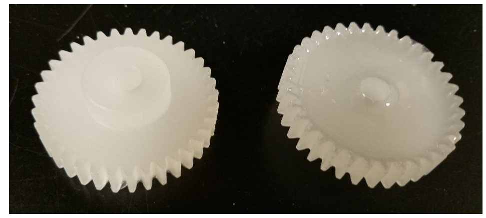
Project: In-House Gear Manufacturing

Description

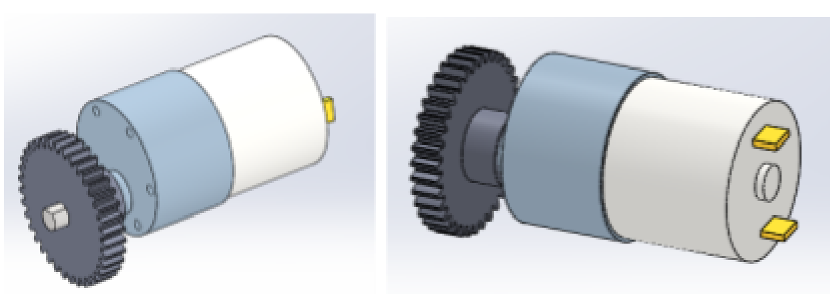


We are part of the mechanical engineering team of a UC Berkeley organization whose mission is to build robotics kits for underrepresented high schools in the Bay Area. The cost of the kits limits the number of teams that we can support each year. This year, we performed a comprehensive analysis of the kit costs and determined that the hub gears (shown on the right) comprise a relatively significant percent of the kit cost. This is the only gear that can be put directly onto the motor. The hub gear's high cost is attributed to the gear's unique design. The shaft diameter is in millimeters due to sourcing the motors abroad, while the pitch diameter is in inches to mesh with our American bought gears. This makes it more expensive to purchase from manufacturers. We are hoping to in-house manufacture our hub gears this year through two potential options: polyurethane molding and laser cutting. Polyurethane is common resin polymer known for its strength and low cost. First, we make a silicone mold of the gear and then pour polyurethane into the mold to create the gear. Once the polyurethane hardens, we remove the gear from the mold and complete the curing process by baking the gears in an oven. In addition, we are simultaneously experimenting with laser cutting the hub gears out of delrin sheets. Through this grant we hope to obtain help from Jacob's Hall design specialist on the laser cutter and advanced 3D printers. We would also like to use the money to purchase equipment and materials to prototype and manufacture the gears for our robotics kit.

Detailed Description

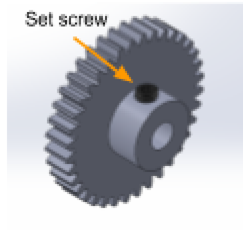
What is the hub gear?

We use the hub gear to connect the rotating motor shaft to other gears on the robot. Because every motor requires a hub gear, many hub gears are required per robot. The following diagram shows how the hub gear attaches to the motor.

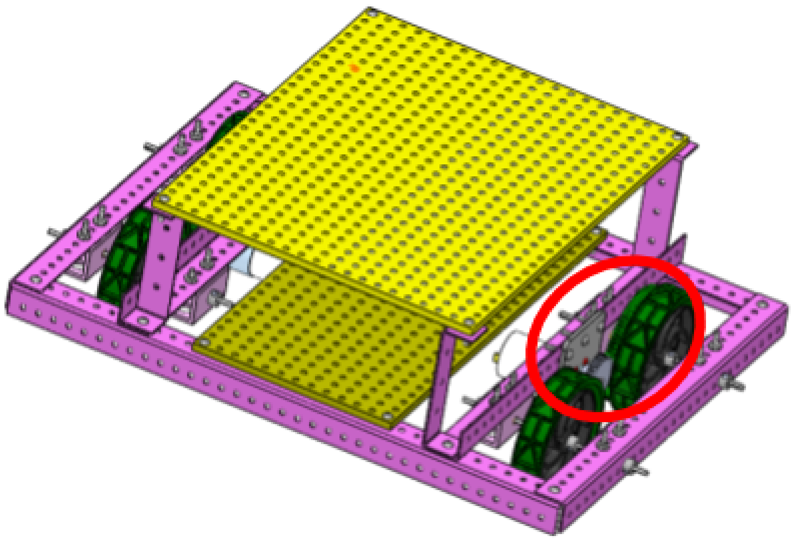


Hub Gear Attached to Motor

A set screw is used to secure the hub gear onto the motor.



An example of how the gear is used in the robotics base kit is provided in the image below.

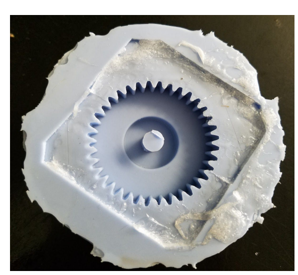


Example of hub gear usage on robot base kit

Current Status

Polyurethane Gears

We obtained free samples of silicone and polyurethane from reaching out to a few companies. These samples were used to prototype molding the gear and decide if this was something we would like to pursue. Silicone is used to make the mold of the gear and polyurethane is used to make the gear. First, we made a mold of the gear, using a gear from last year. Please see ***Appendix 1*** for a detailed description of the silicone mold making process. We



borrowed a vacuum pump, vacuum chamber, and pressure pot[1] from an alumnus while making the mold to save costs. Using our silicone mold (shown above) we created one test gear. Please see ***Appendix 2*** for a detailed description of the polyurethane molding process.

However, after tapping the gear and inserting a set screw, we discovered that the gear would not sufficiently hold onto the motor. With relatively little force along the axis of the motor shaft the gear would slip off the motor shaft.

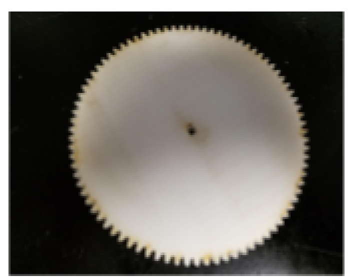
After online research we realized that we needed to bake the gears to complete the curing process. After sourcing a used toaster oven, we baked the gear. However, the gear still did not meet our expectations in terms of strength; the gear would come still come off the motor shaft.

We concluded that the gear needed to be harder, so we manufactured another gear, this time increasing the ratio of hardener to resin when mixing the polyurethane. We could not borrow the vacuum chamber this time, so unfortunately the gear produced was of low quality. As expected, the gear became much harder, but the additional hardener and lack of a vacuum and pressure equipment caused bubbles to form in the gear. These bubbles severely jeopardized the strength of the gear. However, we wanted to test if this harder hub gear would better hold onto the motor, so we tapped and inserted the set screw. The gear held onto the motor better, but it was slightly crooked so that when the motor turned, the gear appeared to wobble. This issue is problematic since a "wobbling" or side to side oscillation of the gear can propagate along a gear train and make the whole gear system less robust.

Laser Cut Delrin Gear

We used the laser cutter to cut out a gear from a 12" x 12" sheet of delrin. Due to tapering on the gear teeth caused by the laser cutter, the gears rotate asymmetrically. Tapering is caused by the dispersion and weakening intensity of the laser as it goes through the delrin. Because we need the delrin gears to be about 0.25 in in thickness we used 0.25 in thick delrin sheets which results in significant tapering. The pictures below show the sheet of delrin we used and a gear we laser cut.

12" x 12" Sheet of Delrin



Laser Cut Gear

How our Project Supports Jacobs Hall's Mission

Our mission to bring engineering opportunities to underrepresented high schools in the Bay Area aligns with Jacobs Hall's focus on societal impact. We provide these high schools with robotics kits and host an 8 week long robotics competition every year. Last year we supported about 250 students. In the same way that Jacobs serves the UC Berkeley community, our

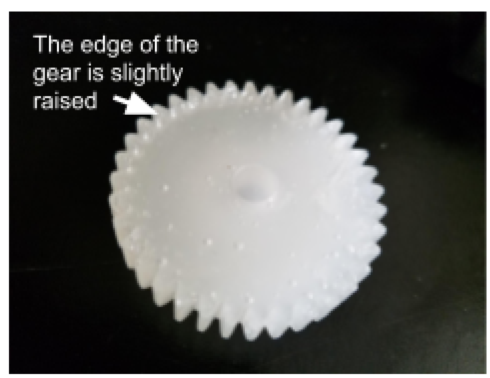
[1] The vacuum chamber and vacuum pump is used to draw out any air bubbles caught in the liquid polyurethane and silicone before they harden. The pressure pot is used to create high pressure around the polyurethane and silicone to shrink any remaining air bubbles while the gear or mold cures.

organization gives these students the opportunity to think like an engineer through designing and creating. In addition, students learn to collaborate with not only their peers, but also with the UC Berkeley student mentors that we provide for each school. Many of the students in our robotics program have very limited STEM resources and the opportunities that we provide may be the only opportunities they have to apply their math and science knowledge outside of the classroom. Schools can participate in our robotics competition for only $100 even though each robotics kit costs around $700. Through donations and grants like this we are able to provide students with this opportunity. The number of schools that can participate in this competition is limited by the cost of the kit, so as we continue to cut excess costs, we will be able to provide this opportunity to more and more students.

Our team's objective is to reduce costs on the hub gears as a part of the kit. Last year each gear cost $4.54 and the total cost of the hub gears for all the teams was $409[2]. After analyzing the cost of the kit, we concluded that spending more than $400 on just the hub gears is unacceptable. Purchasing polyurethane to mold or delrin sheets to laser cut to make enough hub gears for all the teams would cost less than $75. Although there are one-time costs needed for materials used to manufacture the gears, successfully manufacturing our own hub gears will save us a significant amount of money in the long run. These savings will allow us to include more schools now and additional schools in the long run. Furthermore, as we better understand the polyurethane molding process we will be able to manufacture other types of gears and robotics parts that can further reduce costs in the future. Through every school we provide STEM opportunities, we are proud to inspire future innovators and start them on the path toward solving "the pressing challenges of today and tomorrow."

How We Would Benefit from the Grant

Our team receives funding from our organization which prioritizes most of its money to purchase pieces for the kits. For this year's robotics competition, we would like to manufacture polyurethane hub gears. In order to do so, we would like to use this grant to purchase the expensive equipment needed to mold the gears including a vacuum pump, vacuum chamber and pressure pot. For our testing, we borrowed this equipment from an alumnus, but we cannot do this continuously. We would also use the grant to purchase silicone in order to make more molds to make more hub gears at once.

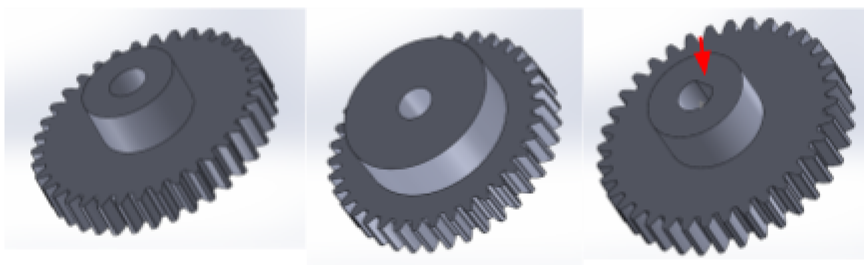


One issue with the gears is that they are not flat on the top. When we pour the polyurethane into the mold it tends to overflow and create raised edges around the teeth. We would like to avoid this, so we are currently researching various methods to make the top of the gear flat such as putting a flat piece of plastic (polypropylene) on top of the polyurethane gear while it dries. We would use the grant money to purchase the polypropylene.

[2] *$4.54 per gear x 18 teams x 5 hub gears per team = $408.60*

When we manufacture our gear, we can only make a mold in the shape of the gear we purchased last year. However, if we wanted to make a change to the shape of our molded gear, like a thicker hub or a different shaped shaft, we do not have the correct shape positive to make the negative mold out of. To make these alternative designs we will be 3D printing different gears to our specifications. We can then use these alternatively designed 3D printed gears to make our desired mold. We will be using the Objet260 Connex3 and 3D Carbon 3D printers to create prototypes of these new gear shapes and then make silicone molds of the 3D printed gears. None of the current team has experience with these 3D printers, so the design specialists' advice will be valuable in teaching us how to use this technology. With the grant, all team members will have access to this equipment in Jacobs Hall and the money can pay for the cost of the filament.

Proposed Changes to Hub Gear Geometry



Original Hub Gear (Current Design) | Alternative Design 1 *Thicker Hub* | Alternative Design 2 *"D" Shaped Shaft Hole*

After the manufacture of the hub gear for this upcoming semester, we are interested in finding cheaper ways to in-house manufacture the other gears used on the robot. Since they do not require a hub, cutting it out of delrin is a possibility if we can find a way to laser cut without a taper. We are interested in obtaining help from the Jacobs Hall design specialists to learn how to optimize the laser cutter settings to reduce the taper. We are thinking of using multiple passes. If we successful minimize the taper, we will make other size gears for the robotics kit using the laser cutter. Historically, we have purchased these gears from VEX robotics; however, this is very expensive, and we are actively considering other options. The grant gives us both access to Jacobs Hall and funding for the laser cutting materials. If we were to manufacture the 84 tooth gears on the robot it would be necessary to have funding for the large delrin sheets.

Through the grant, our entire team is able to get access to the facilities at Jacobs Hall which will be very useful for completing the hub gear project and pursuing a project to replace all gears currently bought from VEX robotics. The funding from the grant can help us greatly reduce the cost of parts per kit and therefore increase the amount of schools we can have an impact on.

Project Plan

Timeline

<table>
<tr><th>Month</th><th>Activities</th></tr>
<tr><td colspan="2" align="center">2017 (Completed Activities)</td></tr>
<tr><td>October</td><td>Sourced Materials
Purchased renshape, a machinable material for the CNC mill. However, for our first gear we just replicated one of the gears from last year, so didn’t need to CNC a gear from renshape.
Obtained polyurethane and silicone samples for free
Glued a gear (from last year) onto the bottom of a cup to make the negative of the gear mold.</td></tr>
<tr><td>November</td><td>Borrowed a pressure pot and vacuum chamber from an alumnus to create a mold of the gear and then used that mold to create a gear
Laser cut a delrin hub gear</td></tr>
<tr><td>December</td><td>Measured polyurethane components (hardener and resin) more accurately and made another gear</td></tr>
<tr><td colspan="2" align="center">2018</td></tr>
<tr><td>January</td><td>(Hub Gear) Use the Connex and Carbon 3D Printers in Jacobs Hall to make a new version of the gear with the hub part on the gear a little thicker. (This will make the polyurethane in the hub part less flexible, resulting in a stiffer gear that will prevent asymmetrical wobbling.)
Use the silicone to make a negative mold of the new 3D printed gear
Cast the polyurethane gear, tap the set screw in the gear, and test it</td></tr>
<tr><td>February</td><td>Make a multi-gear mold that optimizes for space inside the pressure pot and vacuum chamber in order to make as many gears as possible at one time
Manufacture around 150 hub gears for 2018 Robotics Competition
Begin project to replace the VEX gears for the 2019 Competition
Research different manufacturing processes</td></tr>
<tr><td>March</td><td>Continue researching gear techniques
Please see Appendix 3 for a flowchart showing a summary of our potential solutions to optimize polyurethane gear manufacturing
Please see Appendix 4 for a flowchart showing a summary of our potential solutions to optimize gear laser cutting
Make prototypes of gears out of delrin
Try making several passes of the laser to minimize tapering
Laser cut a small circle and cut the gear out of a small circle instead of the whole sheet. (This will insure the sheet of delrin is locally flat in the small circle region.)
Mold one of the gears with silicone and polyurethane using the purchased gear as a positive</td></tr>
<tr><td>April</td><td>Look into slightly alternative designs to the original purchased gear
3D print the alternative design
Use the 3D printed gear to mold a new version of the gear</td></tr>
</table>

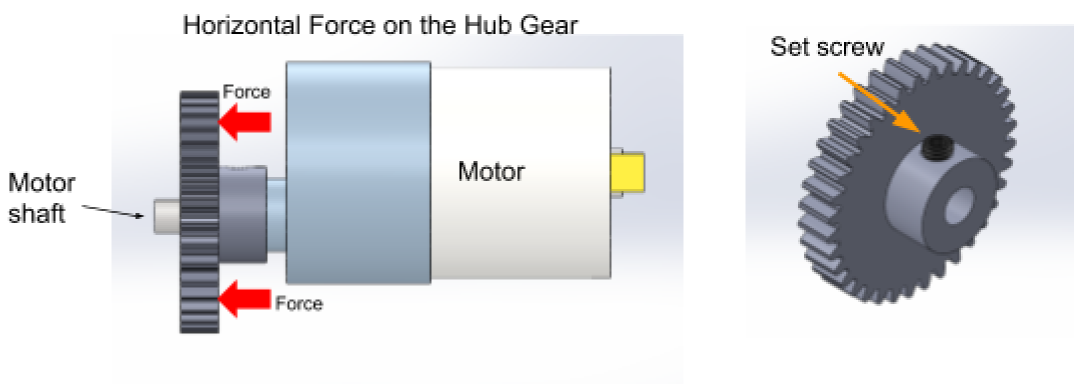
	• Decide on the best design and best manufacturing process for these gears

Metric and Midway Goals

We are accessing the quality of the gears through two metrics

1. Withstanding Horizontal Force

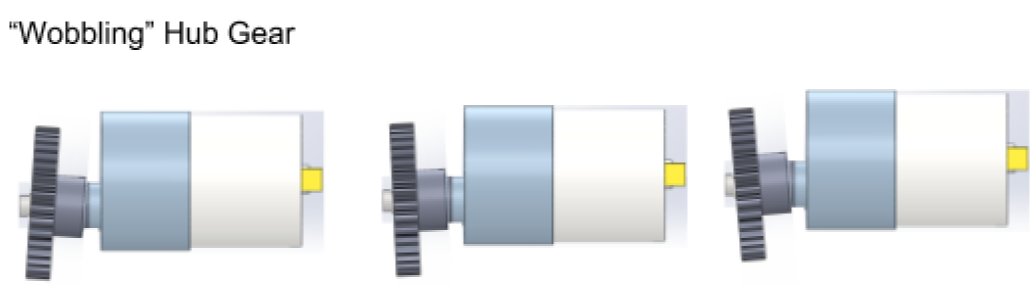
We want the gears to withstand horizontal force well. Please see the diagram below. The horizontal force is a force on the gear along the direction of the motor shaft shown in red on the diagram. The gear should strongly hold onto the motor shaft when a horizontal force is applied and not slip off.



Midway Goal: When a force of 10 Newtons is applied on the gear, the gear should not come off the motor shaft.
End Goal: When 50 Newtons is applied on the gear, the gear should not come off the motor shaft. In other words, once the set screw is tightened removing the gear from the motor shaft should be nearly impossible. The gears we previously purchased held onto the motors this well, so we hope to make our own gears that are just as good.

2. Rotational Symmetry

The gear should rotate symmetrically around the motor shaft and remain as flat as possible as the motor turns. The gear should not wobble, oscillate up and down or back and forth. The diagram below shows snapshots of the hub gear at equally spaced time intervals. Notice how the hub gear appears to wobble asymmetrically. We have exaggerated the wobbling in the diagram to make it easier to visualize.



Midway Goal: The gear face should remain perfectly perpendicular to the output shaft of the motor at all times as the motor turns.
End Goal: Reduce wobbling and oscillation as much as possible. If the gear wobbles, the gear would still work; however, it is undesirable.

Deliverables - as of May 2018

- Finalized design for a hub gear that does not wobble nor easily come off the motor shaft
- A silicone mold that allows us to make multiple gears at once and fits inside the vacuum chamber and pressure pot
- Around 150 manufactured polyurethane hub gears
- Laser cut delrin gears (Polyurethane hub gears are better than delrin hub gears, so we will make hub gears out of polyurethane but make other gears for kits using the laser cutter.)
- Positively-impacted local high school students from 24 schools

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Budget

Item	Purpose	Quantity	Unit Cost	Total Cost
Delrin Sheet for Gears (0.25 in thick)	The current sheet we have is running out of space, so we need more sheets to make additional test gears.	4	$28.03	$112.12
Pressure Pot & Air Compressor	We place the gears under pressure when they cure to shrink any air bubbles in the polyurethane as much as possible. Previously, we asked an alumnus to borrow his work pressure pot. However, the pot does not belong to him and we cannot continue borrowing it.	1	$250.00	$250.00
Vacuum Chamber and Pump	We place the gears under low pressure after mixing the plastic hardener and resin to draw out any air bubbles before the gears dry. Previously, we asked an alumnus to borrow a vacuum chamber and pump from his work. However, the equipment does not belong to him and we cannot continue borrowing it.	1	$300.00	$300.00
Polypropylene or HDPE sheet	We need to place a smooth, hard plastic sheet on top of the gears as they cure in the mold to create a flat top surface	1	$20	$20
Polyurethane IE 3075	We are currently using free samples that we obtained from a company. However, there is not much left, so we will need to purchase more to continue our testing.	1	$75	$75
Silicon QM 262 A and B	We are currently using free samples that we obtained from a company. However, there is not much left, so we will need to purchase more to	1	$75	$75

	continue our testing.			
Filament for Objet260 3D printer	To change the geometry of the gear, we would need to prototype new gears with the high end 3D Printers. (The Type A Printers will not work since we need smooth gears to accurately mold them.)	1	$50	$50
Filament for Carbon 3D printer	To change the geometry of the gear, we would need to prototype new gears with the high end 3D Printers.	1	$50	$50
Sandpaper	To smooth down rough edges of gears.	1	$10	$10
		Total Expected Costs:		**$942.12**

Other Funding

Our organization receives funding from other grants and tax deductible donations from large companies, however most of that money does not go to our team. Most of our budget goes toward purchasing the mechanical and electrical parts for our kit. This Fall we were given a budget of $400, but that was not enough to purchase equipment needed for molding. The budget covered all of our organization's mechanical projects as well for the semester, including building an interactive game field component and electrical enclosures. As a result, we strategically managed to spend nearly nothing on the prototyping process with free samples and borrowed equipment, however that is not sustainable for manufacturing a large quantity of gears. While it is possible that we ask our organization for funding to pay for the equipment to manufacture all of these gears, the cost adds to the price per kit and limits the number of schools that can participate.

Supplemental Material

Appendix 1: Creating the Silicone Mold of the Gear

1 Silicone will be used to make a mold of the gear.

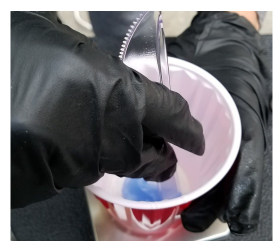
Silicone samples

2 Since we already have a hub gear from last year, we used that gear to make a mold of the gear. We attach the hub gear to the bottom of a cup to make a mold for the negative of the gear.

Homemade mold for gear

3 Measure the proper amounts of silicone QM 262 A and QM 262 B and mix together for about 1 min. (Liquid silicone comes as two solutions that must be mixed together)

Silicone solutions



Mixing silicone

4 Place silicone mixture into a vacuum chamber and “degas” silicone by using the vacuum pump to remove air from the chamber. Low pressure around the silicone causes air bubbles to expand and escape out of the mixture. This prevents pockets of air from being trapped in the viscous liquid silicone.

Vacuum chamber

Degassing silicone in vacuum chamber

5 Turn off vacuum and let air enter the vacuum chamber. (Returning the silicon to standard atmospheric pressure pops all the bubbles that formed in the vacuum) Repeat step 4, twice more to ensure all bubbles are removed from the silicone.

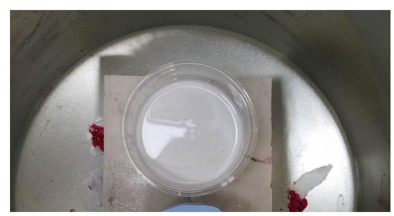
6 Pour the silicone into the mold.

7 Place the silicone mold inside the vacuum chamber and create vacuum to degas the silicone. Repeat twice to ensure all air pockets are removed.

Degassing silicone mold in vacuum chamber

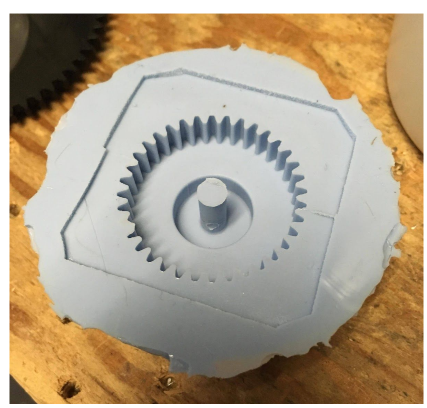
8 Place the mold in a pressure pot at 30 psi. (High pressure ensures that any air bubbles left in the silicone will shrink and become as small as possible while the silicone mold solidifies.) Let mold cure for 24 hours.

Pressure Pot



Silicone mold solidifying in pressure pot

9 Remove silicone mold from plastic cup. Mold is complete.



Completed mold

Appendix 2: Creating the Gear from Polyurethane (IE 3075)

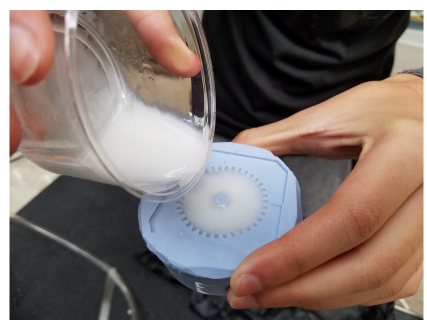
1 Polyurethane will be used to make the hub gear.

Polyurethane samples

2 Measure the proper amounts of the polyurethane resin and hardener. Specifically, we used IE-3075. Mix together for about 1 min. Start timer for 6 minutes. (The work time of polyurethane is about 6 minutes)

Mixing polyurethane

3 Pour the polyurethane into the mold.



Pouring polyurethane into mold

4 Place the polyurethane into a vacuum chamber and “degas” the polyurethane by using the vacuum pump to remove air from the chamber. Low pressure around the polyurethane causes air bubbles to expand and escape out of the mixture. This prevents pockets of air from

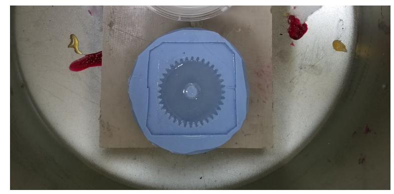
Polyurethane gear inside vacuum chamber

Degassing polyurethane in vacuum chamber set up being trapped in the polyurethane which would structurally weaken the gear and perhaps prevent the liquid from completely filling in the teeth.

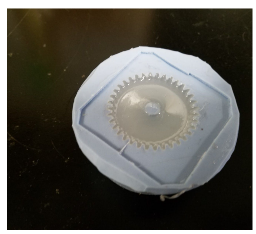
5 Turn off vacuum and let air enter the vacuum chamber. (Returning the polyurethane to standard atmospheric pressure pops all the bubbles that formed in the vacuum.) Repeat step 4, twice more to ensure all bubbles are removed from the polyurethane.

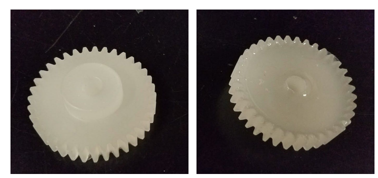
6 Place the mold in a pressure pot at 30 psi. (High pressure causes any air bubbles left in the polyurethane to shrink and become as small as possible while the polyurethane cures.) Let cure in pressure pot for 24 hours.


Pressure Pot


Polyurethane curing in pressure pot

7 Remove gear from pressure pot and remove the gear from the silicone mold.


Hardened polyurethane gear in the mold


Gear removed from the mold

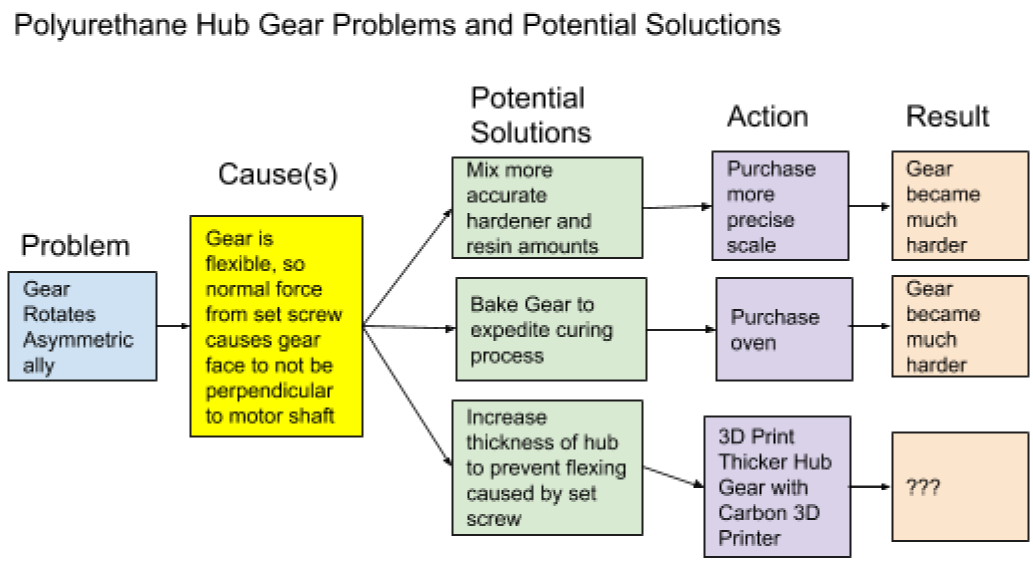
8 Bake gears in oven at 200°F for 24 hours to complete the curing process.


Oven used to bake gears

9 Remove gear from oven. Hub gear is now complete.


Final Product

Appendix 3: Flowchart of Polyurethane Gear Manufacturing Problems and Solutions



Appendix 4: Flowchart of Laser Cut Gear Manufacturing Problems and Solutions