

**Tolerance Assigning, Machining and Testing of a Two-Part Assembly**

**Manufacturing Processes ENGR 3350-001**

**Team 9**

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## LIST OF NOMENCLATURE

- ° - Degree of an angle
- ∅ - Diameter of a circle
- RPM – Rotations per Minute  $\left(\frac{rev}{min}\right)$

- $\delta$  - Minimum Radial Interference (*in*)
- $\nu$  - Poisson's Ratio ( $\frac{in}{in}$ )
- $E$  - Young's Modulus  $\frac{lb}{in^2}$
- $\mu$  - Coefficient of Friction
- $w$  - Thickness of the plate (*in*)
- $T$  – Torque ( $FT - lbs$ )

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|                                                    |        |
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## ABSTRACT

The end goal of this lab was to machine two parts which would combine into an assembly that can succeed the final test to hold 10 foot-pounds of force without the shaft turning. The assembly was constructed with 2 6061-T6 Aluminum pieces, specifically a 3" by .5" bar and a 1" shaft. The dimensions for the part were given by the dimension guidelines and allowed  $\pm 0.005$ " tolerance. To machine the assembly, the parts were cut, milled, and drilled. This was accomplished using the Metal Mizer band saw, the Enco and the Acer milling machines, and the Jet lathe. The parts completed the progression tests which allowed the assembly to be created and complete the final torque test without the shaft slipping, meaning the contact pressure did not exceed the yield strength of the material.

## INTRODUCTION

The goal of the experiment was to machine and assemble a part to hold 10ft-lb of torque using a press fit between the reduced diameter shaft and the center hole of the plate. The plate was cut using the Metal Mizer bandsaw, milled to size using the Acer milling machine, and drilled using the Enco milling machine. The plate was tested after all five holes were drilled by bolting the four corners to the given test plate to see if all the bolts could be fastened. The shaft was cut using the Metal Mizer bandsaw, turned using the Jet lathe to 2.50" length, tapped  $\frac{3}{4}$  of an inch deep with  $\frac{1}{4}$  - 20 thread, and the opposite end's diameter was reduced with the same lathe. The shaft was tested after the center threading was completed by threading a bolt through it until the bolt was flushed with the shaft. Lastly, the parts were assembled with the Strong Way 20-ton press. The assembly was tested by bolting it to the vertical holder and attaching a 1 ft arm with a

10 pound force to see if the shaft would pass the test. The parts passed each test, which allowed the assembly to pass its final test.

## THEORY

In the lab, an assembly was created with an interference fit for the rod inserted into the plate. The part specified that an interference fit of  $\pm 0.003 - 0.005$  inches was required. This means that the reduced diameter of the rod should be larger than the diameter of the hole it is being inserted into. More importantly, the part must manage to hold a 10ft-lb torque applied to the shaft. Knowing the minimum interference needed proved useful in making sure the assembly did not fail the 10ft-lb torque test. The theoretical interference fit that would be able to support a 10ft-lb torque test can be calculated by using this equation [1].

$$p = \frac{\delta}{\frac{d}{E_o} \left( \frac{d_o^2 + d^2}{d_o^2 - d^2} + \nu_o \right) + \frac{d}{E_i} \left( \frac{d^2 + d_i^2}{d^2 - d_i^2} - \nu_i \right)} \quad (1)$$

The formula listed will calculate the pressure that is exerted over the area where the two pieces contact. There are a few parameters that the equation takes into consideration. The first two variables  $E_o = E_i = 10,000,000$  PSI, are Young's modulus for Aluminum. It defines the rubber like characteristics of your material; this assembly only used one material, so the variables are equal. The next variable is  $\delta$  and this variable defines the maximum radial interference. The maximum radial interference for our part was 0.005 inches. The next variable in the equation is  $\nu$  which is Poisson's ratio. This defines the change in height versus the change in cross sectional area. Again, since the parts are only using one material the two values  $\nu_o = \nu_i$  this value will be 0.330. Finally, there are three diameters that must be account for  $d, d_i, d_o$ . The first variable  $d$  is 0.750 inches and that represents the theoretical diameter of the drilled center hole for the calculations. The next variable is  $d_i$ , this is the shafts internal diameter. For this part, an internal diameter of 0.00 inches was used, as there is no hole drilled through the entire shaft.

Finally, the last variable is  $d_o$ , this diameter is the outer diameter of the shaft which is 1.00 inches for the part. Knowing that this is the maximum pressure that is exerted within the part allows for the calculation of the force. Another equation is used to solve for force [2].

$$F = \mu \cdot p_{max} \cdot A \quad (2)$$

When calculating force, the area where the shaft contacts the plate must be solved. Area can be solved by measuring the diameter drilled center hole, denoted by  $d$ , and multiplying it by  $\pi$  to calculate the circumference and  $w$  represents measured the th'k

. This comes together with the next equation [3].

$$A = \pi d \cdot w \quad (3)$$

The other variable listed in equation [2] is  $\mu$ . This equation can be used to solve the force exerted with respect to the pressure obtained from equation [1], and it is the coefficient for friction, this coefficient allows for the calculation of the friction force generated from the exerted pressure over the area. The value of  $\mu$  for the assembly for all the calculations will be equal to 0.33. Once equation [2] is solved, then the variables can be plugged into the following equation [4].

$$T = F \cdot \frac{d}{2} \quad (4)$$

From this equation you can solve the torque required for the shaft to slip in the drilled hole. The only new variable is  $d$ , which is just the diameter of the drilled center hole.

## EQUIPMENT

The Acer milling machine had a turning velocity of 300 RPM and was used to mill the plate to the correct size of a three-inch square ( $\pm 0.005$ ). The machine had increments of .002 inches and allowed for automatic movement of the clamped bed to achieve a smooth and steady cut. The assembly was also set into the Acer milling machine to mill the 0.156-inch notch in the shaft.

The Enco milling machine had a turning velocity of 270 RPM and was used to drill the five holes into the plate. The machine allowed the center drill bit to make a pilot hole and keep the exact location while the center drill bit was switched for  $\frac{3}{8}$  inch or the  $\frac{3}{4}$  inch drill bit. Allowing for exact placements of the holes.

The Jet lathe machine had a turning velocity of 415 RPM and was used to turn the shaft to the final required size. The machine had increments of .002 inches and allowed for automatic movement of the tool post to achieve smooth and steady turning. The Jet lathe was also used to reduce the diameter of the shaft and to chamfer the edges of the shaft. The tailstock on the lathe was used to drill the hole to start threading.

The Metal Mizer band saw machine had a blade velocity of 14 inches per second and was used to cut the Aluminum bar stock and shaft stock. Extra length ( $\frac{1}{8}$  inches) was added to the needed measurement to account for the kerf and blade drift.

The Strong Way 20-ton press fit machine was used to press fit the two parts together, creating the assembly.

## PROCEDURE

### PLATE

Step 1. A 3" by  $\frac{1}{2}$ " Aluminum bar was cut using a Metal Mizer band saw to  $3 + \frac{1}{8}$ " length, with a 14 inches per second cutting velocity.

Step 2. The Aluminum plate was clamped in the Acer milling machine, with a 300 RPM velocity.

Step 3. One side of the plate was slab milled to obtain a machined finish (Figure 1).



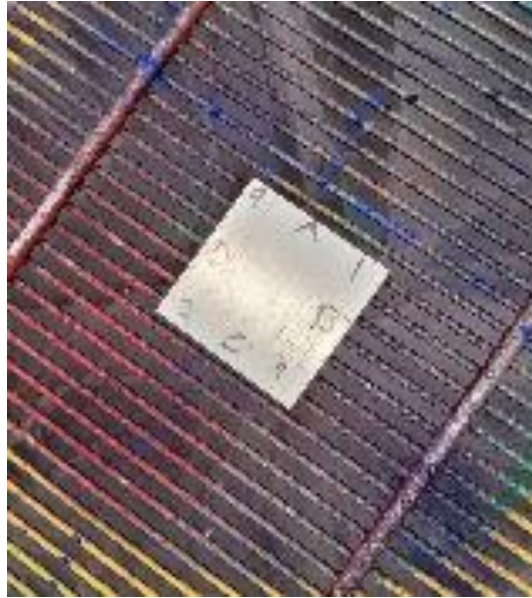
*Figure 1. The plate being slab milled*

Step 4. The opposite side of the Aluminum plate was face milled using a 4 flute endmill to create a length of  $2.994 (\pm 0.005)$  inches (Figure 2).



*Figure 2. The plate being face milled on the Acer milling machine*

Step 5. The plate was sprayed with marking blue spray paint (Figure 3).



*Figure 3. The labeled plate ready to be sprayed with marking blue*

Step 6. A height gage was used to mark crosses 2.25" at the corners of the plate and to mark a cross at the center of the plate.

Step 7. The plate was set into the Enco milling machine, with a 270 RPM.

Step 8. The Aluminum plate was tapped at one of the four corners, at the mark from the height gage, using a drill tap.

Step 9. A 4 flute  $\frac{3}{8}$ " drill bit was used to through drill the tapped hole.

Step 10. Steps 8-9 were repeated until all 4 corners were through drilled.

Step 11. A 4 flute  $\frac{3}{4}$ " end mill was used to through drill the center creating a center hole 0.756 inches in diameter.

Step 12. The plate was bolted onto the test piece to ensure the four corner holes were correctly drilled (Figure 4).



*Figure 4. The plate passing the bolt test*

## SHAFT

Step 1. A 1" Aluminum round stock was cut using a Metal Mizer band saw to  $2.5 + \frac{1}{8}$ " length, with a 14 inches per second cutting velocity.

Step 2. The shaft was set in the Jet lathe, with a 415 RPM velocity.

Step 3. The Aluminum shaft was turned to 2.502 inches in total length (Figure 5).



*Figure 5. The shaft on the Jet lathe being turned to 2.502 inches*

Step 4. The drill tap was set into the tailstock.

Step 5. The drill tap was used to machine a pilot hole into the shaft.

Step 6. The  $\frac{1}{4}$  inch drill bit was set into the tailstock.

Step 7. The tailstock and machine oil were used to drill a hole with  $\frac{3}{4}$ " depth into the center of the shaft (Figure 6).



*Figure 6. The shaft on the Jet lathe after the center hole has been drilled*

Step 8. The  $\frac{1}{4}$ " drill bit was removed, and a taper tap was set into the tailstock.

Step 9. The tailstock and the Jet lathe were manually turned to produce the taper threads.

Step 10. While the taper tap was inside the shaft, the taper tap was removed from the tailstock.

Step 11. An adjustable tap wrench was used to remove the taper tap.

Step 12. An adjustable tap wrench and a plug tap were used to create deeper threads in the shaft.

Step 13. An adjustable tap wrench and a bottom tap were used to create deeper threads in the shaft.

Step 14. Machining oil was used in steps 9, 12, and 13 to lubricate and remove chips.

Step 15. A bolt was screwed into the center hole to ensure the shaft was threaded correctly (Figure 7).



*Figure 7. The shaft with bolt fully threaded*

Step 16. A file and the Jet lathe were used to create a 0.05" x 45° chamfer on the shaft.

Step 17. The shaft was removed and was set in the Jet lathe with the non-chamfered side exposed.

Step 18. The Aluminum shaft was turned to reduce its diameter to 0.758 inches for  $\frac{1}{2}$  inches in length.

Step 19. A file was used to create a 0.01" x 45° chamfer on the shaft of the reduced diameter.

## TWO-PART ASSEMBLY

Step 1. The Strong Way 20-ton capacity press was used to insert the 0.758 inches diameter side of the shaft into the 0.756 inches center hole of the plate.

Step 2. The assembly was set into the Acer milling machine, with a 300 RPM velocity.

Step 3. A  $\frac{5}{8}$ " length by .156" depth cut was machined into the 1" diameter shaft.

Step 4. The assembly was attached to an arm of 1 ft length with a 1.1 lb<sub>f</sub> hanger and a 10 kg disk attached to the end (Figure 8).



*Figure 8. The completed assembly enduring the 10 foot-pounds of force*

Step 5. Ending the assembly, a ball-peen hammer and a punching kit were used to imprint the semester, year, Team 9 and the initials of the group members (Figure 9).



*Figure 9. The completed assembly with the team number, semester, year, and initials*

## DATA

Table 1: Final Measured Values of the Plate

| Final Side Length of Square Part |                 |
|----------------------------------|-----------------|
| Side                             | Length (inches) |
| A                                | 2.994 inches    |
| B                                | 3.004 inches    |
| C                                | 2.992 inches    |
| D                                | 3.003 inches    |

Table 2: Shaft Measurements

| Final Shaft Dimensions (inches) |              |
|---------------------------------|--------------|
| Total Length                    | 2.502 inches |
| Reduced Shaft                   | 0.758 inches |
| Full Shaft                      | 1.000 inch   |
| Length Reduced                  | 0.242 inches |

Table 3: Center Hole Diameter

| Center Hole Diameter |              |
|----------------------|--------------|
| 1 Diameter           | 0.756 inches |
| 2 Diameters          | 0.756 inches |
| 3 Diameters          | 0.755 inches |
| Average Diameter     | 0.756 inches |

## SAMPLE CALCULATION

Calculation of the theoretical interference fit forces

$$A = 0.750 \text{ inches} \cdot \pi \cdot 0.5 \text{ inches} \quad (3)$$

$$A = 1.178 \text{ inches}^2$$

$$T = F \cdot \frac{d}{2} \quad (4)$$

$$F = \frac{2T}{d}$$

$$F = \frac{2 \cdot 10 \text{ FT} - \text{lbs}}{0.750 \text{ inches}} \cdot \frac{12 \text{ inches}}{1 \text{ FT}}$$

$$F = 320 \text{ lbs}$$

$$F = \mu \cdot P \cdot A \quad (2)$$

$$P = \frac{F}{\mu \cdot A}$$

$$P = \frac{320 \text{ lbs}}{0.33 \cdot 1.178 \text{ inches}^2}$$

$$P = 823.172 \text{ PSI}$$

$$\delta = P \cdot \left( \frac{d}{E_o} \left( \frac{d_o^2 + d}{d_o^2 - d} + \nu_o \right) + \frac{d}{E_i} \left( \frac{d^2 - d_i^2}{d^2 - d_i^2} + \nu_i \right) \right) \quad (1)$$

$$\delta = 823.172 \text{ PSI}$$

$$\cdot \left( \frac{0.750 \text{ inches}}{10000000 \text{ PSI}} \left( \frac{3.00 \text{ inches}^2 + 0.750 \text{ inches}^2}{3.00 \text{ inches}^2 - 0.750 \text{ inches}^2} + 0.33 \right) + \frac{0.750 \text{ inches}}{10000000 \text{ PSI}} \left( \frac{0.750 \text{ inches}^2 + 0 \text{ inches}^2}{0.750 \text{ inches}^2 - 0 \text{ inches}^2} + \nu_i \right) \right)$$

$$\delta = 0.00017245 \text{ inches} = \text{radial interference}$$

$$d = 2\delta$$

$$d = 0.000345 \text{ inches}$$

## Calculation of the experimental values

$$\delta = \frac{d_{max} - d_{min}}{2}$$

$$(5)$$

$$\delta = \frac{0.758 - 0.756}{2}$$

$$\delta = 0.001$$

$$P = \frac{0.001 \text{ inches}}{\frac{0.756 \text{ inches}}{10000000 \text{ PSI}} \left( \frac{3.004 \text{ inches}^2 + 0.756 \text{ inches}^2}{3.004 \text{ inches}^2 - 0.756 \text{ inches}^2} + 0.33 \right) + \frac{0.756 \text{ inches}}{10000000 \text{ PSI}} \left( \frac{0.756 \text{ inches}^2 + 0 \text{ inches}^2}{0.756 \text{ inches}^2 - 0 \text{ inches}^2} + 0.33 \right)} \quad (1)$$

$$P = 4736.028 \text{ PSI}$$

$$A = 0.756 \text{ inches} \cdot 0.5 \text{ inches} \cdot \pi \quad (3)$$

$$A = 1.188 \text{ inches}^2$$

$$F = \mu \cdot P \cdot A \quad (2)$$

$$F = 0.33 \cdot 4736.028 \text{ PSI} \cdot 1.188 \text{ inches}^2$$

$$F = 1855.964 \text{ lbs}$$

$$T = F \cdot \frac{d}{2} \quad (4)$$

$$T = 1855.964 \text{ lbs} \cdot \frac{0.756 \text{ inches}}{2} \cdot \frac{1 \text{ FT}}{12 \text{ inches}}$$

$$T = 58.463 \text{ FT} - \text{lbs}$$

## DISCUSSION AND ANALYSIS

Analyzing all three tests the part was subjected to allows comment upon the quality of work completed and quantifies the manufacturing errors made. For the first test, the plate was bolted onto a test plate with a bolt in all four corners. The corner holes on the plate should be 2.25 inches apart along the edges of the piece. When the test was performed the plate was met with some interference, as the part did not smoothly go onto the jig. With little coercion, the part fell onto the jig and passed the first test. The reason for the part not perfectly fitting on the jig comes down to the process in which the holes were drilled. An improvement to the drilling process could be a way of zeroing the drill bit to the part, and therefore would be able to drill all 4 holes without losing any accuracy. CNC machines do this with a tool called a touch probe. The touch probe sends data of the tool's position relative to the part in a CNC machine. If there was some type of similar technologies for the milling machines, this would greatly increase the accuracy of the hole spacing in our part.

The next test was testing the threads created in our shaft. The shaft was required to have a  $\frac{3}{4}$  inches deep hole and have a diameter of  $\frac{1}{4}$  inches. When it came time to test the fastener was screwed into the hole, unfortunately the screw did not go all the way in and there was an approximate  $\frac{1}{8}$  inch gap from the face of the shaft to the shoulder of the fastener. The solution was to drill the hole deeper and repeat the thread making process as the theory was that the hole had not been drilled deep enough. The issue ultimately was that the bottom tap was not completely run into the threads, and did not create threads at the bottom of the part. After amending the error, the fastener was able to screw all the way into the part validating the success of our test.

The final test was the torque test. This test would show if the assembly had successfully created the necessary tolerance fit needed to secure the two parts together. The part was mounted onto the jig and the 1ft bar was attached. The assembly had fallen out of tolerance when reducing the shaft's diameter. The

shaft and plate only had a radial interference fit of  $\frac{1}{1000}$  inches. The guideline for the part requires a 3 thousandth to 5 thousandth interference. Fortunately, the assembly passed the third and final test. Analyzing these results show that the interference fit was more than enough to support the applied torque. When performing the calculations, the minimum interference fit was found to be much smaller than what was outlined in the parts dimensions. The calculations show that the minimum interference is 0.000345 inches. Compared to the measured 0.002 inches interference, the likelihood of the part failing the test would be slim to none as the assembly had a larger than needed interference.

## CONCLUSION AND RECOMENDADTION

In conclusion, the parts for the assembly were cut using the Metal Mizer bandsaw, milled using the Acer milling machine, drilled using the Enco milling machine, and turned using the Jet lathe. The machined plate passed its test when the four corner holes were successfully bolted onto the provided test plate. The machined shaft passed its test when  $\frac{1}{4}$ -inch bolt was successfully screwed into the threading until flush. After the completed tests, the two parts were assembled using the Strong Way 20-ton capacity press by inserting the reduced diameter shaft into the center hole of the plate. The assembly was then tested by having it bolted to the test plate and attaching a 1 ft arm with a 10 pound weight to the end, creating a 10-foot pound torque, ultimately with the assembly passing the test. In truth, the assembly was subject to a torque larger than 10-foot pounds as test only had access to kilogram plates, and ultimately put a mass larger than 10 pounds on the hanger. If the assembly had used the minimum tolerance needed for a 10-foot pound torque it would not have passed this test, as the part was subjected to many more external forces that would easily cause it to fail the test. Force includes the weight of the hanger, the weight of the bar, and placing the weight onto the hanger, since the impulse of the weight dropping onto the hanger will cause additional force. Taking the extra forces into consideration, the larger interference allows for a much more forgiving test as it allows the assembly to

withstand many more unintended forces. Moreover, when producing the parts, many improvements could be made to the process. The first improvement would be designing a more accurate way of determining positions for the corner holes of the part. Secondly, the height gauge used to mark our parts corner positions could not maintain accuracy when the part is locked into the vise. Alternatively, if an instrument existed to determine an origin point for the part on the milling machine, the piece would have accurately drilled holes in all four corners little room for error, as the process would not be up to human discretion and the parts would be measured relative to the other holes.

## REFERENCES

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Kalpakjian, Serope, and Steven R. Schmid. *Manufacturing Engineering and Technology*. 8th ed., Pearson, 2020.

## APPENDIX

### APPENDIX 1 PICTURES



Figure A1-1



Figure A1-2



Figure A1-3



Figure A1-4



Figure A1-5



Figure A1-6



Figure A1-7



Figure A1-8

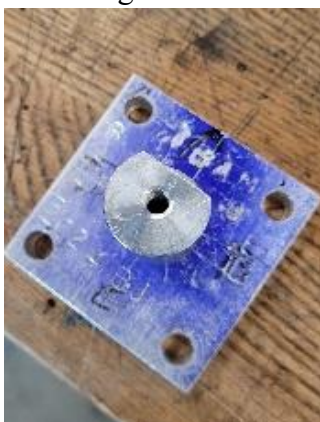


Figure A1-9



Figure A1-10



Figure A1-11



Figure A1-12



Figure A1-13

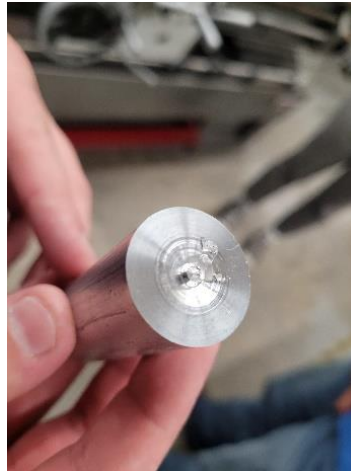


Figure A1-14



Figure A1-15

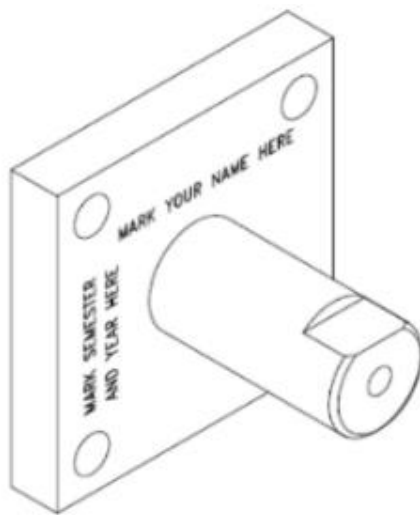


Figure A1-16

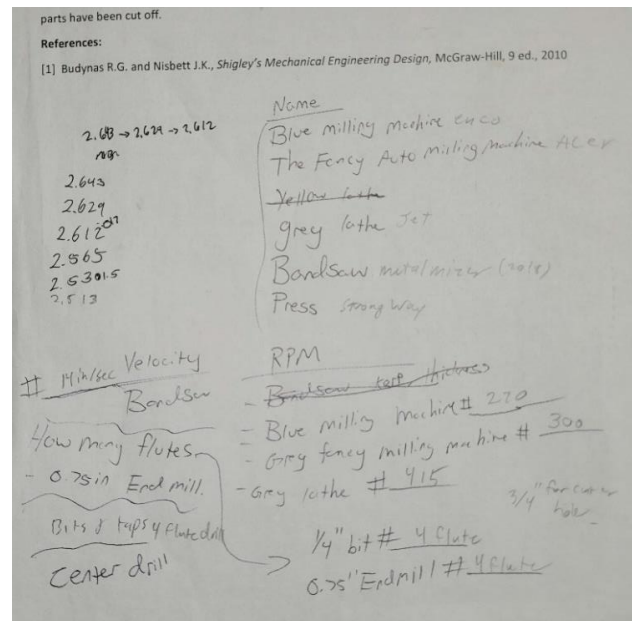


Figure A1-17

## APPENDIX 2 LOG SHEET

Log sheet A2-1

# Dimensional Data for Lab One

| Final Side length of square part |                 |
|----------------------------------|-----------------|
| Side                             | Length (inches) |
| XA                               | 2.994           |
| ZB                               | 3.004           |
| XC                               | 2.992           |
| XD                               | 3.0025<br>2     |

| Name of observer (print) |
|--------------------------|
| J. Morgan                |
| J. Morgan                |
| J. Morgan                |
| J. Morgan                |

| Center Hole Diameter (inches) |        |
|-------------------------------|--------|
| 1                             | 0.756  |
| 2                             | 0.756  |
| 3                             | 0.755  |
| Average $\phi$                | 0.7556 |

| Name of observer (print) |
|--------------------------|
| Grayson Aldrich          |
| Grayson Aldrich          |
| Grayson Aldrich          |
| Grayson Aldrich          |

| Final Shaft Dimensions (inches) |       |
|---------------------------------|-------|
| Total Length                    | 2.502 |
| $\phi$ reduced shaft            | 0.758 |
| $\phi$ full shaft               | 1.00  |
| Length reduced $\phi$           | 0.242 |

| Name of observer (print) |
|--------------------------|
| J. Morgan                |
| J. Morgan                |
| J. Morgan                |
| J. Morgan                |