Induction Machine Fabrication Manual

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1 Introduction

1.1 Purpose

The purpose of this manual is to provide a step-by-step assembly process for a low-voltage induction machine built at the WEMPEC Lab at University of Wisconsin-Madison. This manual includes detailed descriptions and visual aids portraying the fabrication of parts at various stages of the build and the assembly of the motor based on a standard design.

The machine that will be assembled was designed with an emphasis on manufacturability. The motor covered in this manual is a basic 3-phase, 4-pole, 12 slot, single-layer winding, squirrel-cage rotor induction machine. The manual will cover basic working principles of an induction machine followed by the sequential steps to build one. The subassemblies include the rotor, stator and end plates. The rotor and stator assemblies will lead into the testing section, which will walk the user through the process of setting up and performing the High-Pot test. The end plates and final assembly will be put together at the conclusion of the High-Pot test.

Figure 1. Fully assembled 4-pole, 12 slots, squirrel-cage rotor induction motor.

1.2 Technical Background

Induction machines, also known as asynchronous machines, are one of the most widely used electrical motors in both domestic and industrial applications. In fact, about 50 percent of global power is consumed by electric machines and over 90 percent of industrial machines are induction motors. The high efficiency combined with low maintenance and self-starting properties makes the induction machine one of the most popular choices within the industry.

An induction machine comprises of two main components, the stationary stator, and a rotating rotor. An exploded view of a common industrial squirrel cage type induction machine is shown in Figure 2. The main frame, typically made from cast iron, is used to house and protect the stator and rotor from damage as well as protect the user while operating. While sometimes not necessary, fans are also added to the machine to prevent the stator coils from overheating.

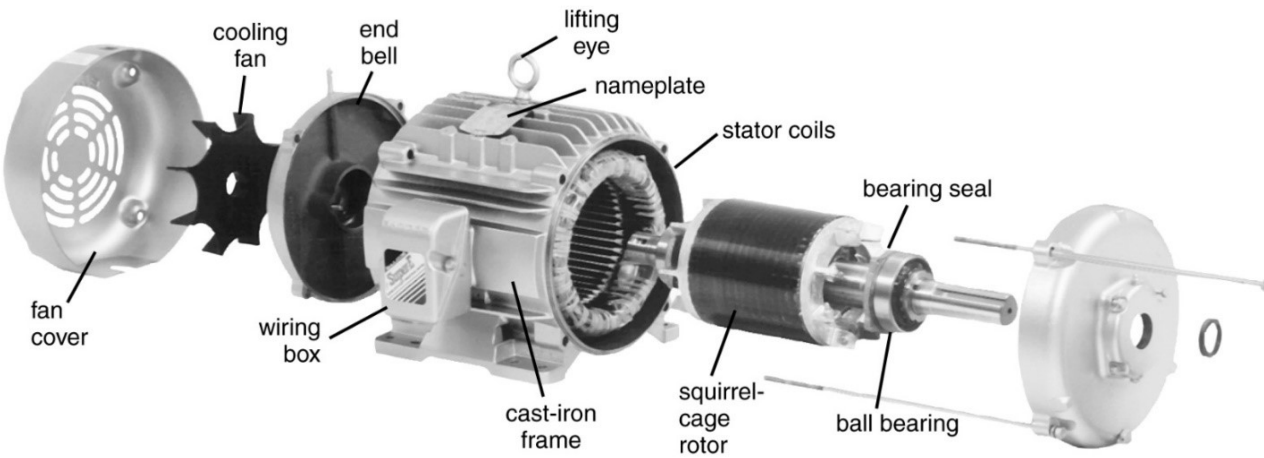


Figure 2. An exploded view of a squirrel-cage type induction motor.

A cross-sectional view of an induction machine is shown in Figure 3. The stator is composed of stator windings and iron laminations. The copper windings in the stator are typically wounded in a distributed fashion, meaning they are typically spread throughout the stator lamination. Since an induction machine typically has three phases, the windings would have three individual input terminals. When the windings in the stator are connected to a three-phase power source, a rotating magnetic field is generated. Note that this is a fundamentally different supply than that from a wall outlet, so this motor will have to be operated in the lab with the correct power supply.

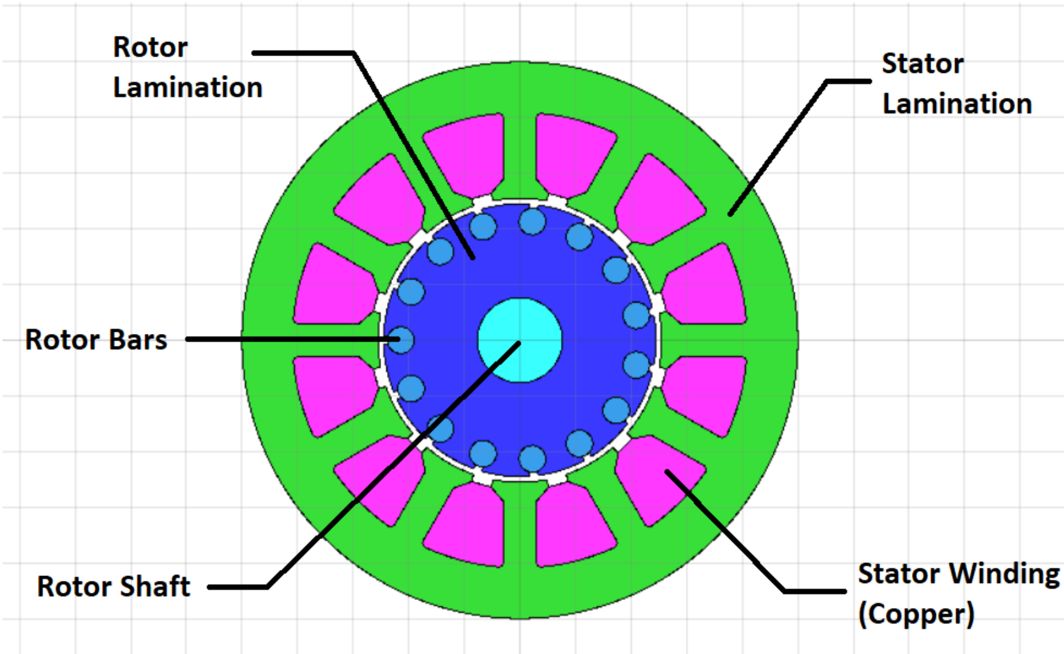


Figure 3. Cross-sectional view of a squirrel cage type induction machine stator and rotor.

One of the most common rotor designs for induction machine is the squirrel cage design. The construction of the squirrel cage rotor is shown in Figure 4 below.

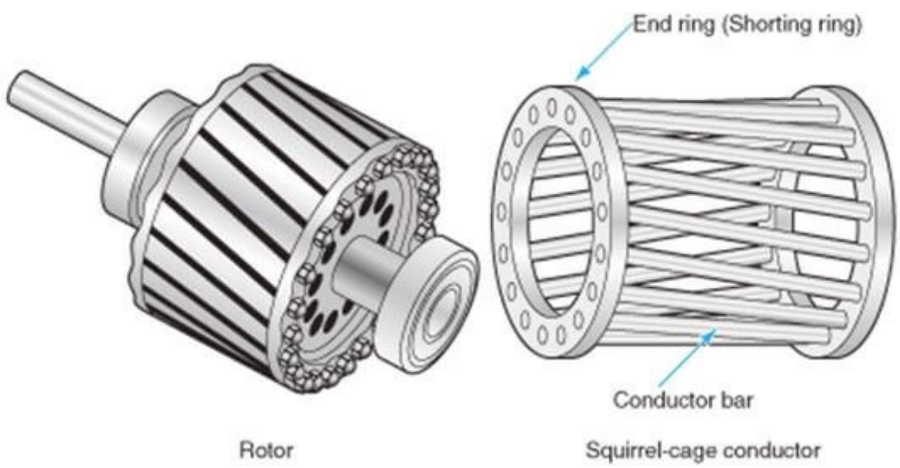


Figure 4. Construction of a squirrel-cage rotor.

The squirrel cage rotor design uses conducting bars (typically made from copper and/or aluminum) connected to an end ring on either end. Within the cage, iron laminations are added to assist the flow of magnetic flux generated by the stator windings. A current is induced in the rotor bars when a rotating magnetic field is generated by the stator windings. The interactions between the induced current in the rotor and the rotating magnetic field in the stator allows the generation of torque in the squirrel cage rotor, creating a rotating motion. As seen above, the bars are skewed at an angle. This is to prevent cogging, which is a locking of the rotor upon startup that commonly occurs when using an equal number of conductor bars and stator teeth.

2 Parts List and Description

Many parts needed for this induction motor are stocked in-house, including copper wire and steel laminations. However, parts such as the rotary shaft and bearings must be purchased from external vendors. All the parts used in this design are shown in Table 1.

Table 1. Full Assembly Bill of Materials.

Item	Description	Material	Source	Quantity	Specifications	Unit Price	Total Price
Bill of Materials							
In House Parts							
Motor Housing	2 Unique Motor Housing End Plates	Onyx Polymer	Stocked in House	1	100mm W x 100mm L	$25.00	$25.00
Lamination Sheet	Stator and rotor core laminations cut from stocked sheet metal	Steel	Stocked in House	varies by sheet size	0.025" th x ~300 sq. in.	$5.00	$5.00
Windings	21 gauge insulated copper wire	Copper	Stocked In House	1	N/A	$10.00	$10.00
Rotor Fasteners	M4 bolts and lock nuts for rotor	Steel	Stocked In House	11	M4 thread x 16mm L	$5.00	$5.00
Electrical Connectors	Terminals and insulated banana plugs	N/A	Stocked In House	6	N/A	$0.00	$0.00
Threaded Inserts	M4 thermal set inserts	Steel	Stocked in House	4	M4	$0.00	$0.00
Loctite	Applied to rotor standoff fasteners	N/A	Stocked In House	N/A	N/A	$0.00	$0.00
Stator Slot Retainers	Small 3D-printed tabs to constrain stator coils	Onyx Polymer	Stocked In House	12	N/A	$0.00	$0.00
						Subtotal:	**$45.00**
Purchased Parts							
Bearings	6201 open ball bearings	Steel	McMaster-Carr [5972K313]	2	12mm ID	$6.06	$12.12
Shaft	Rotary shaft with full-length keyway	Steel	McMaster-Carr [7398K215]	1	200mm L x 12mm OD	$13.93	$13.93
Housing Fasteners	Fasteners to secure the housing plates	Steel	Fastenal Bolts:[11113709] Nuts:[90673]	4	Bolts: M6-1 x 130mm L Nuts: M6-1	$2.40	$9.60
Rotor End Plates	Aluminum ring-shaped rotor end plates cut from flat stock	6061 Aluminum	McMaster-Carr [89015K184]	0.125	0.063" th x 6" W x 12" L	$11.53	$1.44
Aluminum Rotor Standoffs	Male female M4 threaded hex standoff for rotor cage	6061 Aluminum	McMaster-Carr [98952A155]	11	8mm hex x 20mm L	$1.62	$17.82
						Subtotal:	**$54.91**
						Total:	**$99.91**
Note: In house material prices are an estimate only. Purchased part prices and supply may fluctuate.							

For the motor that this manual is based around, one would expect to spend approximately $50 on purchased parts. An estimate of $40-50 of in-house part cost to the lab brings the total cost estimate to the desired limit of $100 per motor. As this design focuses on a single motor having extremely high manufacturability, there is plenty of room for cost minimization in alternative designs and high-volume orders.

Certain considerations were implemented in the effort of saving raw material, money, and time. The aluminum flat sheet stock used for the rotor end plates was oversized and thus each build only requires a portion of the sheet. The rotor laminations are superimposed concentrically with the stator laminations, dramatically reducing the amount of waste. The rotary shaft with a full-length keyway was chosen with respect to simplicity and price by eliminating the need for a standard machine key, which was used in one of the iterative motor designs. The rotor assembly can be very flexible in terms of design constraints, and several unique designs were tested before deciding on the final design. Possible rotor design changes are discussed further in the Rotor section.

3 Assembly

The induction machine has three main assemblies, each of which will be built independently and assembled once all are completed. The subassemblies include the rotor, stator, and end plates. The end plates are 3D printed and require minimal further assembly. The rotor and stator represent the working principles of the machine and are the most intensive components to manufacture. The fabrication of rotor and stator parts requires the use of a laser cutter, winding jig, soldering iron, and other miscellaneous tools, all of which can be found in the WEMPEC lab.

3.1 Rotor

The rotor spins due to its interaction with the rotating magnetic field generated by the stator windings, and it is what produces mechanical work from the input of the electrical work. The rotor is commonly from materials such as solid copper bars or cast aluminum with shorted end-rings for electrical conduction.

Instead of implementing the skewed rotor cage design, the rotor that will be covered in this section is a non-skewed cage design was implemented to simplify the manufacturing process. Additionally, threaded aluminum standoffs are used in place of solid copper for the conducting bars. This is because a copper rotor requires the process of soldering, and aluminum standoffs can simply be fastened with nuts and bolts, drastically increasing manufacturability.

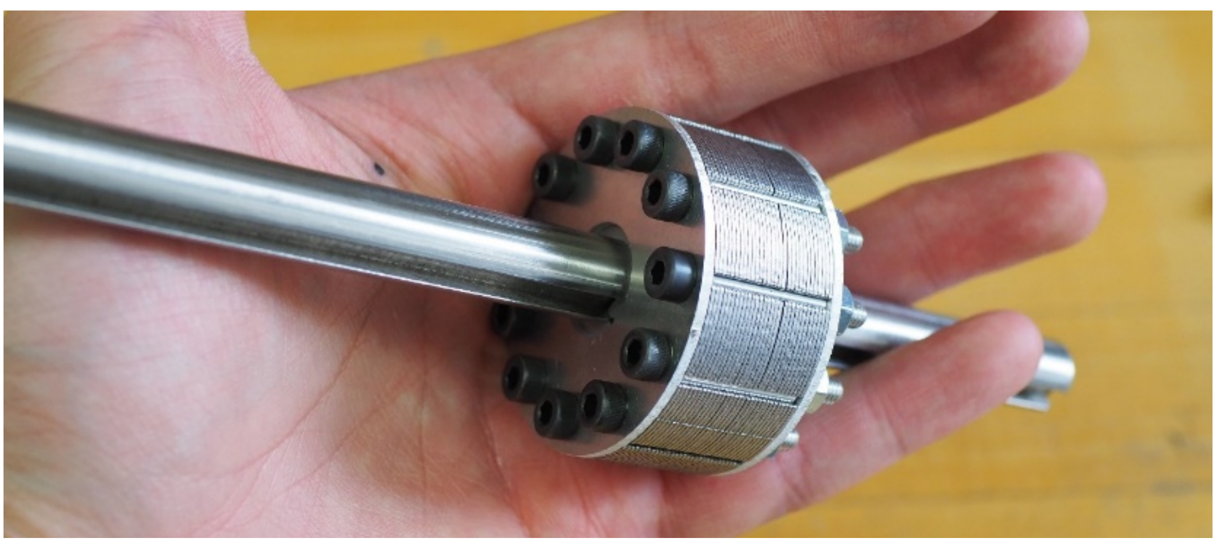


Figure 5. Final rotor assembly.

Parts and Materials

The parts and their respective quantities are shown in Table 2 along with a picture in Figure 5. The rotor mainly consists of the keyed rotary shaft and the core, which consists of stacked laminations and the squirrel cage components. In this design, aluminum standoffs fastened to an aluminum end ring (creating the squirrel-cage) were used to create the shorted circuit for the induced current. The rotor cage can be made from aluminum or copper, but their difference in conductivity requires a correction to the cross-sectional area of conductor needed. Generally, the conductivity of aluminum is about 60 percent of the conductivity of copper.

The rotor laminations are the smaller of the two laminations cut together from steel sheet metal stocked in the lab. The rotor lamination stack should be equal in height to the stator lamination stack. The tabs present in the center hole of the rotor laminations stack to create an integrated key that should fit snug on the keyed rotary shaft. The final rotor assembly can be found in Figure 6.

Table 2. Parts needed for rotor assembly.

Part	Quantity
Keyed Rotary Shaft (not pictured)	1
Steel Rotor Laminations	~31
8mm x 20mm Aluminum Standoff	11
Aluminum End Plate	2
M4 Lock Nuts	11
M4 Fasteners	11
Locktite	1

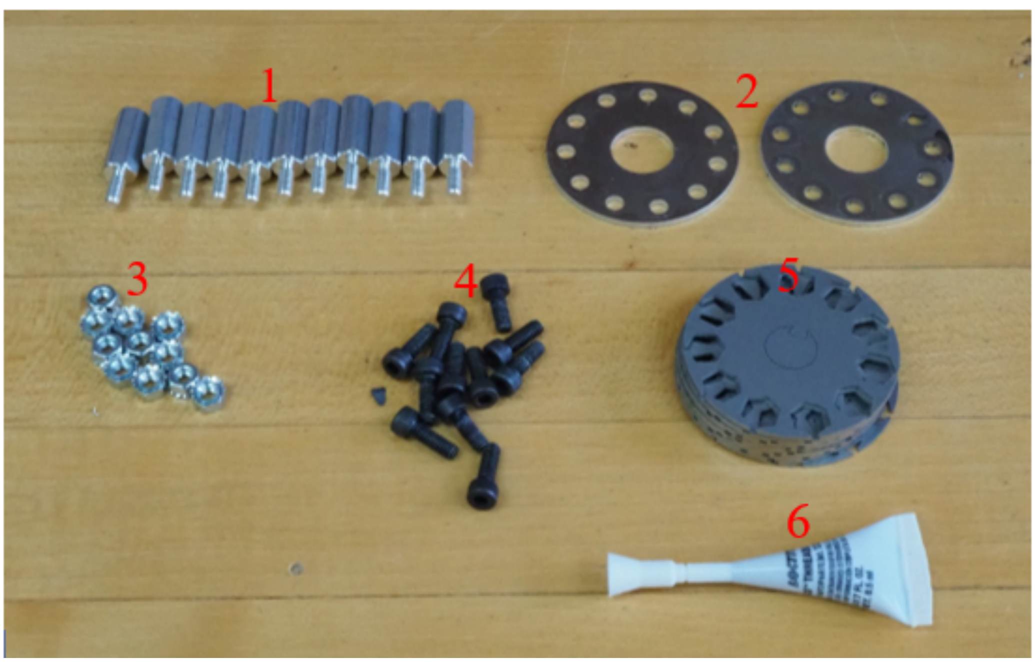
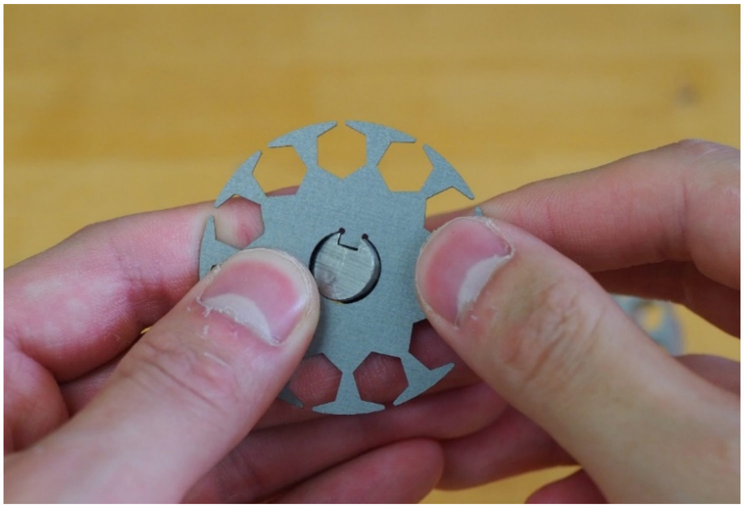


Figure 6. Parts needed for rotor assembly.

3.1.1 Place rotor laminations onto rotor shaft

Prepare the rotor laminations by removing all excess material left from the laser-cutting process, making sure not to bend the slot tabs. Slide each lamination onto the rotary shaft, ensuring that all are stacked in the same orientation. Figure 8 shows an improper mix of lamination orientations.



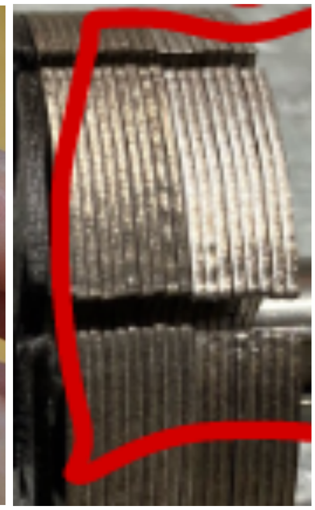


Figure 7 (Left): Placing rotor laminations on the rotary shaft.

Figure 8 (Right): Lamination when not stacked in the same orientation. Visible through the shininess on the side

3.1.2 Measure rotor lamination stack length

Use calipers to measure the final thickness of the rotor laminations. Each lamination is 0.025 [in] thick, and the final thickness should be at or just under 0.787 [in], or 20 [mm]. This translates to an estimated 31 laminations needed. A thickness of over 20 [mm] would prevent the alumnium endplate from having full contact with the standoffs.

Figure 9. Ensure the rotor lamination thickness is at or no greater than 20 [mm].

3.1.3 Place the standoffs in the rotor slots

Align the rotor laminations and place the standoffs into the hexagonal slots. Some force may be required depending on the accuracy of the stack alignment. The female end should be flush with the top of the rotor core, and all standoffs should face the same direction.

Figure 10. Placing the standoffs through the rotor laminations.

3.1.4 Sand and install the first end plate

The rotor end plates are cut from a 0.063 [in] thick multipurpose 6061 aluminum sheet. Clean the endplate surface by using sand paper and place it on the threaded end. Sanding and cleaning the end plates are necessary to ensure low contact resistance between the ring and standoffs.

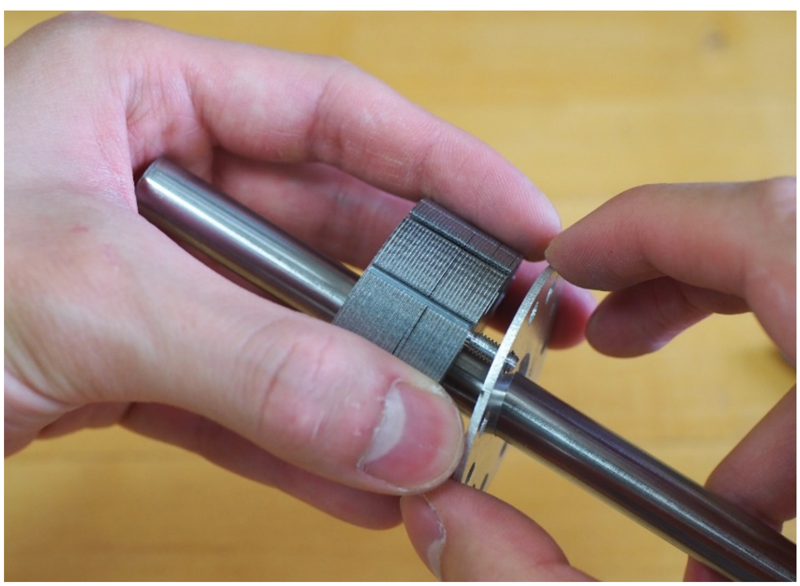


Figure **11**. Placing one end plate through the male ends.

3.1.5 Set the locking nuts in place

Place a lock nut on the male end of the standoff and tighten it with hand. Repeat for all remaining slots. Visually ensure that all lock nuts sit flush on the end ring with the standoffs unable to shift in that direction.

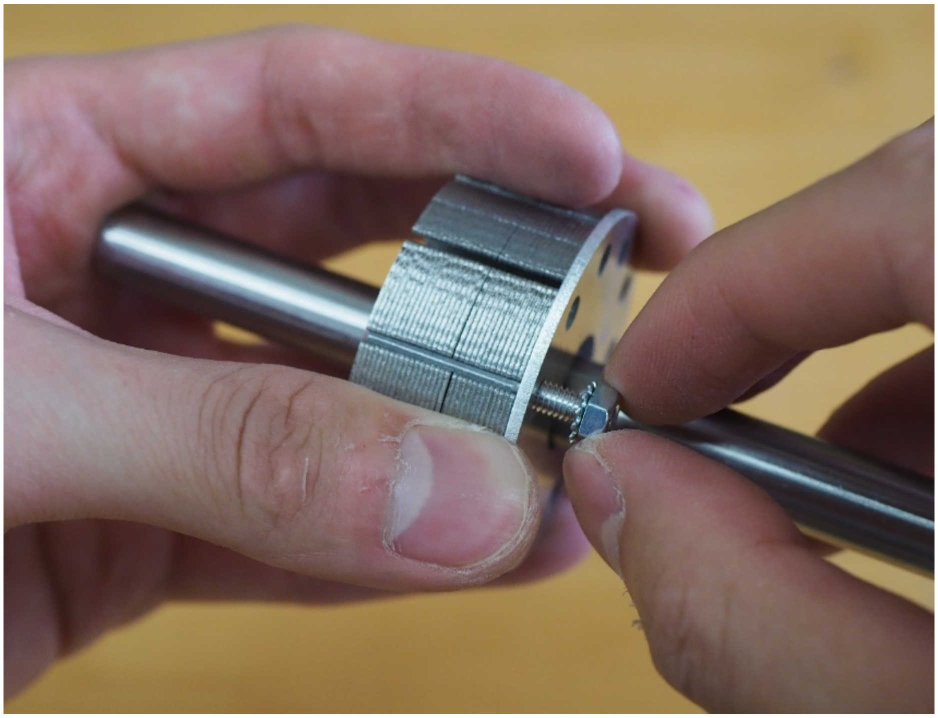
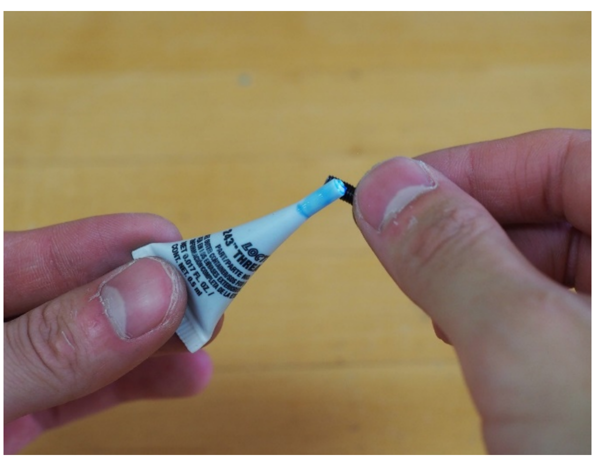
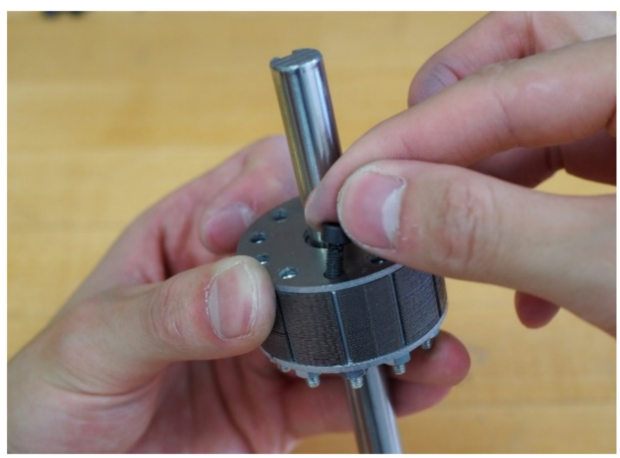


Figure 12. Adding locking nuts to the male end of the standoffs.

3.1.6 Apply Locktite and screw on fasteners

Place the other aluminum endplate on the bottom of the rotor core. Apply a small amount of locktite (a one drop) on the M4 fasteners and tighten them by hand into the female end of the standoffs. Again, there should be no clearance between the fastener head and the end ring.

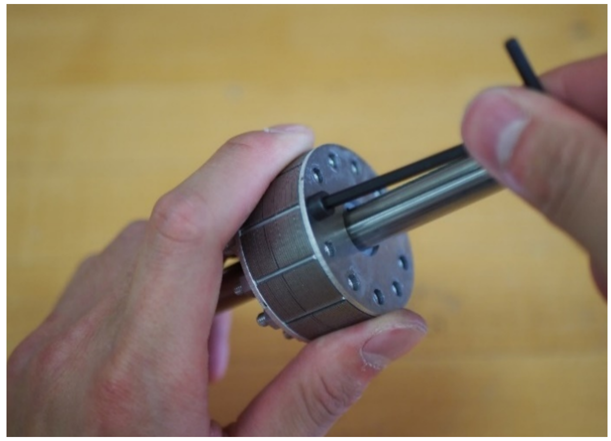




Figures 13 (Left) and **14** (Right). Applying the Loctite and placing the fasteners in the female end of the standoff.

3.1.7 Tighten the assembly

Tighten all the lock nuts using a needle pliers or wrench. Use an Allen wrench to tighten the M4 fasteners on the other end. Ensure a snug, even fit all around to conclude the rotor assembly process.



Figures 15 (Left) and **16** (Right). Tightening both sides of the aluminum standoffs.

3.2 Stator

The stator of the motor is comprised of two main components: steel laminations and copper windings. This is one of the most delicate and critical pieces of the motor assembly process, so it is critical that each step be followed precisely and carefully. The stator generates the rotating magnetic field and is the part of the motor with supplied excitation current/voltage.

This stator is designed with 12 slots and has single layer windings with a 40% fill-factor. While a double-layer wound machine has a better efficiency due to less harmonic fluxes, a single-layer wound machine is easier to manufacture due to its simplified winding configuration. The coils utilized in the stator must not be shorted together whatsoever, so the insulated coating must not be damaged. To help avoid accidental shorts, the stator slots will be lined. Each coil must be the same length to ensure that the resistance is the same for each phase.

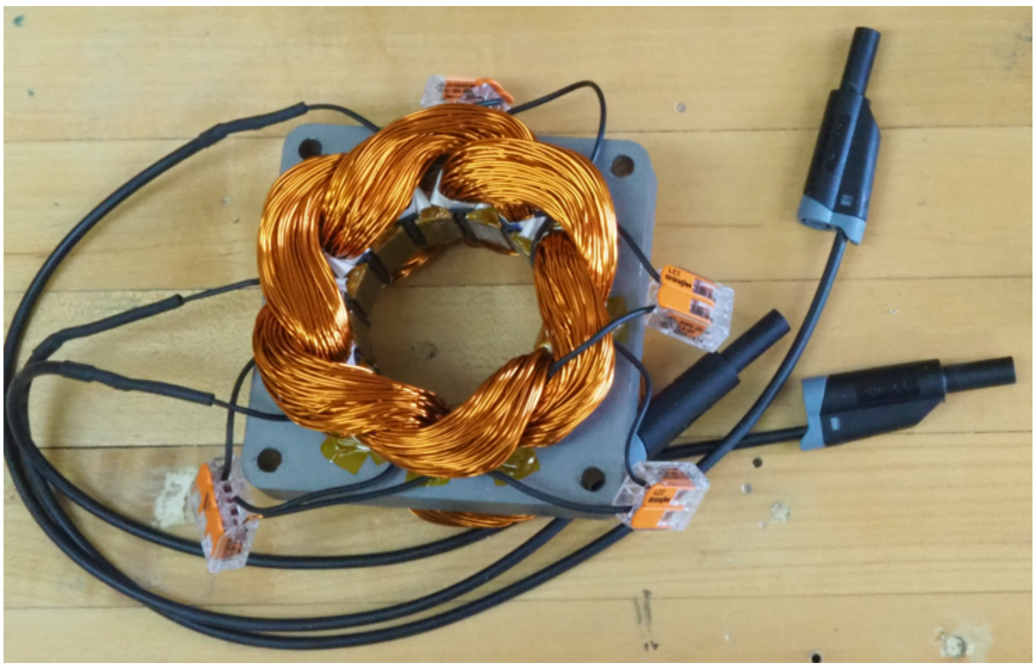


Figure 17. Final stator assembly.

Parts and Materials

Table 3. Parts needed for stator assembly.

Part	Quantity
Steel Stator Laminations	~31
Polyimide Tape	N/A
21 AWG Copper Wire	N/A
Winding Jig	1
3D Printed Stator Slot Retainers	12
Folded Insulation Paper	12
Clamp Down Wire Connectors (2 terminals)	3
Clamp Down Wire Connectors (3 terminals)	1
Banana Plugs	3

3.2.1 Stack stator laminations

Stack all steel stator laminations together ensuring that each lamination is stacked in the same orientation just like the rotor laminations. The side with the better finish should point towards the top of the motor. The different sides can be seen and compared in Figure 3 above. Stacking them in the correct orientation, while not critical, can help with the reduction of eddy currents in the stator and general alignment of the assembly. Use M6 fasteners and wing nuts to secure the stator laminations together. 3D printed slot retaining tabs were implemented to help with the stator winding process and they should be printed before starting that process.

Once the lamination stack is completed, generously apply polyimide tape to the interior edges of the stator. Ensure the tape fully covers each slot, especially the edges, to help prevent shorts.

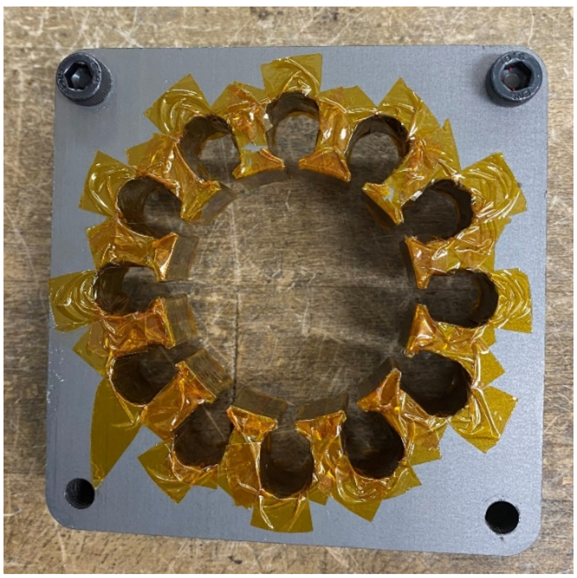
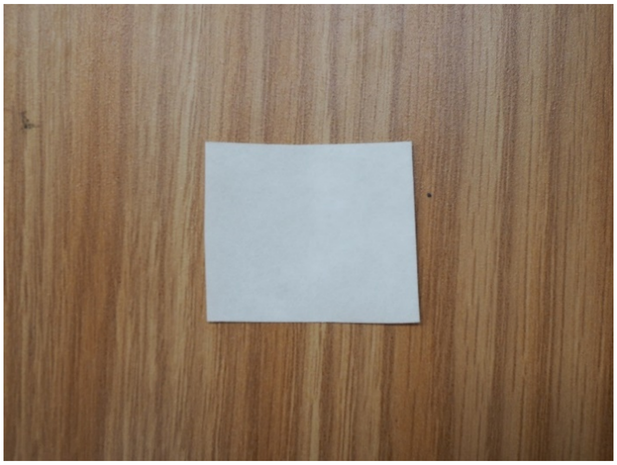


Figure 18 (Left) and **19** (Right). Polyimide tape applied to stator slots

3.2.2 Insert insulation paper into slots

Cut 12 pieces of insulation paper approximately 36mm x 31mm in size. Fold them as shown in Figure 21 below. Roll the paper strips with a round screwdriver to form the slot shape and insert one into each stator slot, as shown below in Figures 22, 23, and 24.



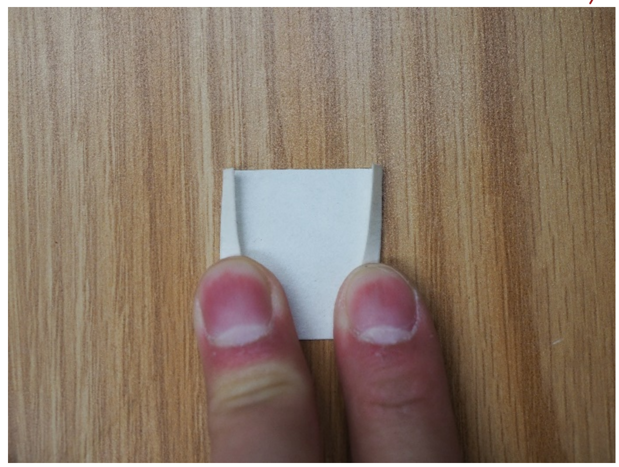


Figure 20 (Left) and **21** (Right). Stator insulation paper folding.

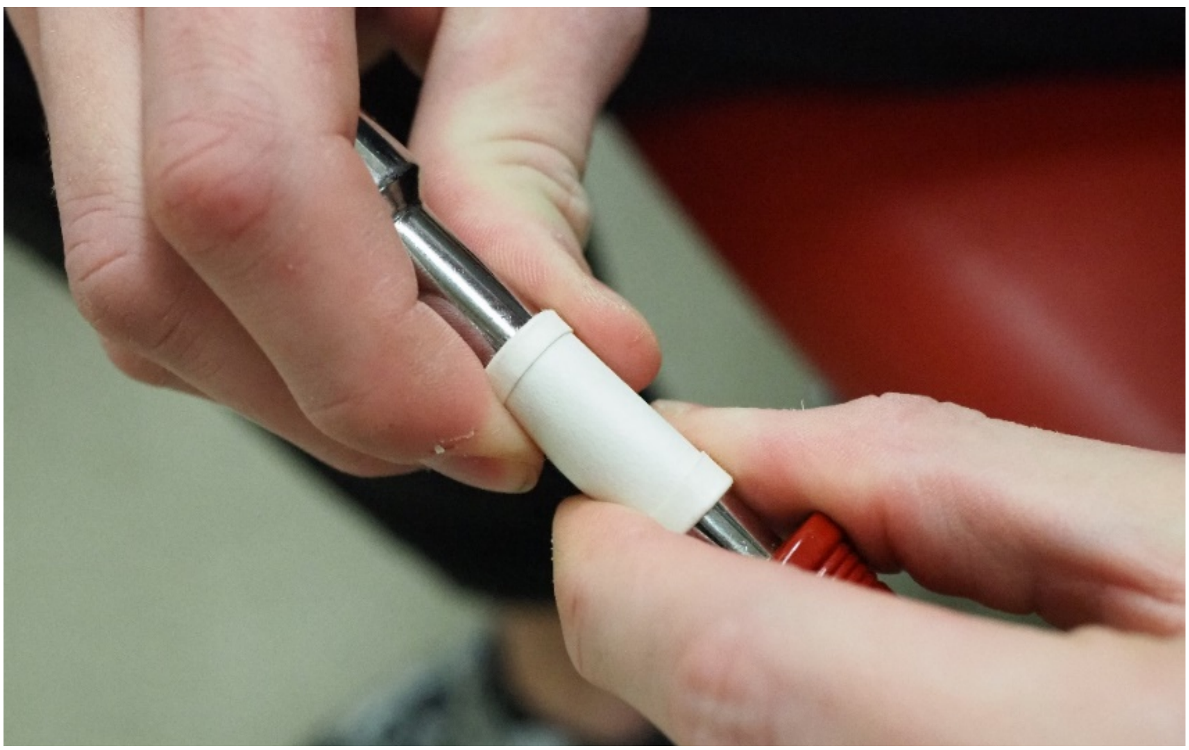


Figure 22. Forming stator insulation paper.

Figure 23 (Left) and **Figure 24** (Right). Polyimide tape applied to stator slots

3.2.3 Setting up the winder

To wind the copper windings, the Adams Maxwell Model 1400-3A or similar chuck-based winder should be used. An image of this winding machine is shown in the next figure.

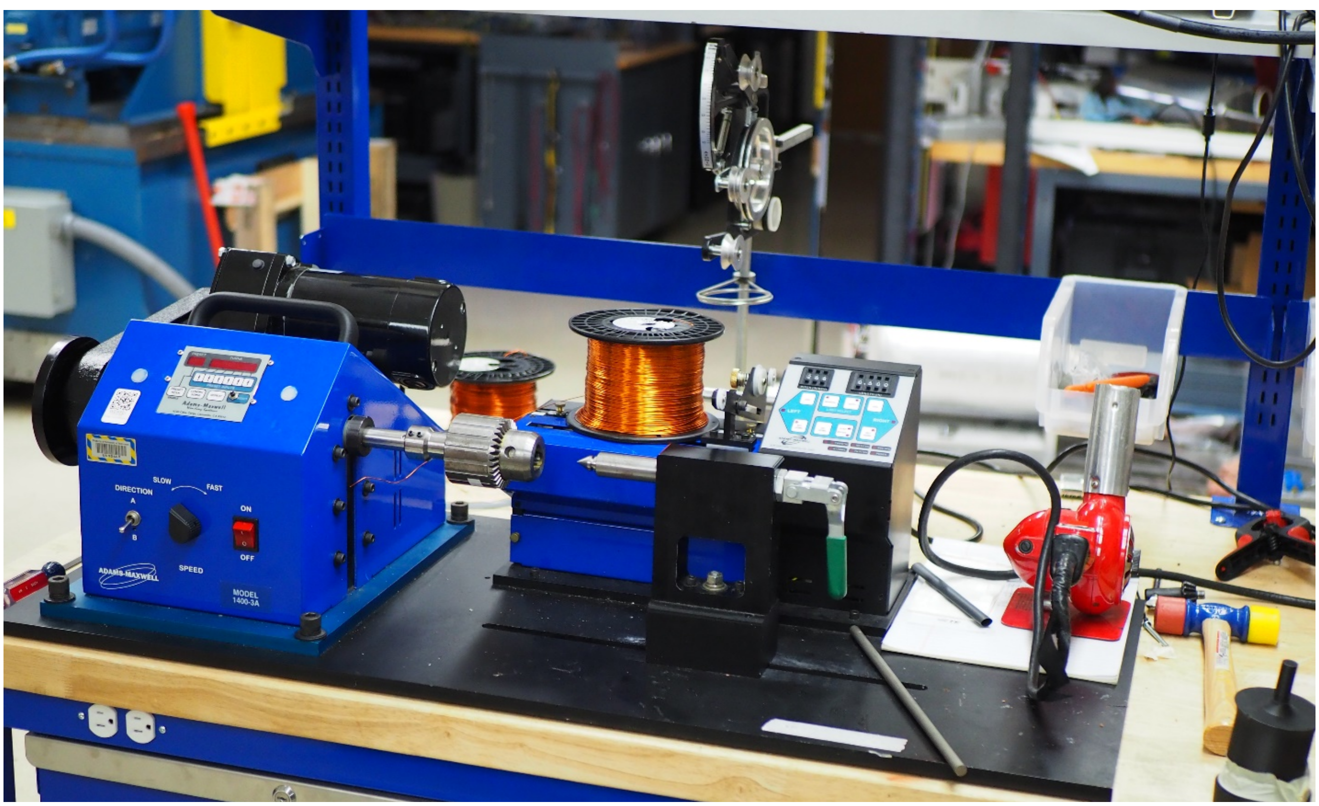


Figure 25. Winding machine used for stator windings.

The first step in this winding process will be loading the 21 AWG copper wire onto the mounting spool which will aid in the unspooling of the pre-wound spool in an organized manner.

After the spool has been mounted, the machine can be turned on by flipping the front switch and the speed set to the slowest possible setting to start.

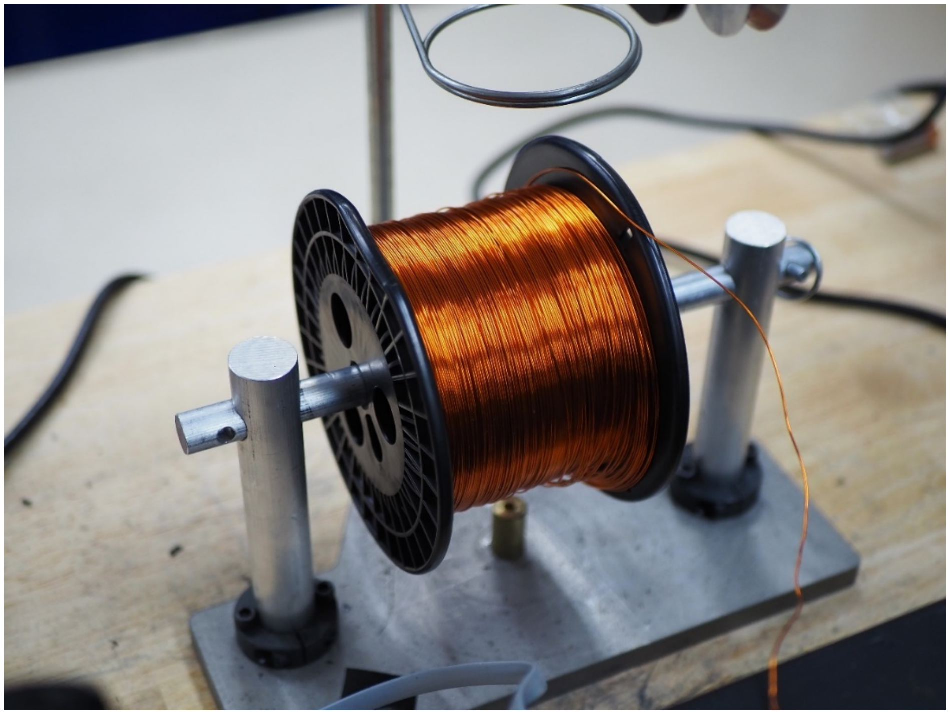


Figure 26. Mounting the spool.

Figure 27. Motor on in the slowest possible setting.

3.2.4 Insert the winding jig

Insert the winding jig into the chuck and tighten hand tight by twising the largest diameter section while preventing the rest of the chuck from spinning.

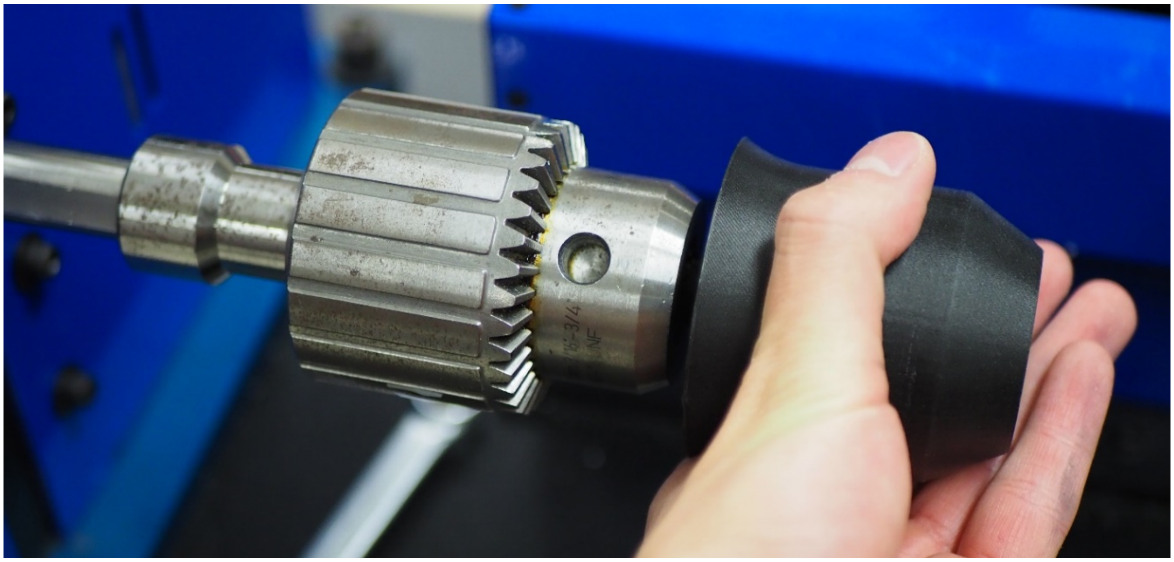


Figure 28. Winding jig inserted into shuck

The dead center on the right should be moved into the piece. The dead center should be tight enough against the jig to prevent wobble but not tight enough to prevent the chuck from spinning. This can be done by loosening the 9/16” nut at the base of the dead center and sliding the dead center into the jig.

Figure 29. Move the chuck into the jig w/ 9/16” wrench.

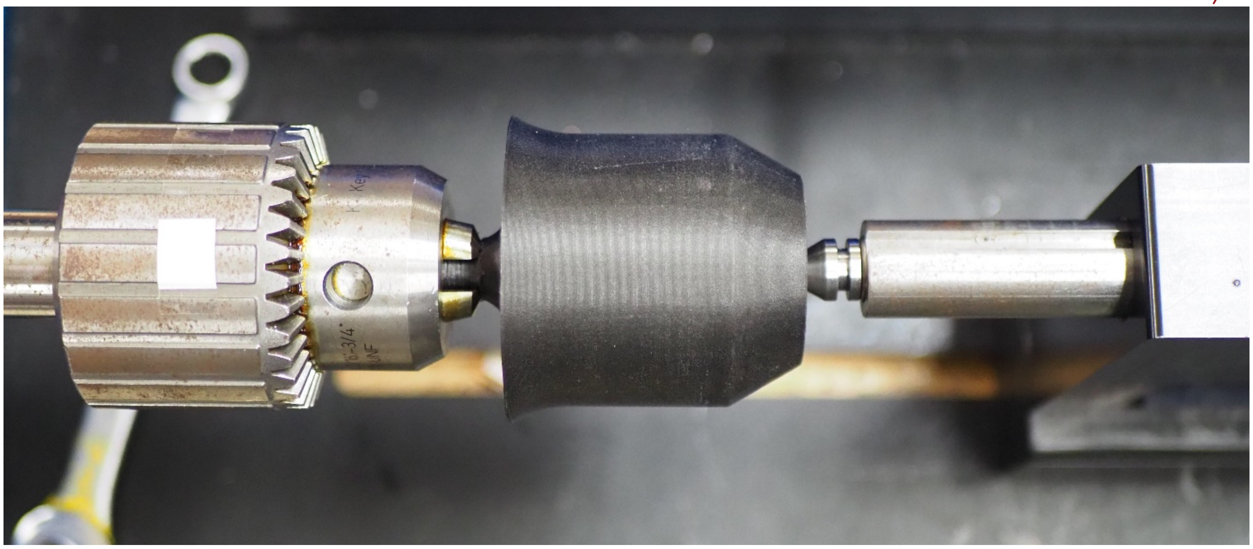


Figure 30. Winding jig tightened in chuck with dead center moved into jig.

3.2.5 Feed the wire through the winder

With the wire fed through the guide loop immediately above the spool, the end of the wire should be clamped down in the chuck to prevent the wire from slipping during the initial windings, as shown in Figure 26 and 27. Note that the powered traverse (gray box on the right) and wire tensioner (the clear spools above the wire spool) are not used.

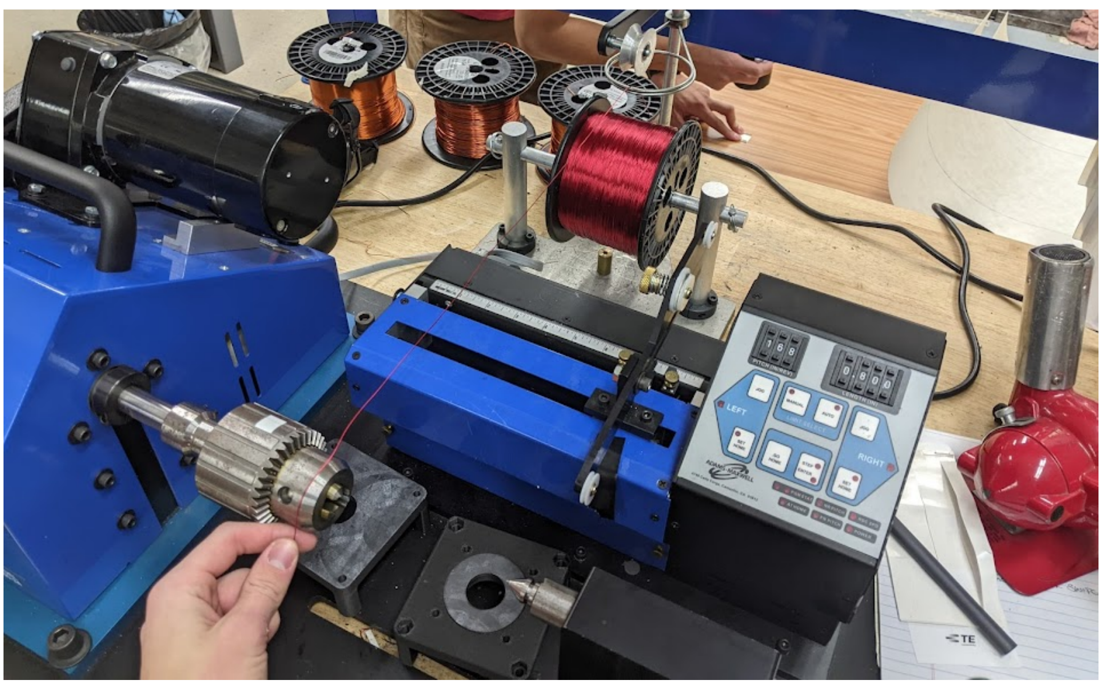


Figure 31. Guide loop threaded with 21-gauge wire from spool (ignore tensioners).

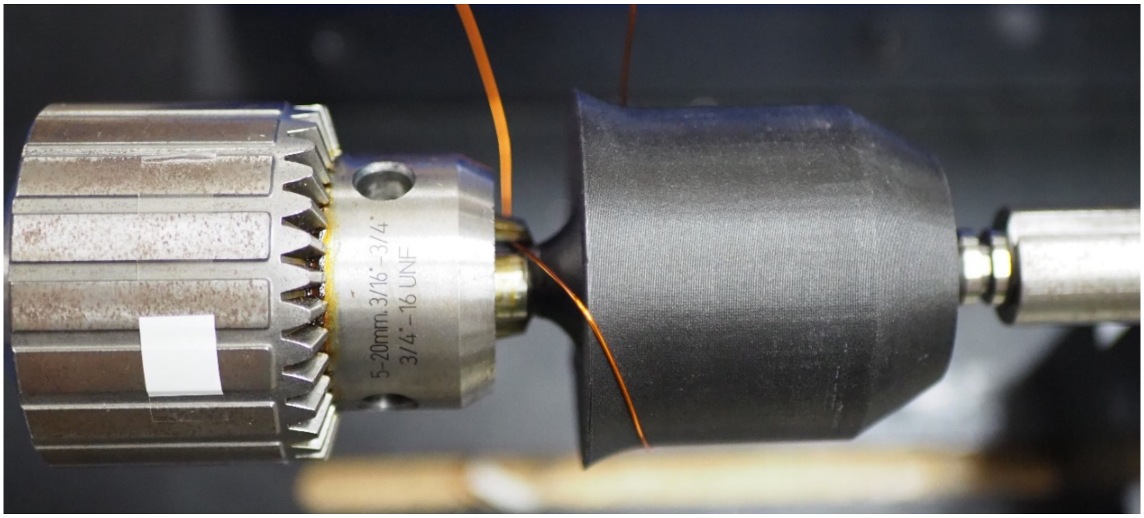


Figure 32. Wire pinched in chuck to prevent spinning.

3.2.6 Begin winding

Once everything is set and the machine is powered, step on the pedal to begin the winding process. Ensure all the windings sit nicely on the jig by guiding it with a finger. The image below shows ideal wrappings, but wrappings can cross and overlap without any drop in performance. Stop the winder when the counter reaches 135 turns. The number of turns is indicated on the panel above the switch and speed settings adjusted previously.

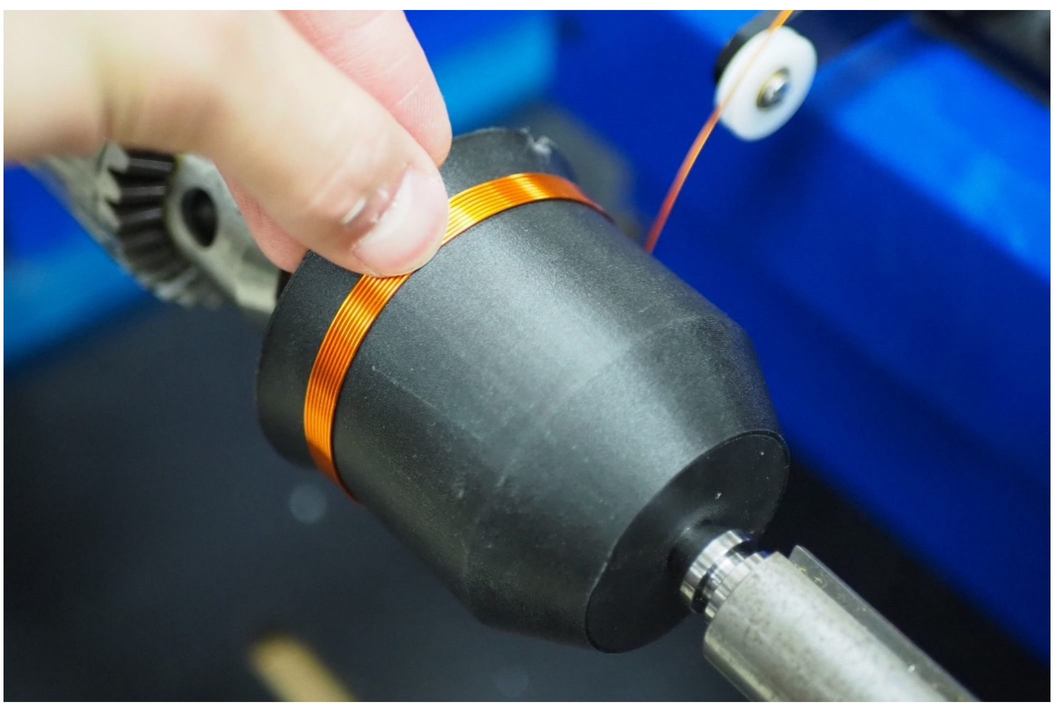


Figure 33. Initial wrappings.

3.2.7 Remove winding from winder

Once finished, grip the wire <u>firmly</u> on the winding jig and hold while cutting the wire. Carefully remove the jig from the chuck while ensuring that the windings do not come undone. Pull the coil from the chuck and use tape or extra wire to secure the coil. Repeat step 3.2.5 to 3.2.7 until you have 6 total coils. Once they are removed from the jig, squeeze them into an oval shape as seen in the image on the right below. This will help with inserting the windings into the stator slots.

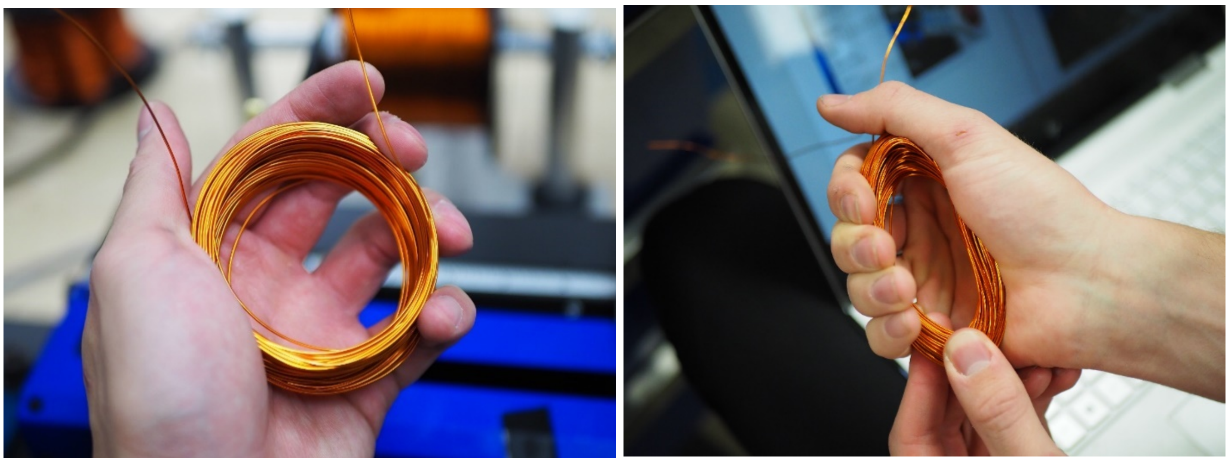


Figure 34. Windings taken off jig.

3.2.8 Insert windings

The next step is inserting the windings into the stator slots. A winding diagram is shown in Figure 35 below. It is crucial that the coils are inserted in the defined orientation. The following steps will outline this process.

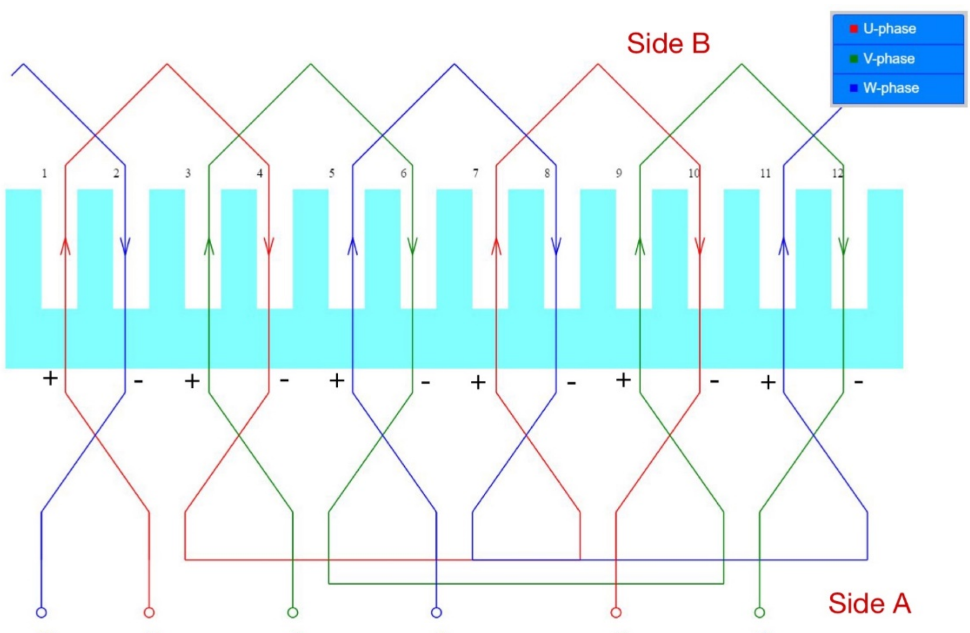


Figure 35. Winding Diagram.

Label the slots and the sides on the stator with a marker as shown in Figure 36 and 37 below.

Figure 36 and **37**. Labeling side and slot numbers on stator lamination.

Take a coil and insert it into one of stator gaps as seen in the Figure 38 below. Slowly and carefully insert the windings into the slots. **Ensure all wire ends are sticking out on Side A.**

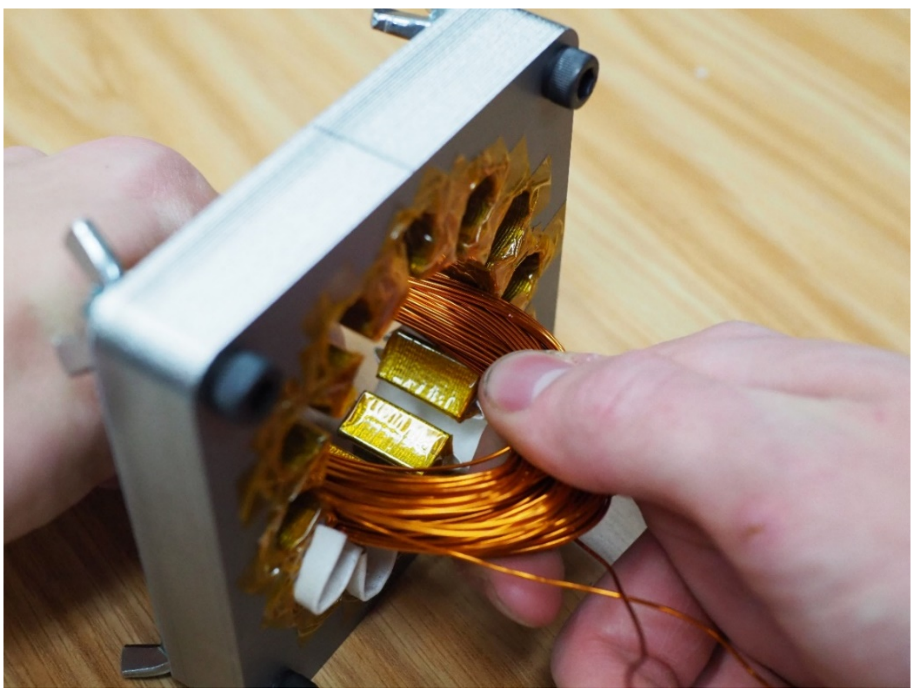


Figure 38. Inserting windings into stator slot.

Once a side is fully inserted, slide the 3D printed retainer above the winding the stator slot to keep windings in place. The retaining tabs were implemented for manufacturability, helping to keep one side of the coil in its respective slot as the other side is pulled to the pairing slot.

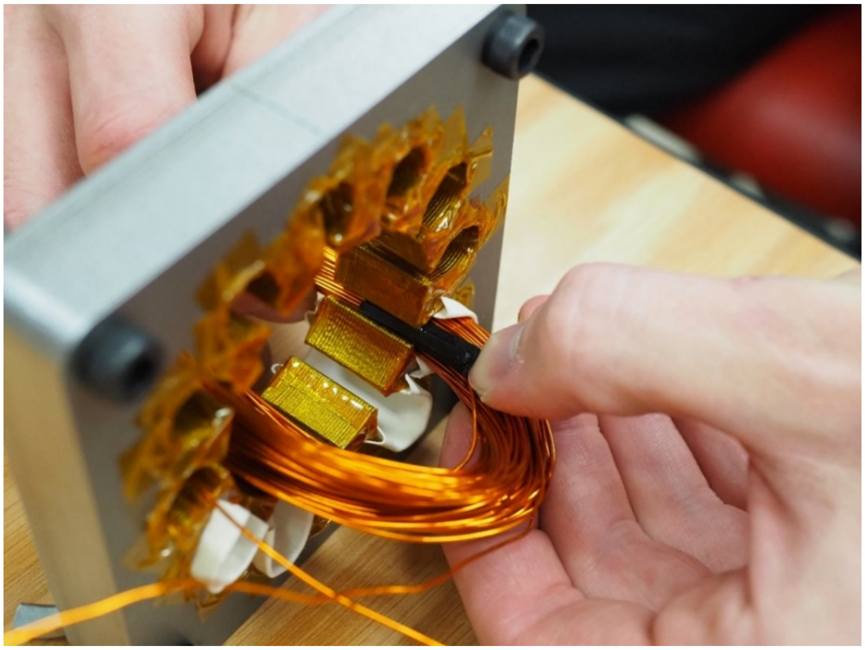


Figure 39. Inserting winding retainer into stator slot.

Repeat this inserting step with the other side of the winding three slots down in either direction from the first. Once this is completed, a screwdriver may be used to help bend the winding out of the way of other slots as seen below. **Be careful and not to damage the varnish on the copper wires by scraping them while inserting the screwdriver.**

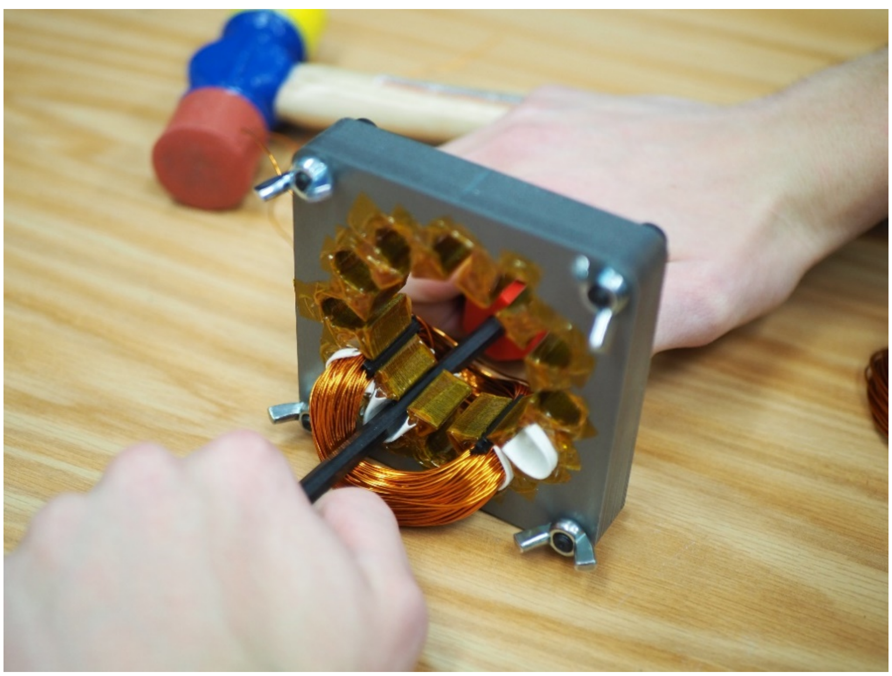


Figure 40. Use a screwdriver to assist bending the coil.

Bend the winding by hand and/or **gently tapping** with a mallet to reduce the endwindings protruding from the slots.

Figure 41. Form the winding shape by hand.

Figure 42. Use a mallet to form the winding.

Repeat these steps to insert the other stator windings until all windings are inserted.

Once the second to last winding is inserted, the first inserted winding will need to be removed so the last winding can be placed underneath the first, making the shape seen below as a final product. Make sure that no windings slip out of the slots while completing this step.

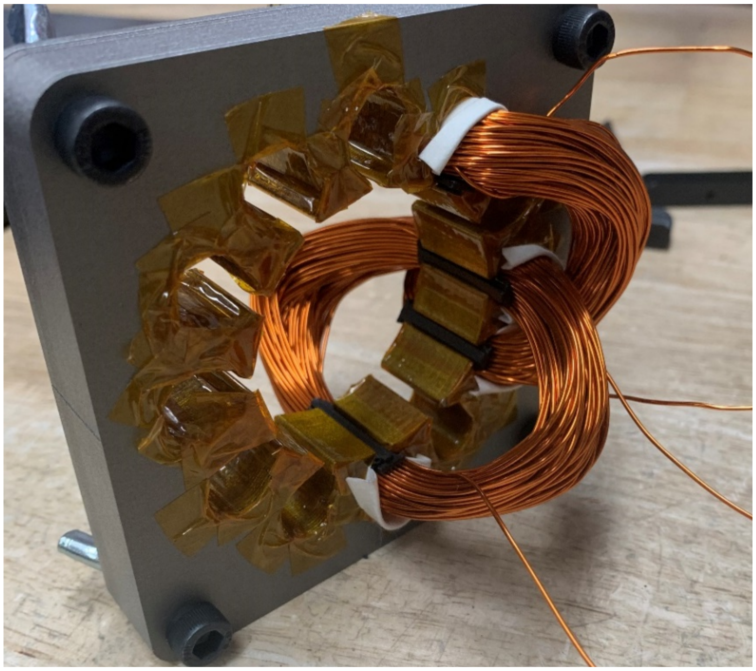


Figure 43. Inserting second winding.

Once the windings are all inserted into the stator, label them based off which slot the wires is coming out of and whether it is a positive or negative terminal as determined by the diagram in Figure 35. Labelling the windings is extremely useful in troubleshooting and to become more familiar with the design in general.

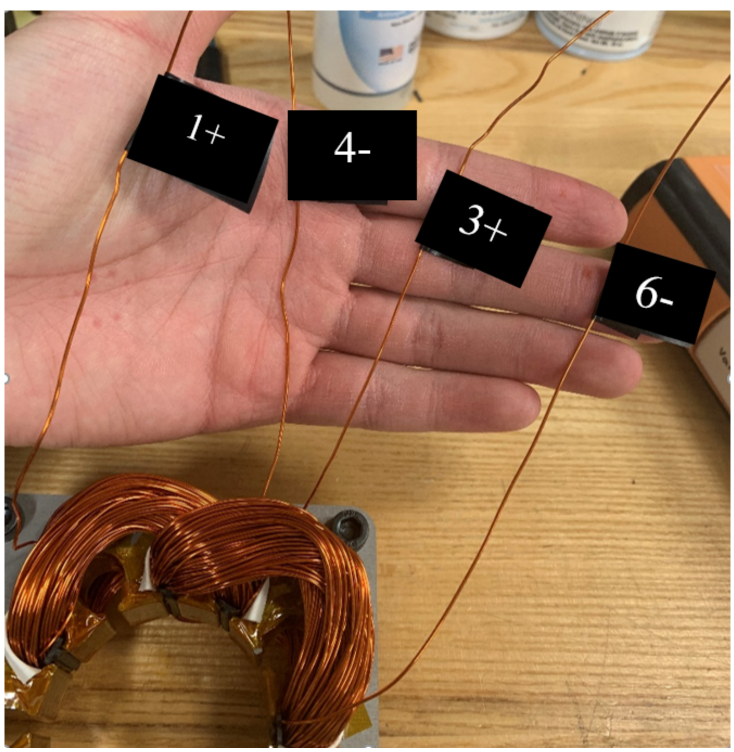


Figure 44. Label each coil terminal with tape.

Figure 45. Stator with all windings inserted.

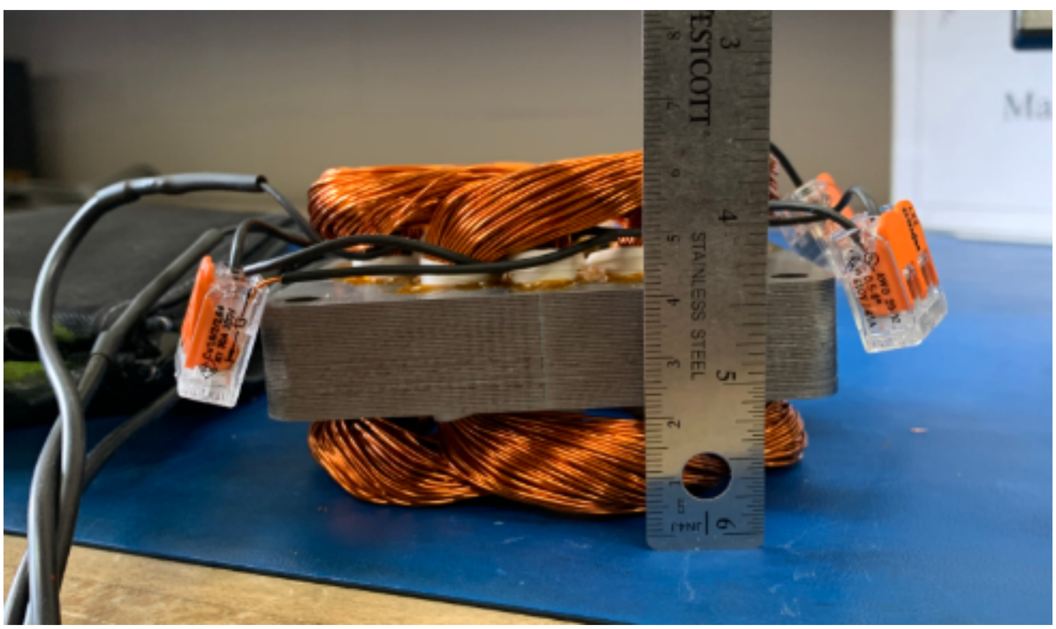


Figure 46. Stator side view.

3.2.9 Apply heat-shrink tubing

Apply heat shrink tubing to each end of the coils to provide protection as shown below in Figure 47. You do not need to apply heat as long as the tubing is relatively snug on the wire.

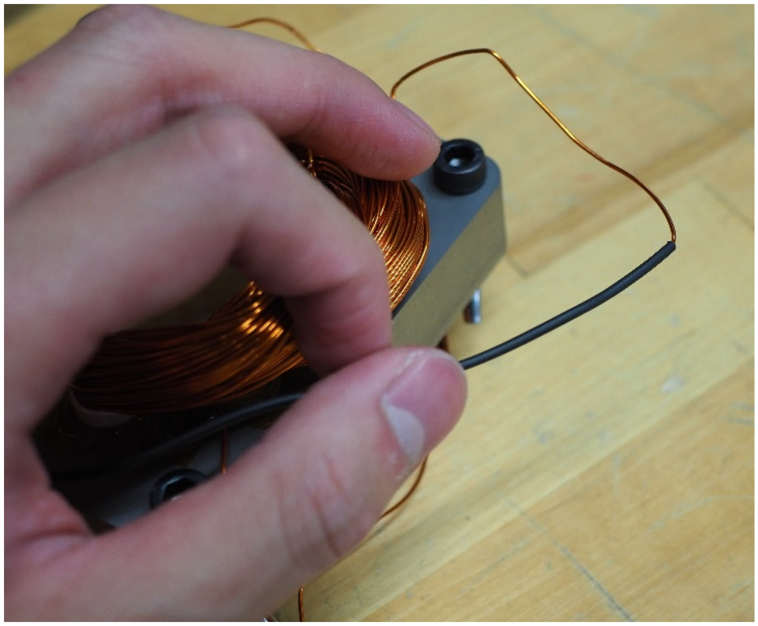


Figure 47. Inserting heat shrink tube to coils.

3.2.10 Perform High-Pot Test on stator windings

To ensure the winding are intact and not shorted to the stator or to other coil, a high-pot test should be performed. When performing the high-pot test, **please ensure that your body does not have any direct contact with the positive lead.**

Figure 48. A high-pot test machine.

When presetting the high-pot test machine, **set the AC voltage to double the working voltage, threshold current to 0.1mA and cutoff current at 3.5mA.** Then, connect the positive lead to one of the coils and the negative lead to one of the wingnuts as shown in figure 49 below.

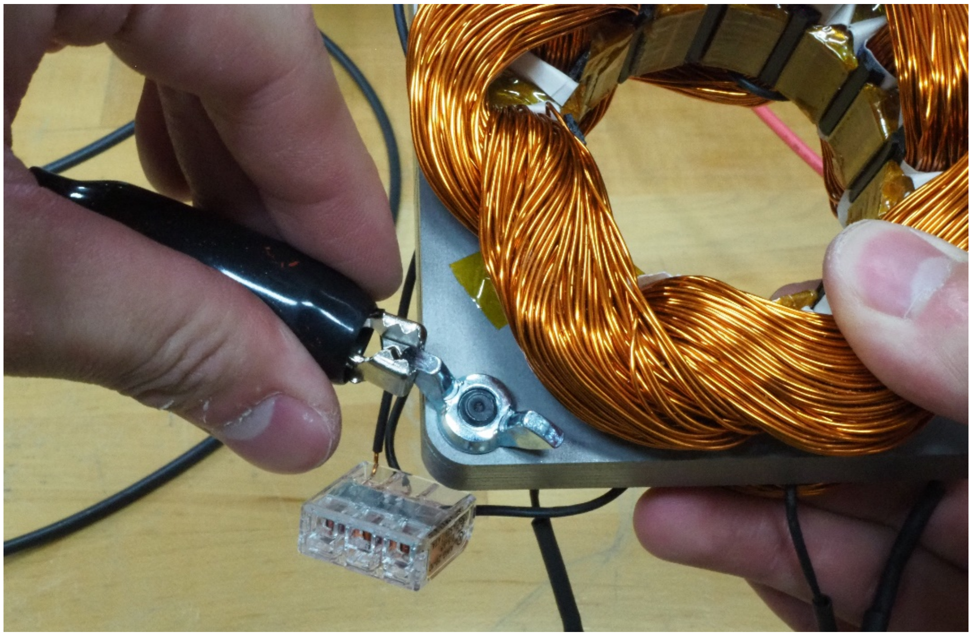


Figure 49. A high-pot test machine.

Before performing the high-pot test, make sure to use an insulation mat to cover the motor and leads to prevent possible shorts.

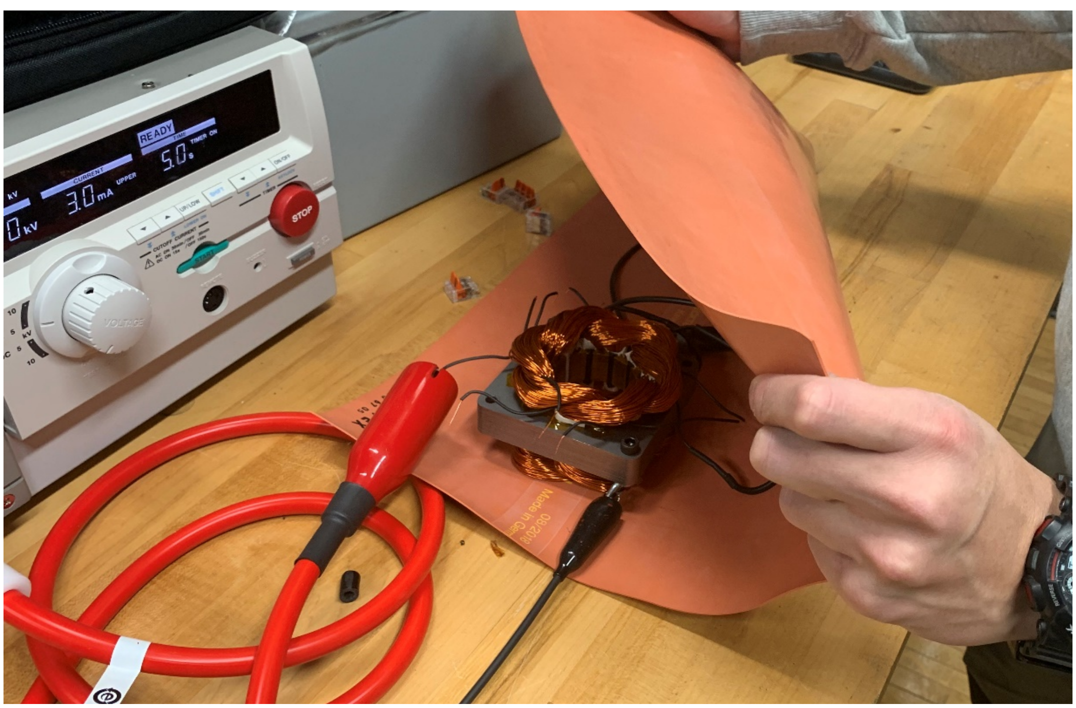


Figure 50. Covering motor with insulation mat when performing high-pot test.

If the test fails, a buzzer will go off and the “FAIL” indicator will show up on the high-pot machine’s digital display.

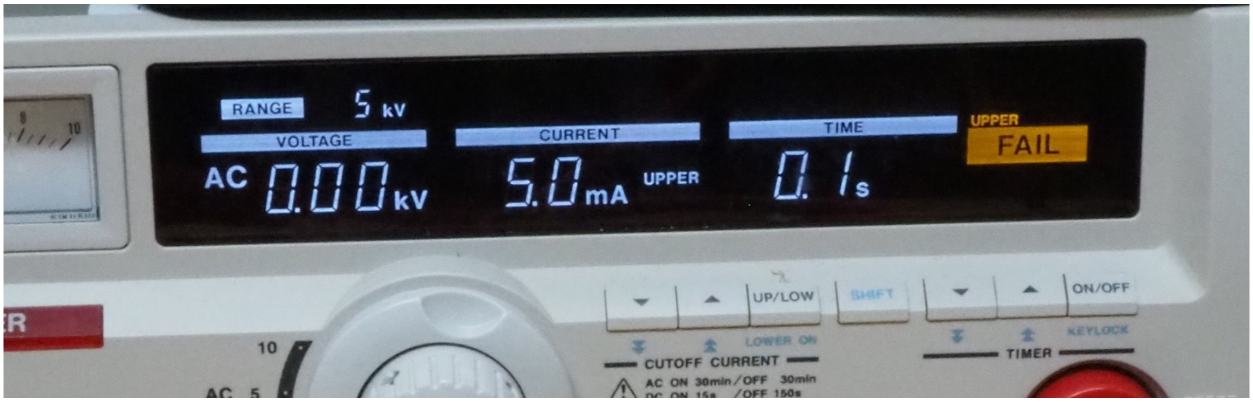


Figure 51. High-Pot machine when test failed.

A failed test indicates that the coil is shorted to the stator lamination. To resolve this, you can either insert more insulation paper or swap out the problematic coil with a new one. Repeat this test for all coils in the stator.

3.2.11 Connecting coils

Once the hot-pot test has passed for all the winding coils, use clamp down wire connectors to connect all coils according to Figure 35 where wire 4 connects to 7, 6 connects to 9, and 8 connects to 11. Note, this motor is connected in a STAR configuration, terminals coming out from slots 10, 12 and 2 are all connected with a three-way clamp down wire connector to cancel out the current input of all windings.

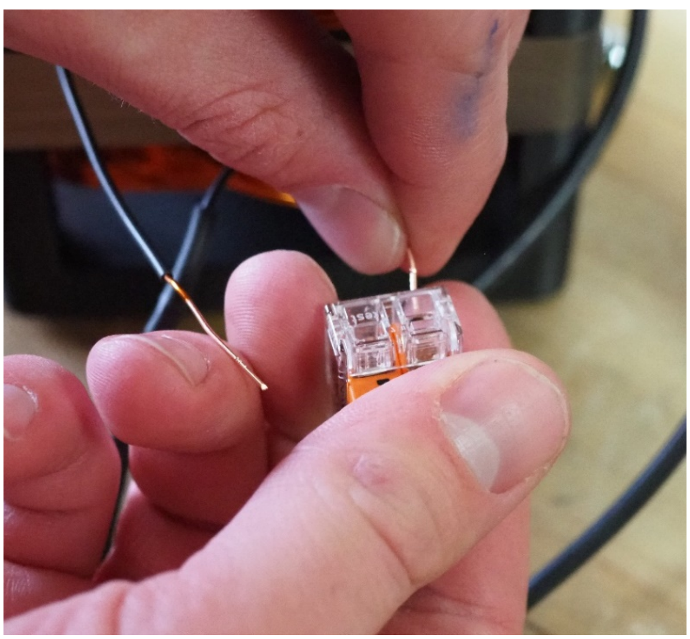


Figure 52. Connecting coils using clamp down wire connectors.

3.2.12 Soldering U, V and W terminals to banana plugs.

Solder the remaining U, V and W terminals (1, 3, & 5) to banana plugs to finish the stator assembly shown in Figure 53.

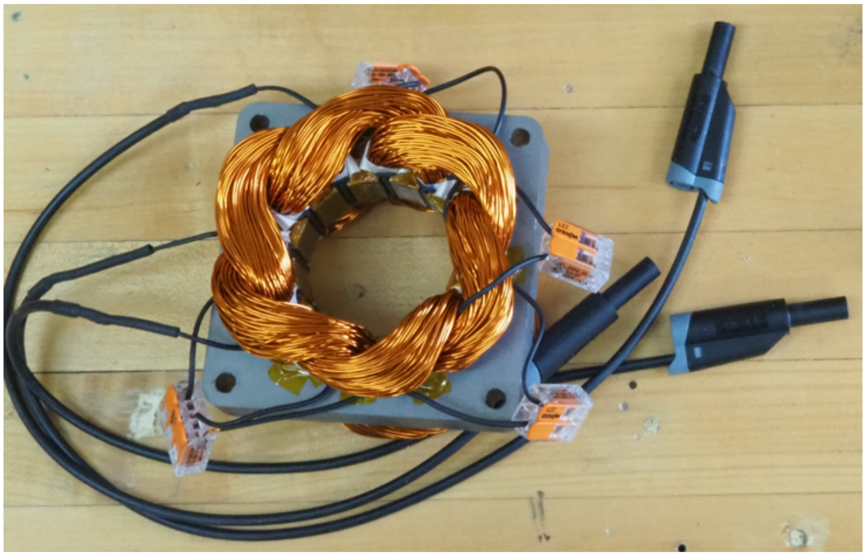


Figure 53. Final stator assembly with banana plugs connected.

3.3 End Plates

Two carbon fiber impregnated nylon end plates are printed to house the stator, bearings, and rotor. The end plates ensure proper alignment between the stator and rotor. Together the end plates form a housing around the motor and provide structure for wire management. Additionally, the endplates also serve a purpose of mounting to a test stand for performance evaluation. This endplate design specifically uses the IEC 63 standard for the mounting feature.

Take precautions to not break the extruded mounting holes off the end plates.

Parts and Materials

Table 4. Parts needed for end plate assembly.

Part	Quantity
3D Printed End Plate (Circular Mounting Holes)	1
3D Printed End Plate (Hex Mounting Holes)	1
25mm ID No. 6201 Ball Bearing	2
M4 Threaded Inserts	4

3.3.1 Insert the bearings

Insert a bearing on each endplate. The hole should be snug enough to hold the bearings in place after insertion. If needed, use a rubber mallet to tab the bearing into place. Ensure that the bearing is parallel to the end plate face. The end plate without the emboss feature will be the top of the motor and requires no further assembly.

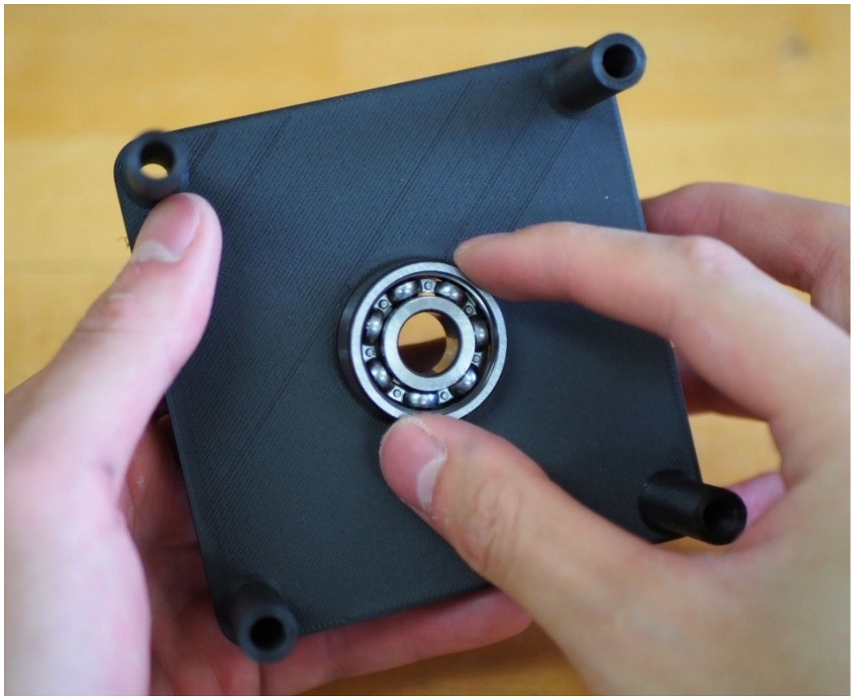


Figure 54. Inserting the bearings.

3.3.2 Insert the threaded inserts

Using a heated soldering iron, press down on the threaded inserts, placed near the center boss as shown below in Figure 55. The end plate material will melt away, allowing the threaded insert to be put in place. Ensure that the inserts are placed straight. Take precautions to not melt other parts of the endplate when using the soldering iron. Repeat this step for all the through holes. This end plate will be the bottom of the motor housing.

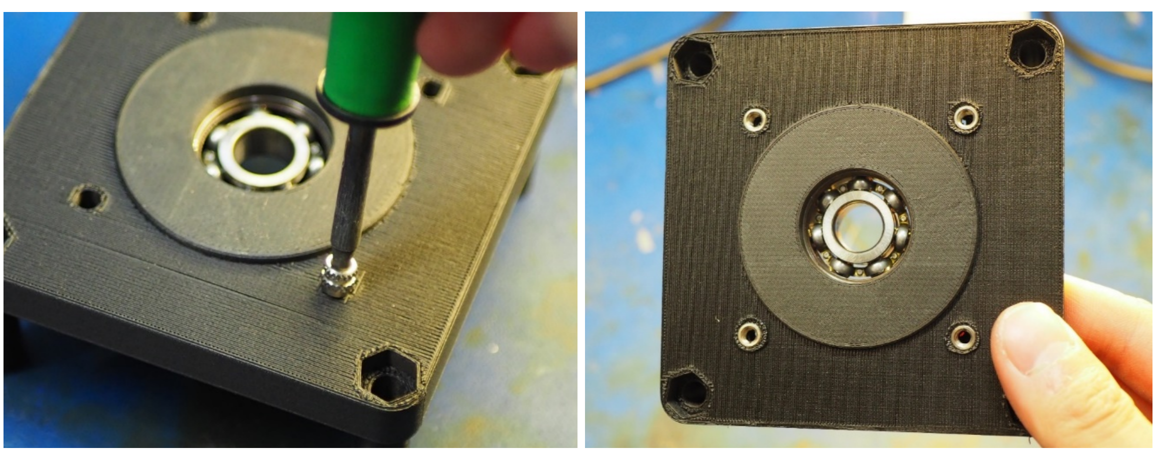


Figure 55. Thermosetting the threaded insert with a heated soldering iron.

3.4 Final Assembly

The final assembly process is quick and simple. All components should now be ready to be placed into the final assembly. These include the end plates, stator, rotor, and M6 bolts with locking nuts, as shown in Figure 56.

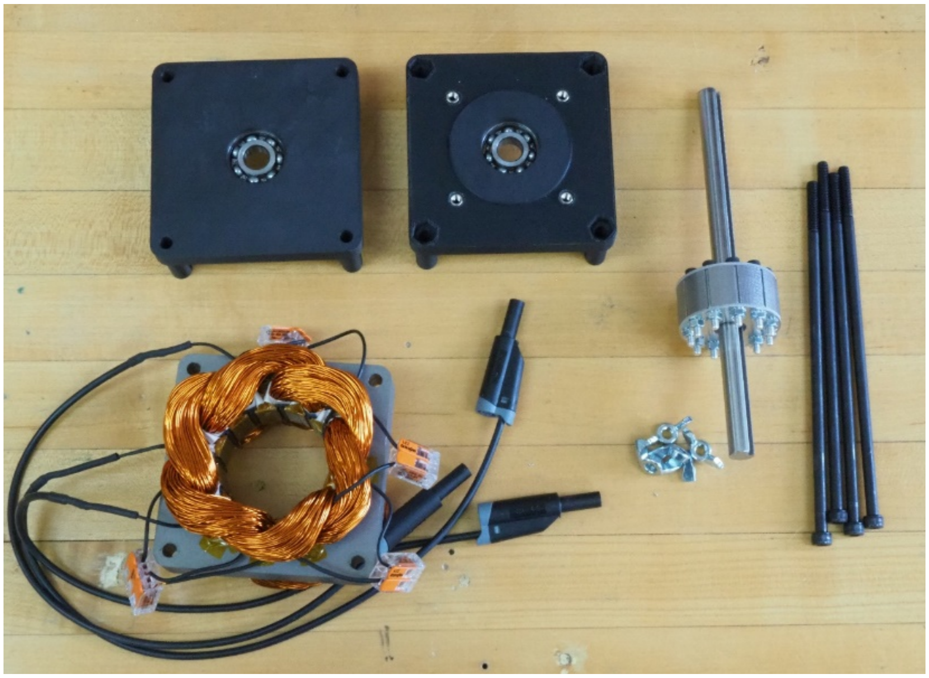


Figure 56. Parts prepared for final assembly.

Parts and Materials

Table 5. Parts needed for final assembly.

Part	Quantity
End Plate with Bearing	1
End Plate with Bearing and Threaded Insert	1
Completed Stator Assembly	1
Completed Rotor Assembly	1
M6 130mm Bolts	4
M6 Locking Wing Nuts	4

3.4.1 Placing the M6 bolts into position

Place the bolts into the end plate that has the four now threaded sections towards the middle as shown in Figure 57.

Figure 57. Placing the M6 bolts into the end plates.

3.4.2 Place the stator assembly into position

Place the four corners of the stator assembly through the bolts with the terminals facing up as shown in Figure 58.

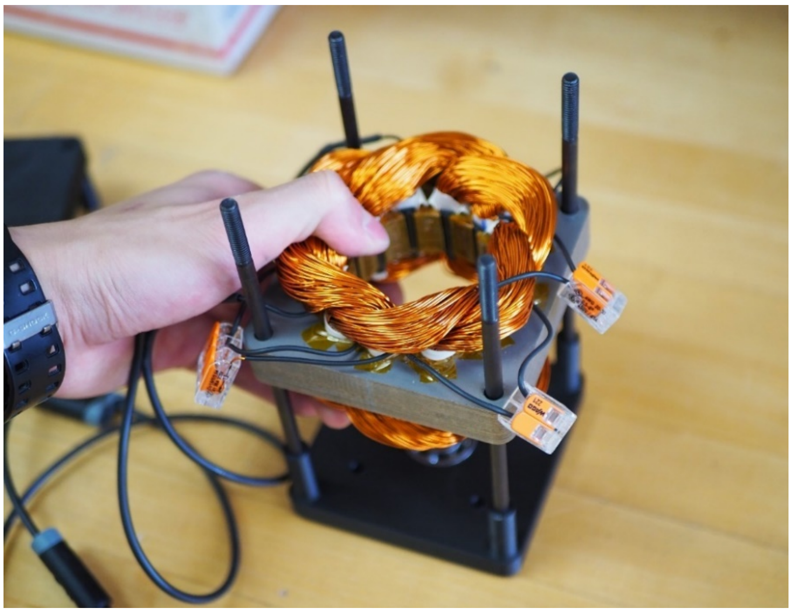


Figure 58. Adding the stator to the final assembly.

3.4.3 Place the stator assembly into position

Ensure that all the windings are out of the way so the rotor assembly can fit and spin without any interference. Place the rotor with the top of the bolts placing upward. Force will need to be applied; push until the rotor is flush with the stator as shown in Figure 59.

Figure 59. Adding the rotor to the final assembly.

3.4.4 Place the other end plate and complete the assembly

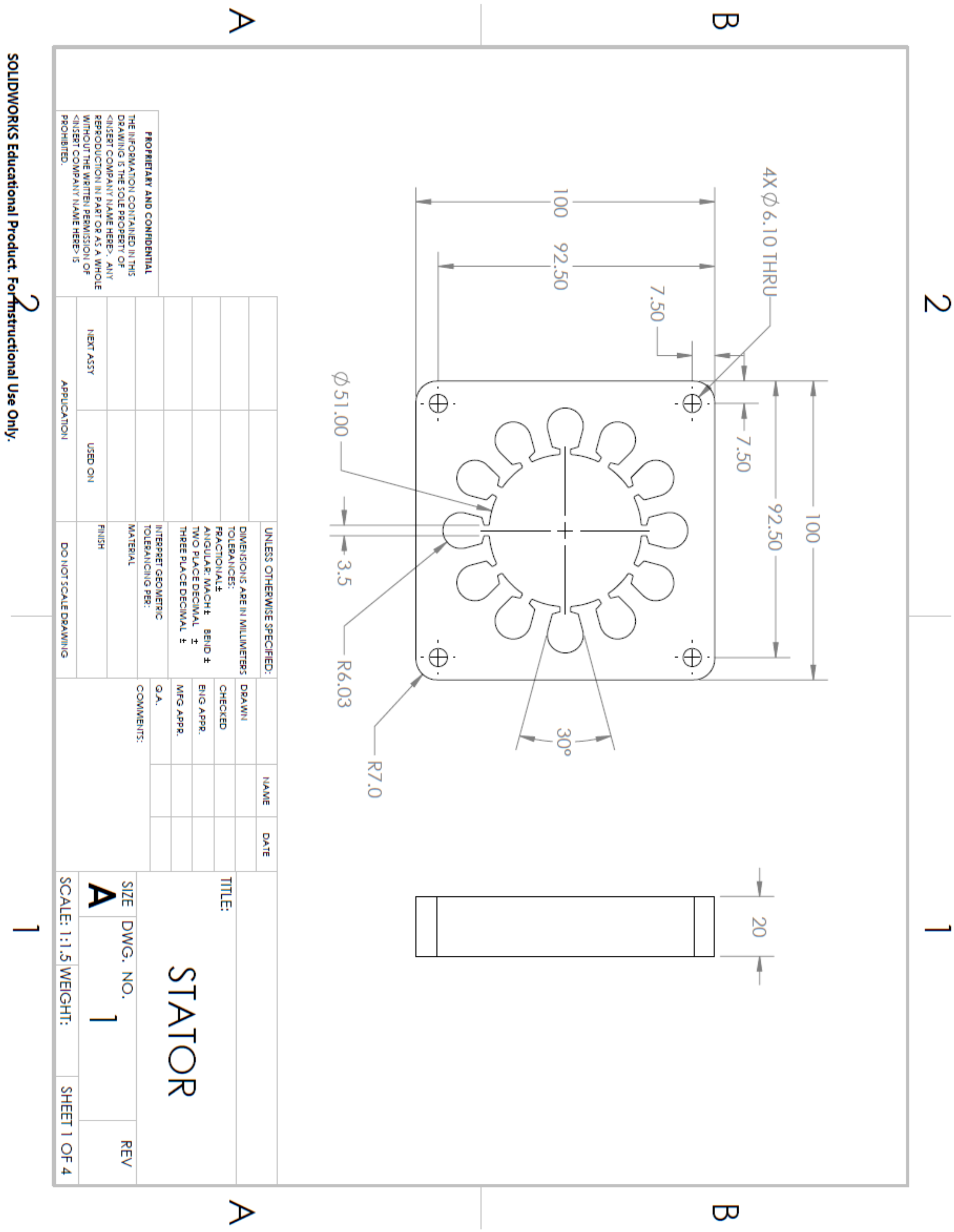
Place the second end plate through the bolts as shown in Figure 60. Use the nuts to keep the end plates in place. Finally, ensure the stator and rotor assemblies are placed at the center in between the two end plates.

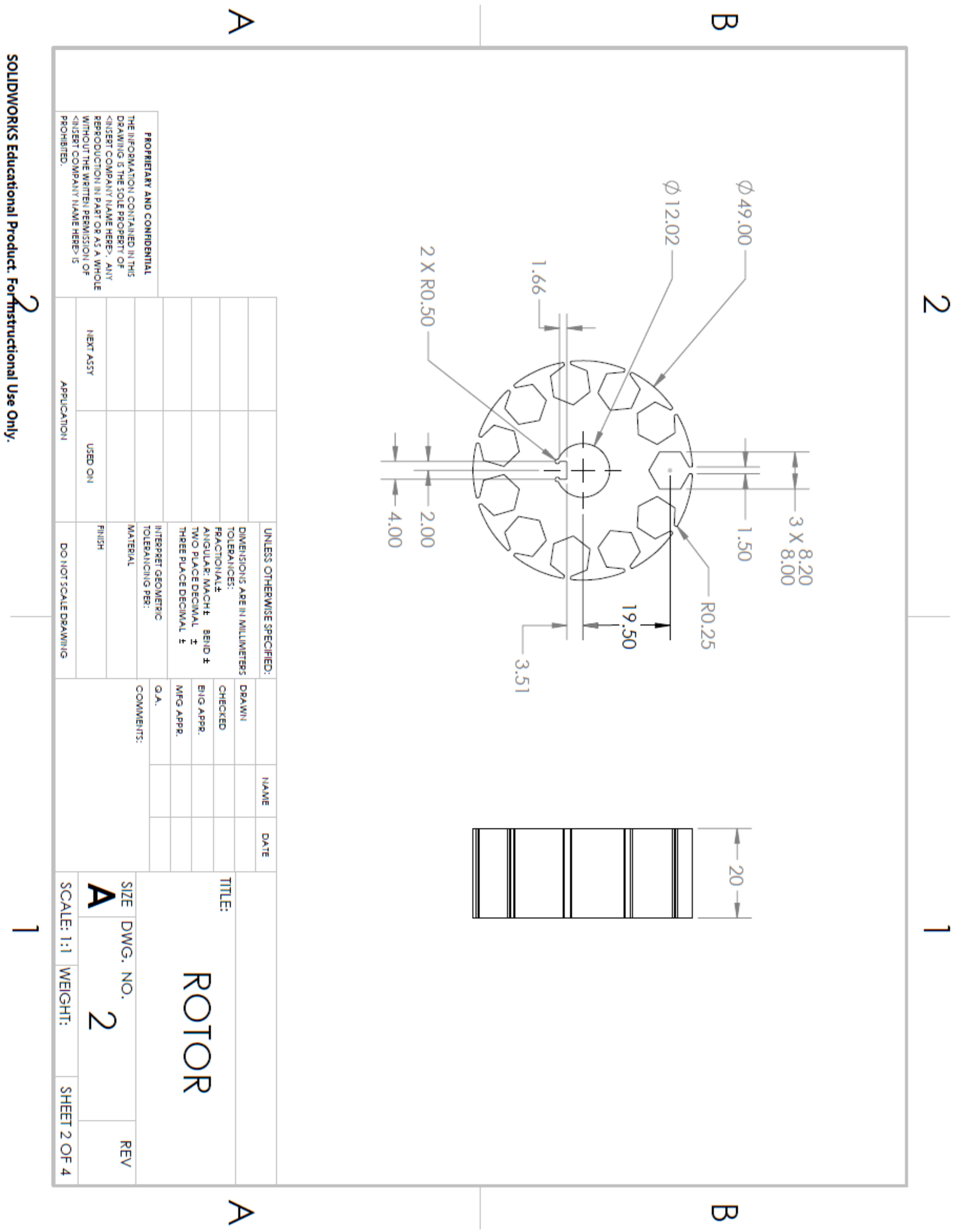
Figure 60. Adding the second end plate to the final assembly.

Figure 61. Fully assembled induction motor.

4 Appendix

4.1 Drawings





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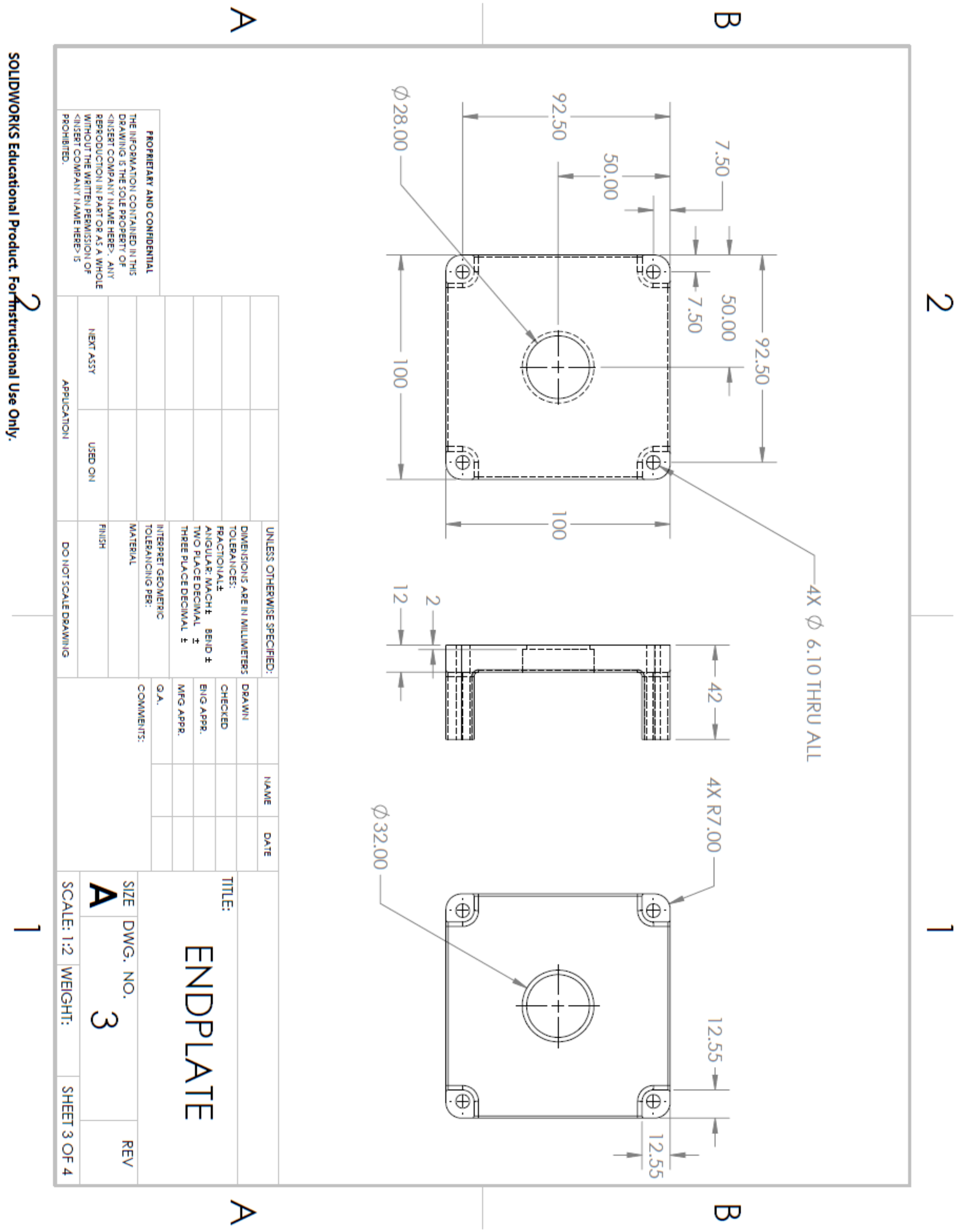

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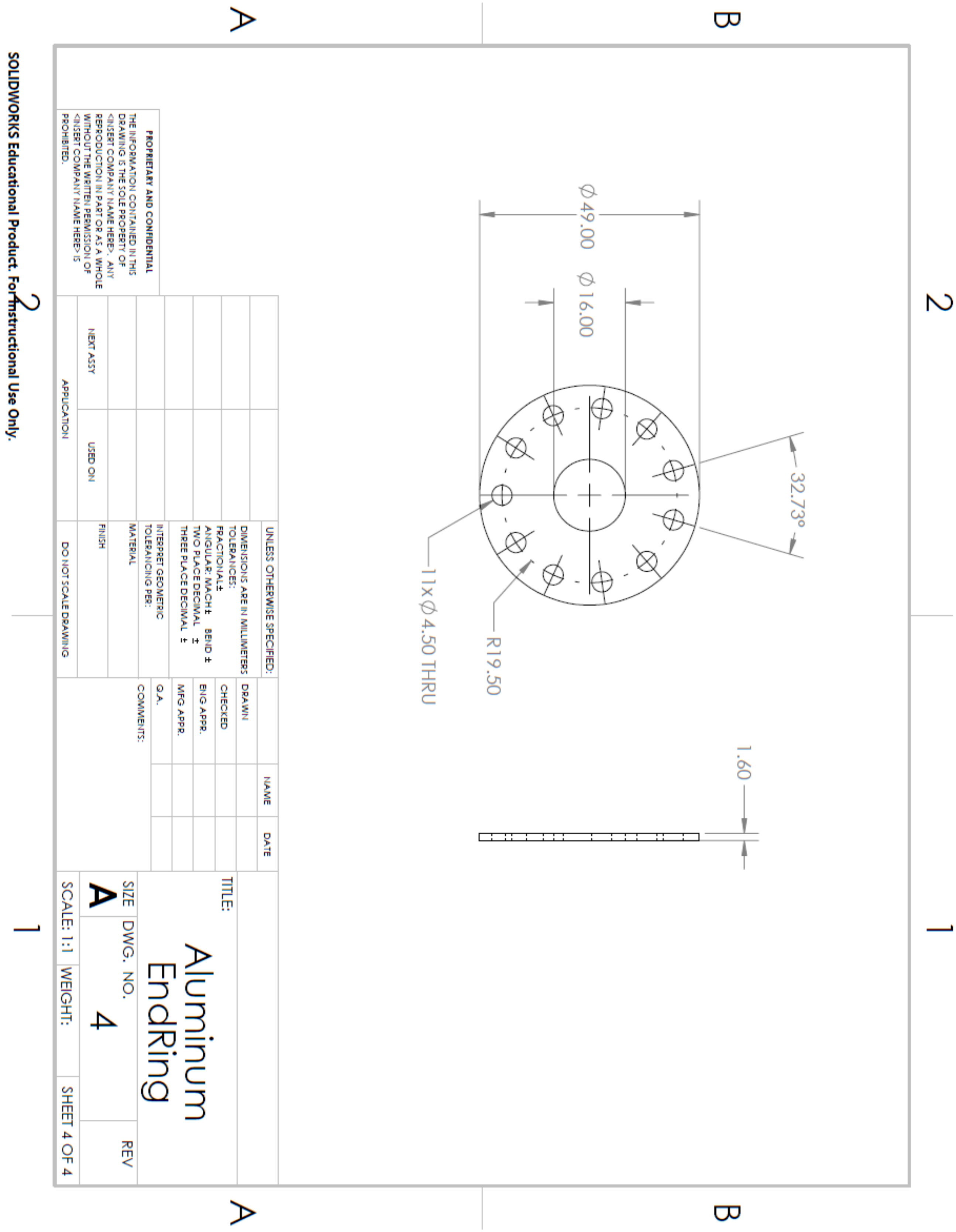
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