating Thickness Test - Experimental Data

From our layer thickness test we wanted to identify the thickness per layer of each coating we could add to our parts. Understanding the thickness of each material is important to making sure the fixtures we create are the correct size for our applications. Ideally each fixture can be designed to the correct size for the specific part it will be holding and the coating applied to it will not provide a change in geometry that is significant enough to affect the seal. 5 measurements were taken for both the top and bottom and the sides of each test piece. The test pieces were then coated on the top and side with a specific coating. Once dry 5 more measurements were taken for both the top and bottom and the sides in the same manner as before. For Plastidip and spray paint a second layer was applied to ensure consistent results. Due to inconsistencies and tolerancing of calipers, some of the measurements taken were inconsistent with what was

expected. With these inconsistencies in mind, the measurements taken were used to calculate the average thickness per 1 layer of each material. Plastidip and spray paint, both applied with a spray can, had a layer thickness of 0.0012” and 0.00125” respectively, while XTC-3D, applied with a brush, had a layer thickness of 0.00025”. This difference in layer thickness may be due to the fact that XTC-3D can be controlled and spread better since it is applied with a brush instead of sprayed on.

Coefficient of Static Friction Test

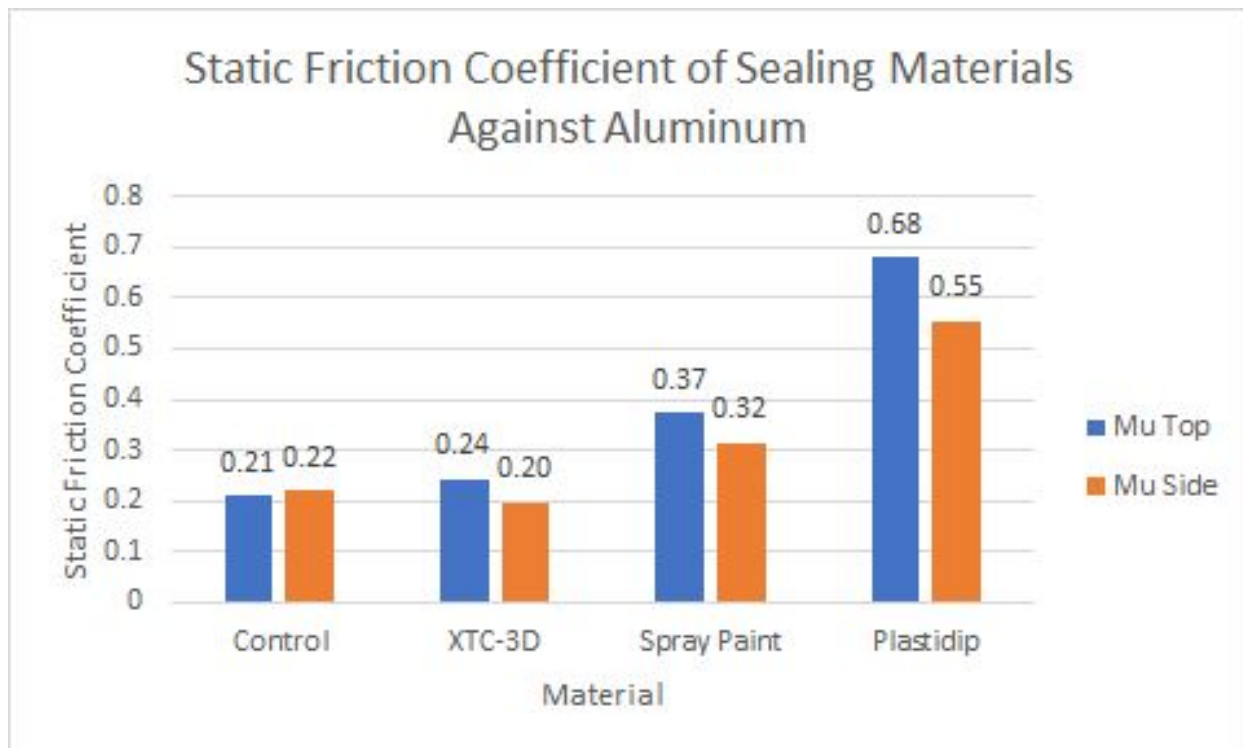


Figure 22: Coefficient of Static Friction Test - Experimental Data

From our static friction coefficient test we wanted to identify which available coating would provide the largest increase in our printed fixtures ability to hold a part with friction.

Machining forces acting in the XY plane would tend to move our part around, so having a coating that helps resist these forces would keep our part in place for proper machining. The static friction coefficients we found are for PLA with the listed coating against aluminum. For this test we coated the side and top of each test piece to get a better idea of the changes in static friction coefficient. Since 3D printers print in layers, the sides of a part will be layered and rough while the top and bottom of a part will be smooth and solid. In theory, this difference will result in different static friction coefficients for our parts. The results for this test showed that Plastidip provided the largest increase in static friction coefficient, effectively tripling the static friction coefficient for our test piece. Spray paint was the next most effective material and almost doubled the static friction coefficient of our test piece. XTC-3D was found to be ineffective as it slightly increased the static friction coefficient for the top of the part but lowered it for the sides of the part. This result is in line with our theory for this experiment. Since the sides of the test parts are layered and rough, some sealants will result in the surface being smoother than it was before.

Final Observations

With each of our tests resulting in a different coating being considered optimal, it is important to consider all of these tests together along with any observations taken during testing in regards to our coatings. When applying the coatings to our test parts it was found that XTC-3D is significantly more difficult to manage than spray paint or Plastidip. XTC-3D requires a mixture of two components at a certain ratio to create a batch of XTC-3D. Once created, XTC-3D begins hardening quickly and will be unusable for future applications. Because of this, any excess XTC-3D will have to be disposed and any brushes or tools used to apply it need to be immediately and thoroughly cleaned or they can become unusable. Spray paint and Plastidip

are applied with a spray can, making them much easier to manage and apply. Applying a material with a spray can does make it slightly more difficult to control the thickness of the coating being applied, but the results of the layer thickness test point to this thickness being easy to account for.

The purpose of coating our 3D printed part is to improve the parts ability to hold a workpiece in place for machining. With this in mind the effect a coating has on all three axes must be considered when identifying which coating is the most effective. Between spray paint and Plastidip, spray paint would provide a better holding force in the Z direction, but Plastidip would provide a better holding force in the XY plane. Since our 3D printed parts will not need to hold a vacuum indefinitely, but instead will be vacuum sealed with a pump, the difference between Plastidip and spray paint holding forces in the Z direction can be treated with less importance than the holding forces in the XY plane. Plastidips static friction coefficient should provide enough holding force in the XY plane to make up for what the material lacks in vacuum seal.

An additional concern that can be addressed by Plastidip is sealing the edges of our 3D printed part in our aluminum fixture plate. Without the edges between these parts being sealed properly, a seal will not be created by our vacuum pump and our part will not be held down with a force strong enough to keep it in place. Plastidip, since it's a spray-on rubber coating, can be easily removed from a surface it was applied to. This allows us to spray Plastidip over our 3D printed part while it is in our aluminum fixture plate to coat our part and create a seal between the part and the plate and then remove the coating of Plastidip when we wish to remove the 3D printed part from the fixture plate.

After considering the results of all tests conducted as well as observations made during testing, Plastidip was chosen as the best coating for our purposes.

Machine Testing

Business Card - Proof of Concept Engraving

The first machining test we conducted involved engraving the letters “MQP” on a 1” x 2” x 1/8” aluminum punching blank. This operation would be possible to do on the average vacuum table and was designed specifically to test if our fixturing method would work for even the simplest of applications.

After a number of trials, it was found that the first fixturing method produced an inadequate holding force even at reduced feed rates, and thus the part was not held in place. Improvements to the seal needed to be made in order to hold the part securely.

During our secondary trials it was noted that the primary source of air leakage was coming from the perimeter of the print where it makes contact with the part. To remedy this, tape was applied around the seam and resulted in an immediate improvement. The part was then leveled on the machine with the leveling set screws and machined. A second part was then put into the nest and machined showing that the process has repeatability. However, the part still showed evidence of adherence after the vacuum was released and teflon was found on the part which indicates that the teflon was also acting as an adhesive, undermining the purpose of our tests.

With our fixturing method we were able to successfully and cleanly finish our engraving operation, demonstrating that our fixturing method could complete operations that a vacuum table would be used for and that our fixturing method works to some extent.



Figure 23: Business Card - Engraving Proof of Concept - Finished Part

Business Card - Pocket Through Test

The second machining test we conducted involved creating a .15" x .75" slot through our aluminum punching blanks. The purpose of this test was to successfully machine a part that could not be done with a simple vacuum table and achieve our goal of machining a part with abnormal geometry.

From this test we found that a trickle of flood coolant, along with reduced cutting rates and step down provided the best surface finish and prevented the piece from moving. Additionally, we discovered that while a layer of duct tape underneath the contact surfaces of the part acted as an ideal gasket, it was unable to conform to more complex surfaces with intricate geometry and contours.

With our fixturing method we were able to successfully pocket through our part. This part could not be completed with a vacuum table because the pocket through the part would break the seal created by the vacuum, releasing the part. Since fixturing this part in a vice would cause large deformation, the fixturing method we created for this abnormal part is the most reasonable for this type of operation.



Figure 24: Business Card - Pocket Through Test - Finished Part

Pyramid - Facing Test

The third machining test we conducted involved facing excess material off of the bottom of a pyramid created using 2.5" diameter aluminum bar stock. There are currently no traditional fixturing methods that are capable of holding a pyramid in place while machining due to the four

sloped sides. Succeeding in this test would prove our fixturing method capable of holding parts with abnormal geometry that are more complex than the part used in the previous test.

With our fixturing method we were able to successfully face the bottom of the pyramid stock.

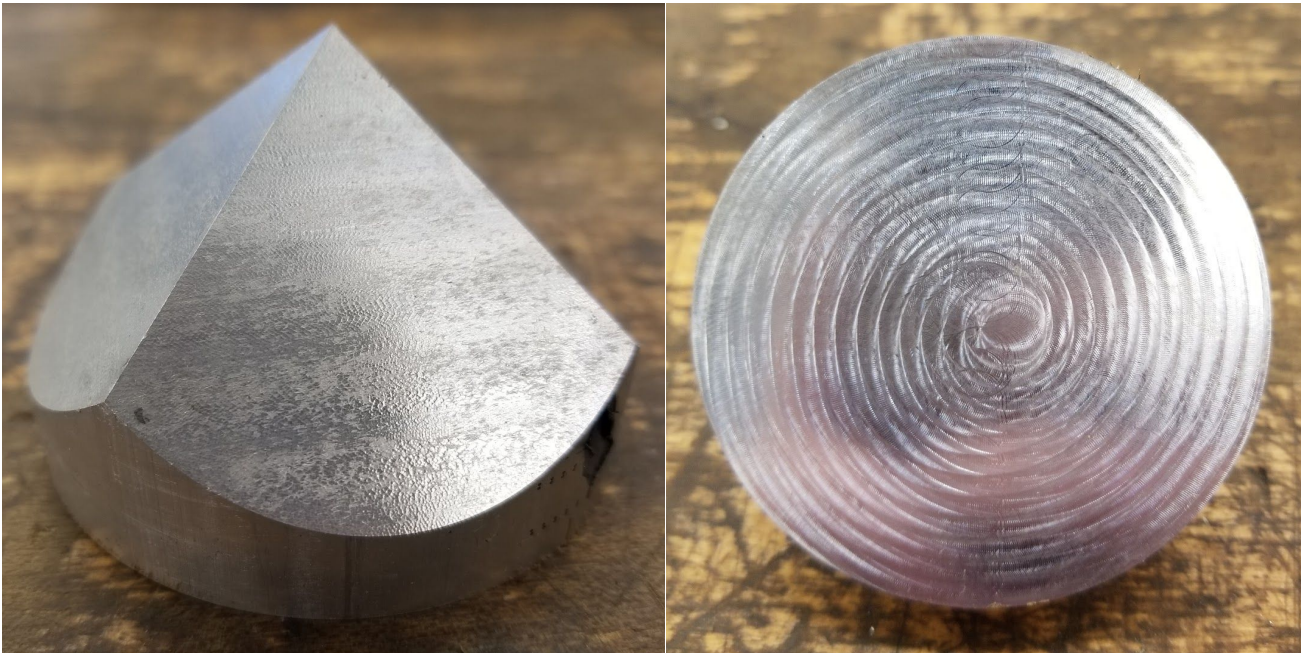


Figure 25: Pyramid - Facing Test - Finished Part

Discussion

Hemisphere Proof of Concept

The minimal inaccuracy of the print caused the sphere to not sit properly in the mold which caused a loss of pressure. A loss of pressure due to the permeability of 3D printed materials was also noted. Additionally the inherent weakness of a 3D printed part limited the possibilities for fixturing the mold itself into a mill as vice or t-slot bolts would cause plastic deformation or fracturing of the fixture.

Following the proof of concept it was decided that the hemisphere part was impractical as a preliminary test part for the 3D printed fixtures. A pyramid was decided as an alternative test part. This part would prove the ultimate versatility of a 3D printed fixture with interior corners that are difficult to machine yet easy to 3D print for a mold of the part. It was therefore decided that the two parts that would test the technology were the business card engraving, to prove the concept; and the pyramid, to show the capabilities.

Fixture Plate

The first adjustment made was to reduce the size of the plate to match the size of the parts that were to be tested as well as reduce printing times. Three leveling set screws were added to compensate for the inherent inaccuracy of 3D prints and insure that fixtured material could be squared relative to the machine tool. These three set screws could be adjusted along with the force of the T-slot bolts, which held the plate to the machine table, in order to change the position of the fixture, rotating about the x and y axis. The second generation of the universal fixture plate was manufactured out of 6061 aluminum. The smaller footprint allowed us

to use smaller 3D prints, cutting down on print time and material use. A final generation of the fixture plate was made with four set screws and a base plate. The base plate allowed for the set screws to make contact with a surface other than the T-slots below.

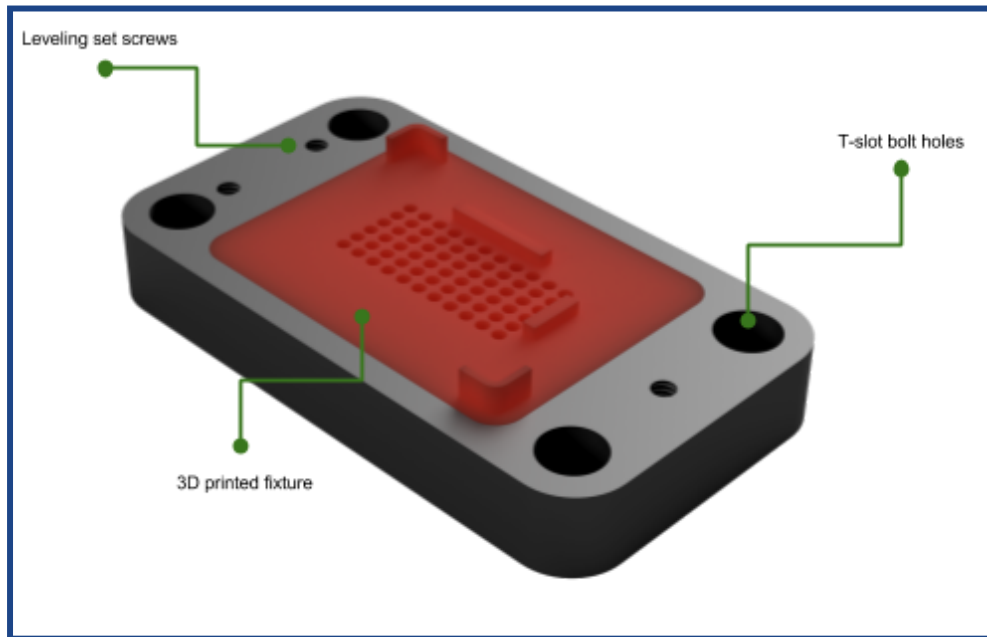


Figure 26: Fixture Plate Assembly



Figure 27: A comparison of our first fixture plate design (left) and our final fixture plate design (right)

3D Printing Materials Testing

As a result of this testing, it was determined that some chemical treatment or coating must be applied to the print to overcome the permeability of FDM prints. At this point it was also decided that ABS as a printing medium could be eliminated as it was subject to warping both during printing and during treatment, the scale of which would make accurate and repeatable workholding unlikely.

Part Coatings Materials Testing

Vacuum Test

The purpose of this test was to determine which of our available coatings would provide the greatest seal on our part and allow us to hold a vacuum for longer. The test focused on the duration a vacuum was held with each coating. Though our fixturing method works with a vacuum being applied constantly, this test demonstrates how effective each sealant is at permeating the 3D printed plastic. The more our sealant permeates the plastic and fills gaps in the material, the stronger and more effective the vacuum seal would be for our fixture. In this regard, spray paint and XTC-3D are the best sealants.

In terms of the overall impact of this test, the vacuum test received our middle priority when choosing a material. The test provided useful insights into the effectiveness of each of our coatings, but we ultimately believed that the differences in sealing ability would not majorly affect our large-scale tests. We instead chose to favor the coefficient of static friction test when choosing our sealant.

Based on the results of this test, the material we would choose for our coating would be spray paint. Though spray paint and XTC-3D had the same results in this test, spray paint is significantly easier to apply to a part than XTC-3D, making it a more manageable coating.

Coating Thickness Test

This test was used to determine which of our coatings would be most effective at reducing potential lateral movement of the workpiece in the nest. This test was done with coated

samples of our 3D printed plastic across aluminum. Adding weight, which transitioned to horizontal force to the sample, demonstrated how much the sample was able to resist lateral movement. This test ended up receiving a higher priority in selecting a coating due to the large jump in friction coefficient when using the plastidip coating.

Based on these results we would choose XTC-3D as our coating since it would provide the least change in geometry for our test pieces. The closer the coated test piece is to the original geometry the less adjustment needs to be made to compensate.

Coefficient of Static Friction Test

We used this test to find if a coating would substantially alter the geometric shape of a 3D printed object. In the end, the XTC-3D had a minimal layer thickness which was about a quarter of the thickness of the other two coatings. There was also a rather large standard deviation of 0.00095 in the 3D print itself and in terms of measurement. What this shows is that while a coating does increase the thickness of the part, the the overall variance due to the print itself can be a larger, less consistent factor in the final shape. Because of this, the layer thickness was given our lowest priority.

Based on the results of this test, the material we would choose for our coating would be Plastidip.

Final Observations

Based on the results of each test, the team was able to select Plastidip as the coating with the most promising properties for vacuum workholding. Plastidip has an average static coefficient of friction of each measured side of .615 compared to the next best of .345 with spray paint. Additionally plasti dip received a relatively high score for the times vacuum trials of 21.32

seconds without a vacuum while the coating was applied and 129.35 seconds with a vacuum when the coating was applied. It was noted after the coating layer thickness tests, that the change in the geometry of any part was negligible.

Machine Testing

Business Card - Proof of Concept Engraving

The purpose of this test was simply to identify if our fixturing method could serve the same purpose as the closest, similar fixturing method: a vacuum table. The operation done for this test was a simple engraving operation of the letters "MQP". This operation could easily be done on a vacuum table as the engraving of these letters would not interfere with the hold of the vacuum table. We believed it was important for us to attempt something this simple in an effort to prove that our fixturing method worked in some capacity.

From the first few attempts of this operation we identified a minor issue in our fixturing method. The seal of our vacuum was getting ruined by a poor seal around the edge of the part we wanted to machine. Because of the inconsistencies in the thickness of a coating of Plastidip, the seal around the edges of our part was inconsistent and insufficient. This caused our part to be shifted by our engraving operation. In order to combat this we needed to quickly explore methods for sealing the edges of the part we are machining. The quick and temporary solution we came to was to place a piece of duct tape over the vacuum pocket and then cut out the duct tape covering the pocket. This very minor change increased the seal around our part to the point where it could be machined properly. This solution works well for flat parts but would not be possible for a part with geometry that isn't flat. In an attempt to get a similar seal that could

possibly adapt to geometry, we used Plastidip to create what was effectively a gasket around our part. After an initial coating of Plastidip had been applied to our part, the aluminum blank was placed on the 3D printed fixture as it would be machined. We then applied a second coating of Plastidip over the blank. This second coating, once dried, would hopefully seal the blank in a way similar to the duct tape used previously while also providing the added versatility of being able to conform to different geometry. The part could then be removed leaving behind a more closely molded nest with a structure provided by the print and an airtight seal provided by the Plastidip.

This method of sealing the edge of our part was tested with the previous parts as well. With it, we achieved better results than when we used just duct tape, as the vacuum being held by the system improved by roughly 2 inHg. We then applied to the other parts we attempted to machine.

Business Card - Pocketing Through Test

The purpose of this test was to create a fixturing method for an operation that can not be easily performed with traditional fixturing methods. The idea was to cut a small pocket through thin pieces of sheet metal. Currently the most reasonable way to perform this operation would be to use a sacrificial plate, a piece of material that the workpiece is attached to having the express purpose of being machined instead of the mill table. Attaching a workpiece to a sacrificial plate requires some method of workholding that could damage or alter the workpiece. Typically this is done by drilling holes through both the workpiece and sacrificial plate and then bolting them together. This method of machining through a piece of sheet metal is really only useful when holes are already needed in the workpiece or if the workpiece can be machined

after to remove the bored holes. Being able to complete this operation with our fixturing method would achieve our goal of creating a fixturing method for work pieces with abnormal geometry.

In order to create a seal around our part with the coating we had chosen, we needed to revise how we coated our piece with Plastidip. Plastidip was allowed to dry with the part in place, creating a gasket with edges contouring to the shape of the part. A Plastidip layer was applied underneath the part. The part was then placed into the fixture and additional Plastidip was sprayed around it. The fixture was then allowed to set for 24 hours. This solution allowed the plastidip gasket to set while in contact with the part, insuring that the edges of the part were uniform to the gasket.

Using the previous fixturing method, we were able to complete a simple machining operation on our workpiece after multiple attempts. During this test we discovered that we needed some way too cool our workpiece as it was machined. The pocketing operation created enough heat that the Plastidip and tape we used to seal our part were beginning to melt and ruin our seal. In addition, chip buildup caused the tool we were using to move our part during our operations. The typical solution to these problems is to use coolant when machining. The issue with using coolant is that the WPI Manufacturing Labs currently only has flood coolant set up. Before resorting to flood coolant, which could get into our pump system and ruin our vacuum seal, we tried different methods of cooling our workpiece.

The two other methods we tried were denatured alcohol and air cooling. Denatured alcohol was applied to our part and fixture with a squeeze bottle before machining. The alcohol was able to cool the workpiece enough to be machined fully, but left the pocket with a terrible surface finish from being heated up. Air cooling was found to have a negligible effect on our workpiece when machining and the test pieces were not able to be machined fully before coming of the fixture. Combining air cooling and denatured alcohol was ruled out, as the air

blast would blow the denatured alcohol off of the workpiece before machining began. Neither of these alternate methods were found to be effective enough to properly machine our parts. Instead we decided to use flood coolant but choke the flow to the point where coolant wouldn't flood our system and would still cool down our workpiece. As an added measure to keep coolant out of our pump system, a filter was added to the system. This filter would keep coolant out of our pump and could be easily drained after each operation.

With coolant being applied we were able to fully and cleanly machine a small pocket through our workpiece.

Pyramid - Facing Test

The purpose of this operation was to create a fixturing method for a part that cannot be machined using standard fixturing methods. For this operation we machined a square pyramid out of 2.5 inch round stock. Because of a pyramids shape it cannot be fixtured in vice jaws. The only reasonable method for holding a part such as the one we used would be holding the bar stock in a collet. This would leave a section of the round bar stock left at the base of the pyramid and the part could not be flattened out to look like a normal square pyramid. Being able to complete this operation would prove our design is viable for simple parts with abnormal geometry.

Initial test of our fixturing method for this part had a total stock length of 3 inches. The idea behind having a large amount of remaining stock was that it would give us numerous attempts at fine tuning our fixturing method. If the part where to be removed from the fixture during machining, the amount of material that was ruined would be relatively minor, and we would have enough material for more attempts.

The first attempt at facing the bottom of the part was successful, but resulted in an uneven surface finish that revealed there was chatter during the operation. We believed that the weight of the workpiece and the distance of the machining from the fixture plate contributed to this chatter. To compensate we used a bandsaw to remove a large amount of material from the pyramid. This shorter version of our workpiece was machined properly without any chatter, allowing for a clean surface finish that is expected of similar milling operations.

After completing multiple facing operations on the base of our pyramid and proving our fixturing method was successful, we did not continue to machine the workpiece and instead left a portion of the round stock on the base of the pyramid. This was done to ensure we had material to work with if we decided to attempt a more aggressive facing operation or a different operation for this workpiece.

Conclusions

- Plastidip, or a similar spray-on rubber coating, will provide the best combination of vacuum seal and part holding for this application
- The fixturing method we created can be used to machine parts that could normally be machined with a simple vacuum table.
- The fixturing method we created can be used to machine simple parts, such as sheet metal with pockets through it, that cannot be fixtured with traditional fixturing methods.
- The fixturing method we created can be used to machine moderately complex parts, such as a square pyramid, that cannot be fixtured with traditional fixturing methods.

References

- [1] Pachbhai, S. S., & Raut, L. P. (2014). *A Review on Design of Fixtures*. *International Journal of Engineering Research and General Science*, 2(2), 126-146. Retrieved from <http://www.ijergs.org/>
- [2] Tormach. (n.d.). *T Slot Square* [Digital image]. Retrieved from https://www.tormach.com/uploads/images/Gallery/products/workholding/Clamps_Hold-Downs/31855-T-Slot_Square-MG_8197.jpg
- [3] “7 CNC Fixturing Tips for a Small Shop | Make:” *Make: DIY Projects and Ideas for Makers*, 17 June 2016, makezine.com/2016/06/20/7-cnc-fixturing-tips-small-shop/.
- [4] Kurt Workholding. (n.d.). *Kurt DX6* [Digital image]. Retrieved from <https://www.kurtworkholding.com/images/DX6/KURT-DX6-CrossOver-angled-web.jpg>
- [5] Mirco Machine Shop. (n.d.). *5C Collets* [Digital image]. Retrieved from http://www.micro-machine-shop.com/collets_R8_5C_ER40_ER16.jpg
- [6] Riten. (n.d.). *Collet Chucks and Collets*. Retrieved 2015.
- [7] Gaunce, M. (2016, May). *May the force be with you: unlocking the true potential of magnetic workholding for machining mold bases and inserts lies in understanding clamping and machining forces*. *MoldMaking Technology*, 19(5), 22+. Retrieved from http://link.galegroup.com/apps/doc/A453292182/ITOF?u=mlin_c_worpoly&sid=ITOF&xid=147a4ab2
- [8] Koepfer, Chris. “Is Magnetic Workholding For You?” *Modern Machine Shop*, *Modern Machine Shop*, 14 May 2000, www.mmsonline.com/articles/is-magnetic-workholding-for-you.
- [9] OtherMachine. (n.d.). *Tapel* [Digital image]. Retrieved from <https://othermachine.co/assets/tapel.png>
- [10] Carter. (n.d.). *Carter Pod Pannel* [Digital image]. Retrieved from <http://www.carterproducts.com/media/catalog/category/podpanel.jpg>
- [11] “Vacuum Clamping FlipPod™.” *Vacuum Clamp - Vacuum Clamping System & Flip-Pod Components* | Carter Products, www.carterproducts.com/technology/flip-pod-vacuum-clamping-system.

[12] *Schmalz Basic Holding Feature [3D Vacuum Clamp]*. (n.d.). Retrieved from https://www.schmalz.com/media/catalog/category/cache/thumbnail/438x/basic-holding-fixture-bhf-PGE-05243-10-214_D_1010x673_52.jpg

[13] “*J. Schmalz GmbH: Innovative Vacuum Technology from Schmalz.*” > 3D Clamping Solutions | Schmalz, www.schmalz.com/en/vacuum-clamping-technology/3d-clamping-solutions/basic-holding-fixture-bhf.

[14] *CNCCookbook*. (n.d.). *VacTable1 [Digital image]*. Retrieved from <https://www.cnccookbook.com/wp-content/uploads/2017/08/VacTable1.jpg>

[15] *Sridharakeshava, K., & Babu K., R. (2013). A SYSTEMATIC APPROACH TO MILLING FIXTURING DESIGN . IET Conference Proceedings,1-5.*

[16] *All That 3D*. (2017, February 15). *16 Type of 3D Printer Filament | Buyer's Guide and Review 2017*. Retrieved January 22, 2018, from <https://www.allthat3d.com/3d-printer-filament/>

