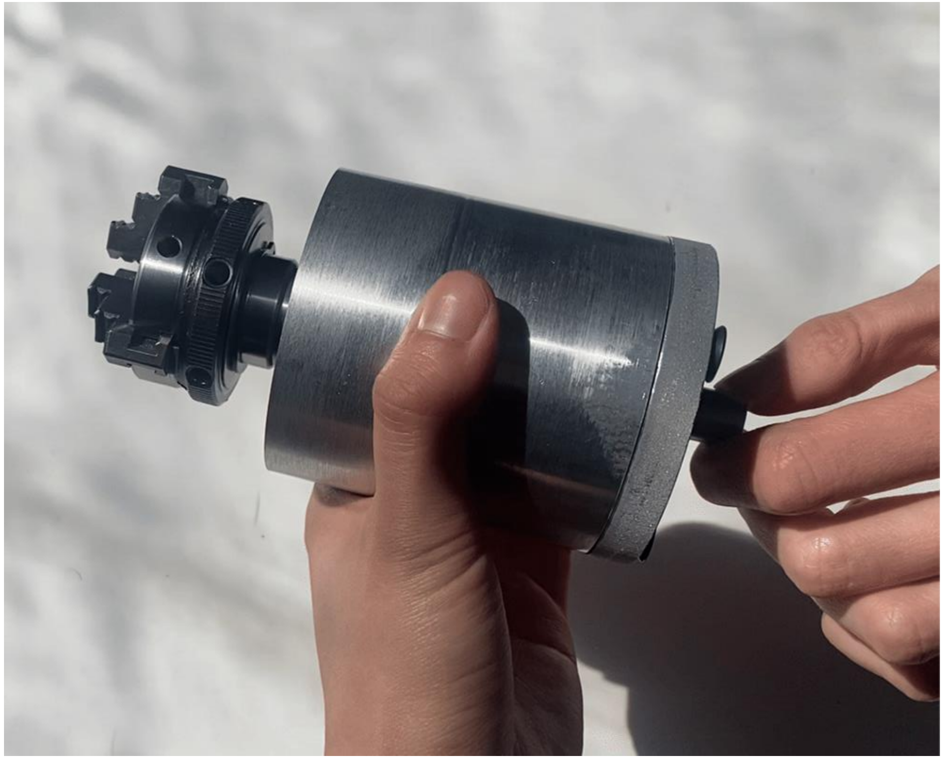
# 2.720 D-Lab 1



March 18th, 2024
Pen Palz

# Purpose/Goals

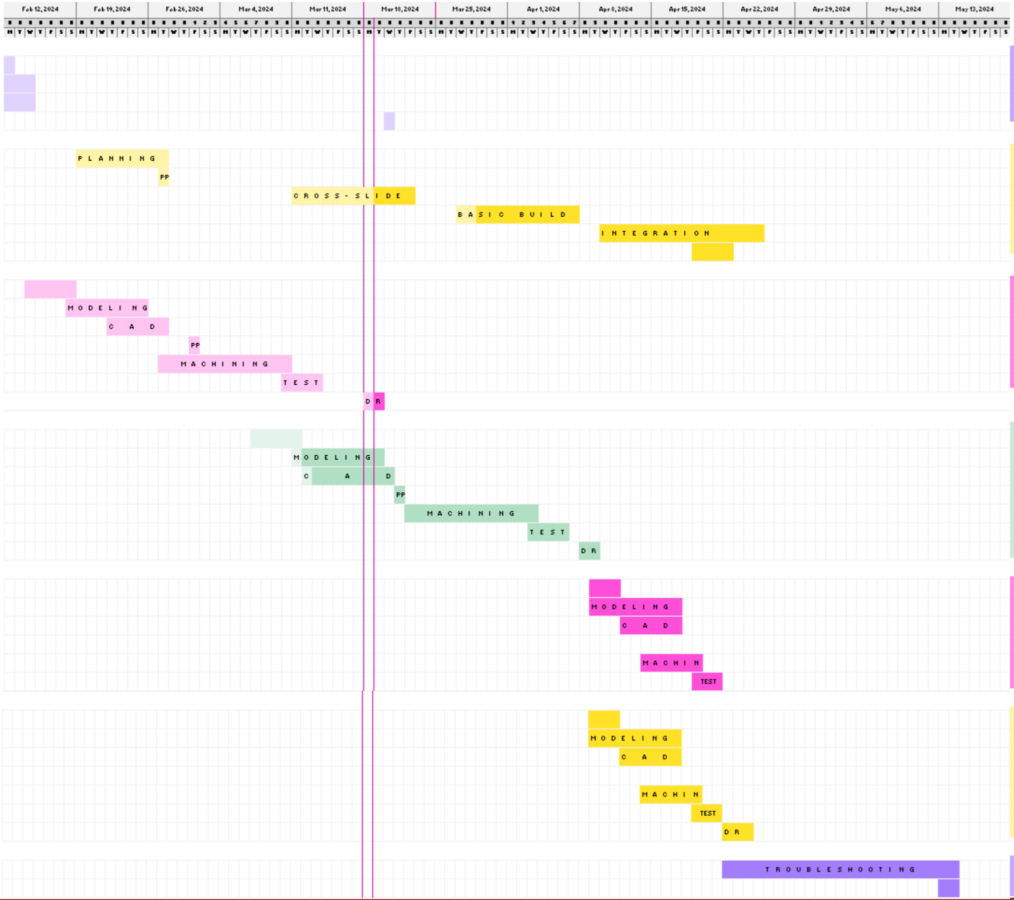
- Update Staff on our spindle design
- Receive useful feedback to incorporate in remaining subassemblies of lathe
- Customer: Hobbyists and small businesses such as Allegory

Interview with Allegory:

- In-house CNC turning capability will be a huge cost-saver
- Precision is not a big issue as long as parts flush against each other

# Gantt Chart

| TASK | ASSIGNED TO | PROGRESS | START | END | Span |
|---|---|---|---|---|---|
| **Project Initiation** | | | | | |
| Define Customer | Team | 100% | 2-12-24 | 2-12-24 | |
| Define Functional Requirements | Team | 100% | 2-12-24 | 2-14-24 | 2 |
| Establish guru positions | Team | 100% | 2-12-24 | 2-14-24 | 2 |
| Final Gurus and Gantt | Team | 100% | 3-20-24 | 3-20-24 | 1 |
| **CNC** | Patrick | | | | |
| CNC Planning | Carolina | 100% | 2-19-24 | 2-27-24 | 8 |
| CNC Planning Meeting | Patrick | 100% | 2-27-24 | 2-27-24 | 1 |
| Integration with X-Slide(Engineering) | Yarin & Ruben | 70% | 3-11-24 | 3-22-24 | 11 |
| CNC Core System Build Out | Patrick | 20% | 3-27-24 | 4-7-24 | 11 |
| Integration with Z-Slide(Engineering) | Michael | 0% | 4-10-24 | 4-25-24 | 15 |
| CNC Implementation | Patrick | 0% | 4-19-24 | 4-22-24 | 3 |
| **Spindle Assembly** | Jessica & Olivia | | | | |
| Spindle Functional Requirements | Yarin | 100% | 2-14-24 | 2-18-24 | 4 |
| Spindle Modeling | Ruben | 100% | 2-18-24 | 2-25-24 | 7 |
| Spindle CAD | Michael | 100% | 2-22-24 | 2-27-24 | 5 |
| Spindle Process Plan Meeting | Jessica | 100% | 3-1-24 | 3-1-24 | 1 |
| Spindle Machining and Assembly | Olivia | 100% | 2-27-24 | 3-10-24 | 12 |
| Spindle Testing | Olivia | 100% | 3-10-24 | 3-13-24 | 3 |
| Design Review I | Jessica | 95% | 3-18-24 | 3-19-24 | 1 |
| **Cross-Slide Assembly** | Yarin & Ruben | | | | |
| X-Slide Functional Requirements | Ruben | 100% | 3-7-24 | 3-11-24 | 2 |
| X-Slide Modeling | Yarin | 15% | 3-11-24 | 3-19-24 | 8 |
| X-Slide CAD | Ruben | 15% | 3-12-24 | 3-20-24 | 8 |
| X-Slide Process Plan Meeting | Yarin | 0% | 3-21-24 | 3-21-24 | 1 |
| X-Slide Maching and Assembly | Patrick | 0% | 3-22-24 | 4-3-24 | 12 |
| X-Slide Testing | Patrick | 0% | 4-3-24 | 4-6-24 | 3 |
| Design Review II | Yarin | 0% | 4-8-24 | 4-9-24 | 1 |
| **Headstock and Tailstock** | Carolina | | | | |
| HS/TS Functional Requirements | Carolina | 0% | 4-9-24 | 4-11-24 | 2 |
| HS/TS Modeling | Carolina | 0% | 4-9-24 | 4-17-24 | 8 |
| HS/TS CAD | Carolina | 0% | 4-12-24 | 4-17-24 | 5 |
| HS/TS Process Plan Meeting | Carolina | 0% | TBD | TBD | 1 |
| HS/TS Machining and Assembly | Olivia | 0% | 4-14-24 | 4-19-24 | 5 |
| HS/TS Testing | Olivia | 0% | 4-19-24 | 4-21-24 | 2 |
| **Assembly Smoke Test** | Michael | | | | |
| Z-Slide Functional Requirements | Michael | 0% | 4-9-24 | 4-11-24 | 2 |
| Z-Slide Modeling | Michael | 0% | 4-9-24 | 4-17-24 | 8 |
| Z-Slide CAD | Michael | 0% | 4-12-24 | 4-17-24 | 5 |
| Z-Slide Process Plan Meeting | Michael | 0% | TBD | TBD | 1 |
| Z-Slide Machining and Lathe Assembly | Olivia | 0% | 4-14-24 | 4-19-24 | 5 |
| Integrated Testing | Jessica | 0% | 4-19-24 | 4-21-24 | 2 |
| Design Review III | Carolina | 0% | 4-22-24 | 4-24-24 | 2 |
| **Final Demo** | | | | | |
| Troubleshooting | Team | 0% | 4-22-24 | 5-14-24 | 22 |
| Demo Day | Team | 0% | 5-13-24 | 5-14-24 | 1 |




Project Initiation

CNC

Spindle Assembly

Cross-Slide Assembly

Headstock/Tailstock Assemblies

Z-Slide Assembly

Final Demo

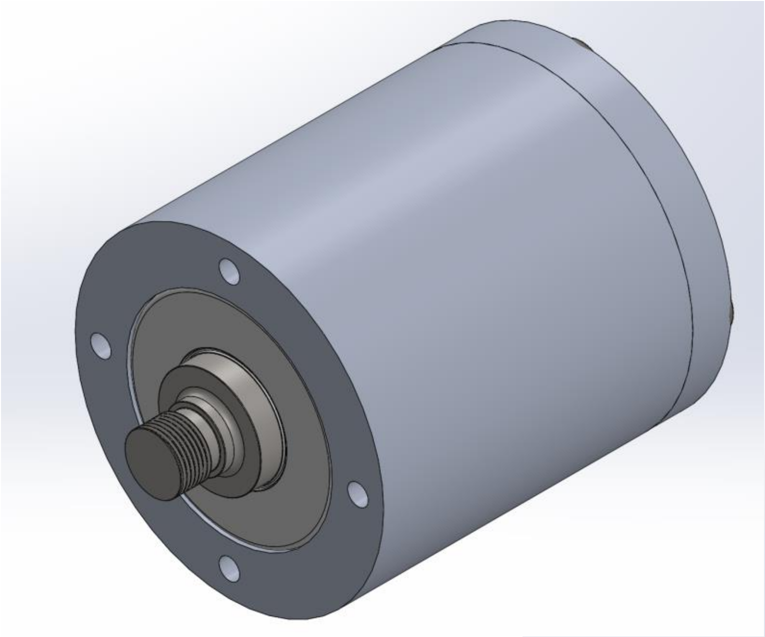


MITMECHE

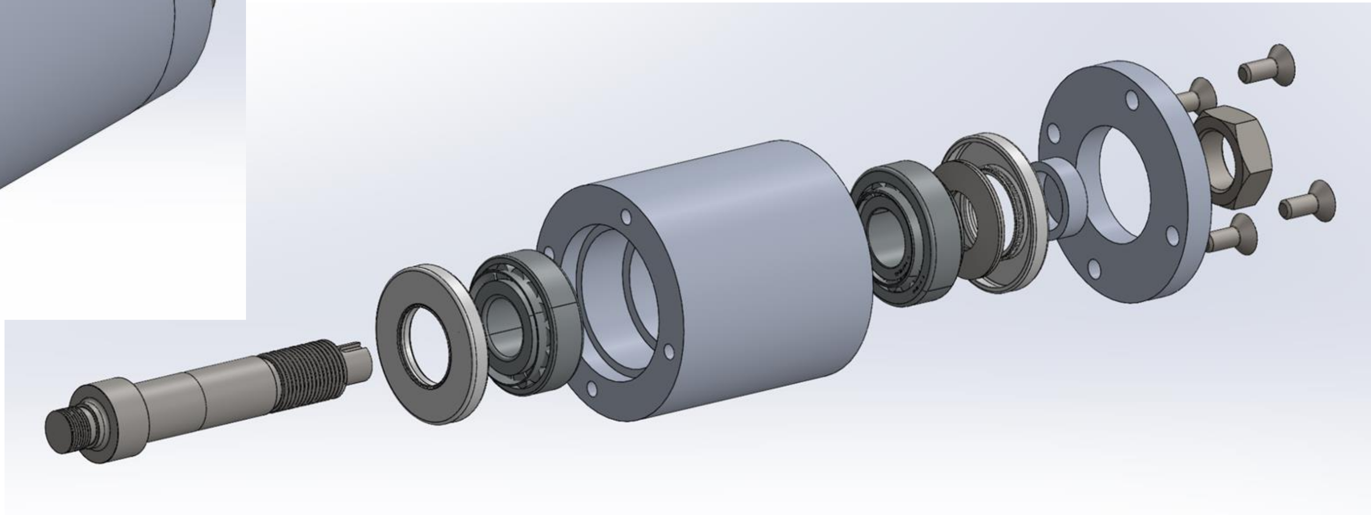
# Spindle Functional Requirements

| Name | Definition | Value & Range | Measurement | Requirement Met? |
|---|---|---|---|---|
| **Stiffness** | Deflection allowed at end of spindle under 100N | Max 0.001” | 0.00065” | ✔ |
| **Runout** | Runout of spindle shaft at chuck end | Max 0.003” | 0.0014’’ | ✔ |
| **Friction Torque** | Energy dissipated due to static friction | Max 75W | 48.5±4.1 W | ✔ |
| **Impulse Load** | Spindle absorbs and dissipates energy from high-intensity forces w/o breaking | Max 2250 lbf | 2250 lbf (modelling) | ✔ |
| **Size** | Length and diameter of spindle assembly | Length: 7” ± 3”<br>Diameter: 3” ± 1” | Diameter: 2.98”<br>Length: 4.8” | ✔ |
| **Weight** | Weight of spindle assembly | Max: 15 lbs | 2.75 lbs | ✔ |
| **Lifetime** | # of hours of operation before replacement | Minimum 6000 hrs | 540 million cycles | ✔ |
| **Load Capacity** | Max axial, radial and torsion forces that spindle can withstand w/o compromising performance | Max Axial: 110,400 lbf<br>Radial: 4597 lbf Torsional: 827 lbf | Axial: 1200 lbf ($C_{90}$)<br>Radial: 7200 lbf (static)/2250 lbf ($C_{10}$) | ✔ |
| **Sealing** | Keep grease and dust/chips in/out w/o wear up to speed | Max 3800 RPM | 3100 RPM | ✔ |

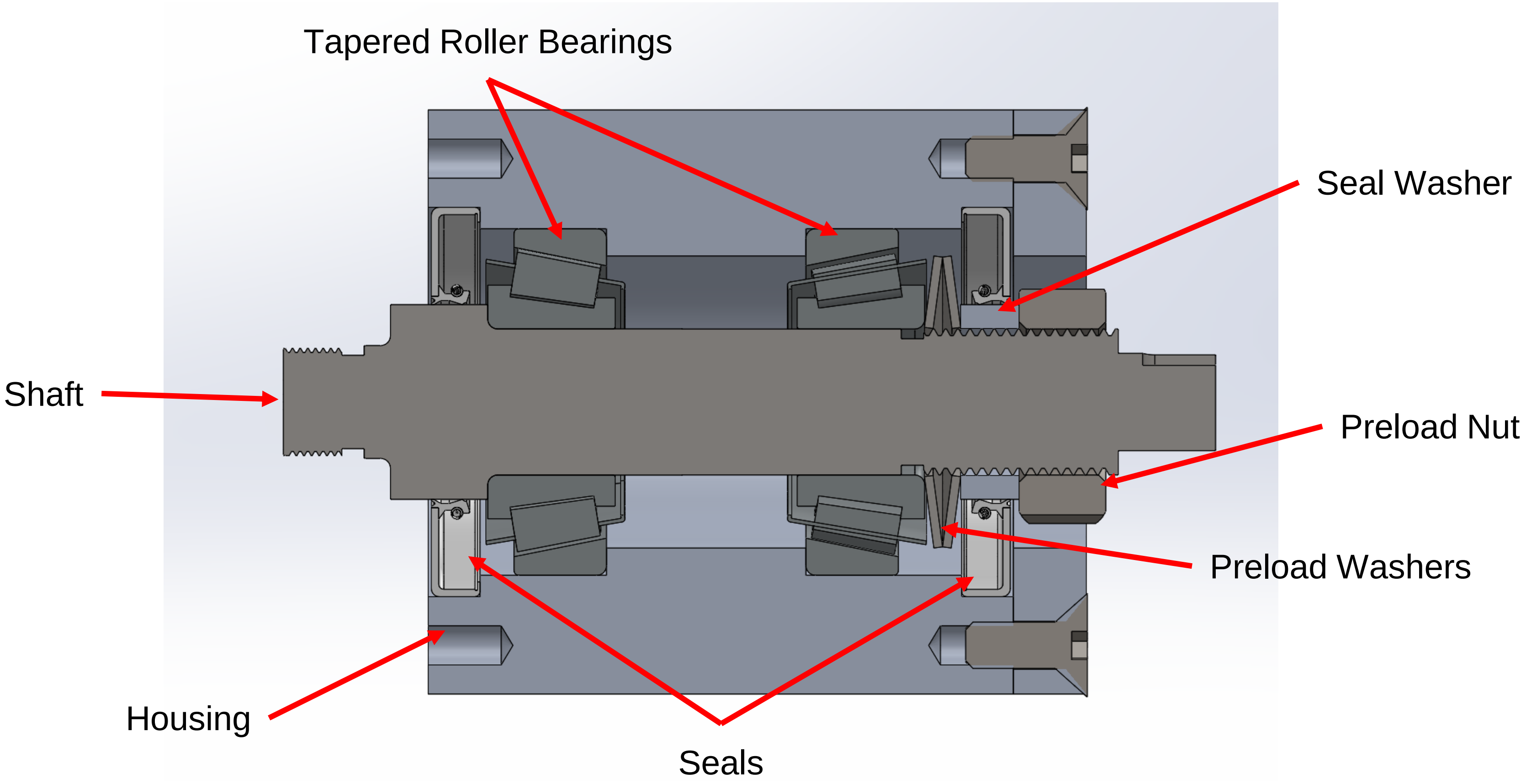
# Spindle Design



Housing and end cap made of 6061 aluminum
Shaft made of 12L14 carbon steel
Tapered roller bearings press fit into housing
Bearings preloaded with washer + nut assembly



# Spindle Design



# Cutting Power and Force Calculations

- 8 minutes, 8 passes for a pen
- 0.5” → 0.415”, 0.015” depth of cut
- *MRR = 0.04 in^3/min*
- Spindle speeds from Fswizard, 970 RPM
- ~70 Watts power to cut

Power calculation for lathe

$$MRR_{SS304} := 0.04\ \frac{in^3}{min} \qquad \mu_{SS304} := 6\ \frac{J}{mm^3} \qquad \omega_{SS304} := 970\ \frac{rev}{min} = 101.578\ \frac{1}{s}$$

$$Power := MRR_{SS304} \cdot \mu_{SS304} = 65.548\ W$$

$$v := \omega_{SS304} \cdot \pi \cdot 0.5\ \frac{in}{rev} = 0.645\ \frac{m}{s}$$

$$F_{cutting} := \frac{Power}{v} = 101.622\ N$$

$$F_{radial} := F_{cutting} \cdot 0.5 = 50.811\ N$$

$$F_{feed} := F_{cutting} \cdot 0.25 = 25.405\ N$$

Stainless Steel 304 Deflection of workpiece

$$E := 200 \cdot 10^9\ Pa \qquad d := 0.415\ in \qquad L := 3\ in \qquad F := 80\ N$$

$$I := \frac{\pi \cdot \left(\frac{d}{2}\right)^4}{4} = \left(6.06 \cdot 10^{-10}\right)\ m^4$$

$$\delta := \frac{F \cdot L^3}{3 \cdot E \cdot I} = \left(9.734 \cdot 10^{-5}\right)\ m$$

**Significant deflection!!**
***(~90 microns)***

***Design choice:*** slower, less powerful lathe that still cuts a range of materials and makes pens in a timely fashion

# Bearing Life

$$Cycles\_Desired := 6000\ hr \cdot 1500\ \frac{1}{min} \cdot 60\ \frac{min}{hr} = 5.4 \cdot 10^{8}$$

$$F_{ra} := 3900\ N \qquad K_b := 1.94$$

$$F_{rb} := 3900\ N$$

$$F_{thrust} := 150\ N \qquad F_{aA} := \frac{0.47 \cdot F_{rb}}{K_b} + F_{thrust} = \left(1.095 \cdot 10^{3}\right)\ N$$

$$P_a := 0.4 \cdot F_{ra} + K_b \cdot F_{aA} = \left(3.684 \cdot 10^{3}\right)\ N$$

$$P_b := F_{rb} = \left(3.9 \cdot 10^{3}\right)\ N$$

(1)If PA < FrA, use PA = FrA
or if PB < FrB, use PB = FrB.

$$C_{a90} := 10100\ N \qquad P := F_{ra}$$

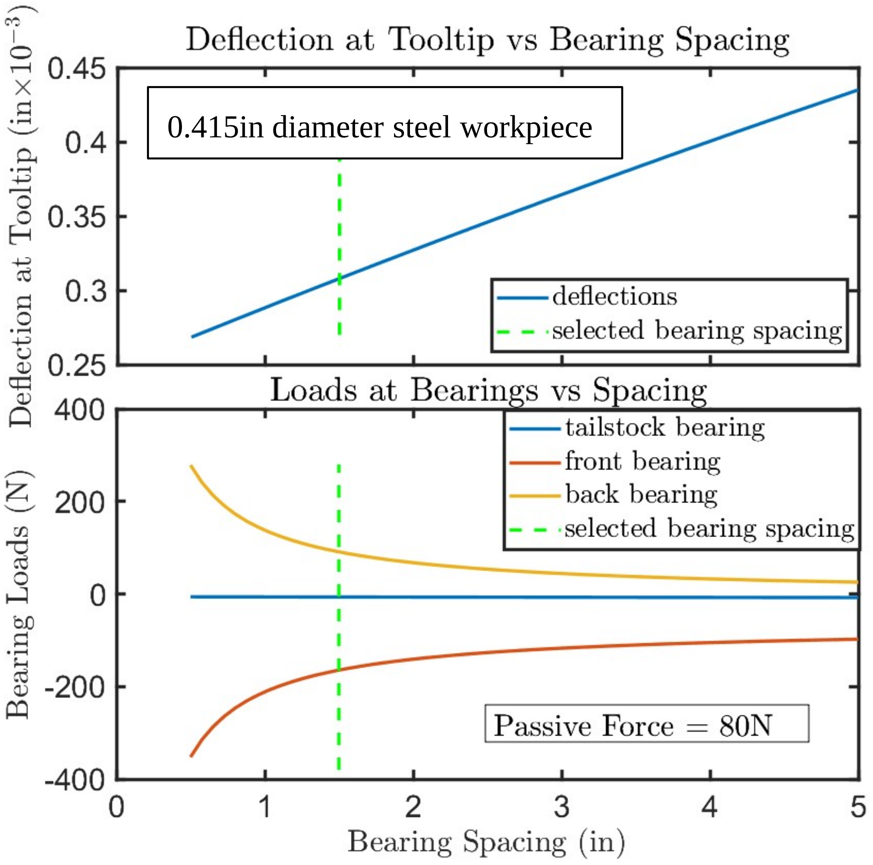
$$L_{10} := \left(\frac{C_{a90}}{P}\right)^{\frac{10}{3}} \cdot 90\ 10^{6} = 2.147 \cdot 10^{9}$$

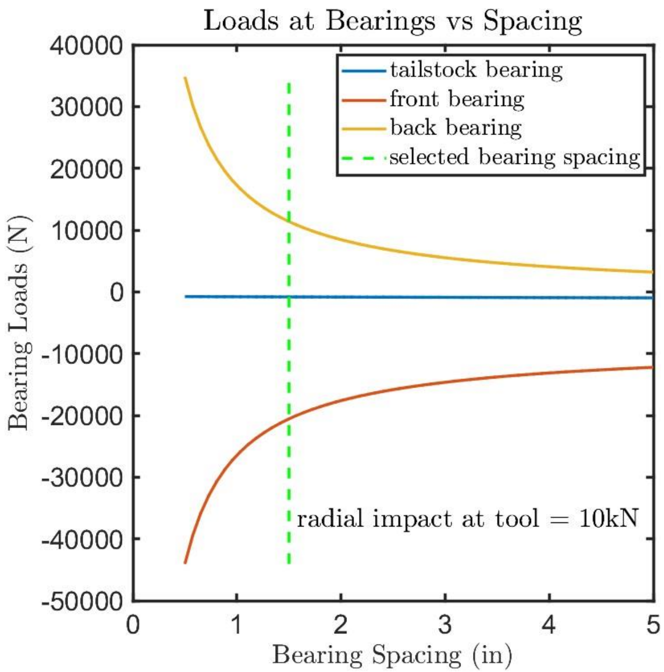
$$A_{1\_99Reliability} := 0.25$$

$$L_1 := A_{1\_99Reliability} \cdot L_{10} = 5.367 \cdot 10^{8}$$

- Chose to go with Timken LM11949
  - Largest diameter for higher stiffness without going over budget
- Customer desires a reliability of 99% for an expected 6 year lifespan
- 3900N bearing dynamic radial load rating both bearings
- 10kN expected maximum impact radial load

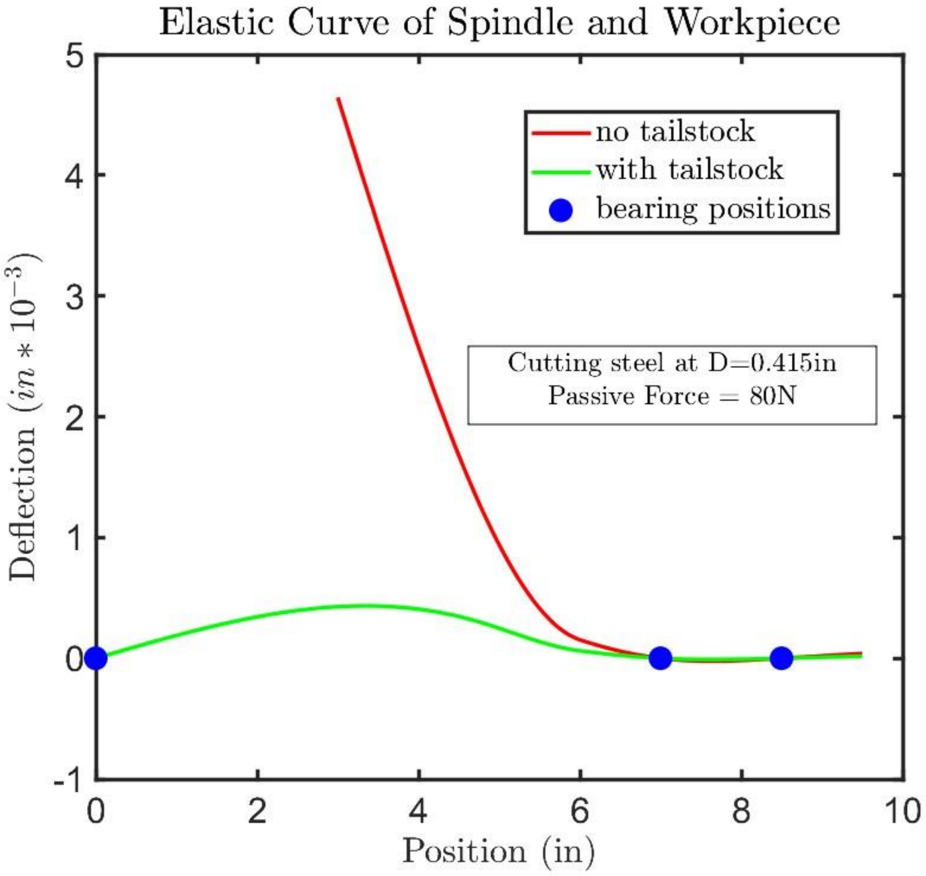
# Spindle Deflection + Tailstock




- Bearing spacing selected according to maximum anticipated impact load (10kN) and minimizing deflection. Bearing static load rating = 30kN
- Loads are largest with tool at 4.72in from the tailstock (6in workpiece)

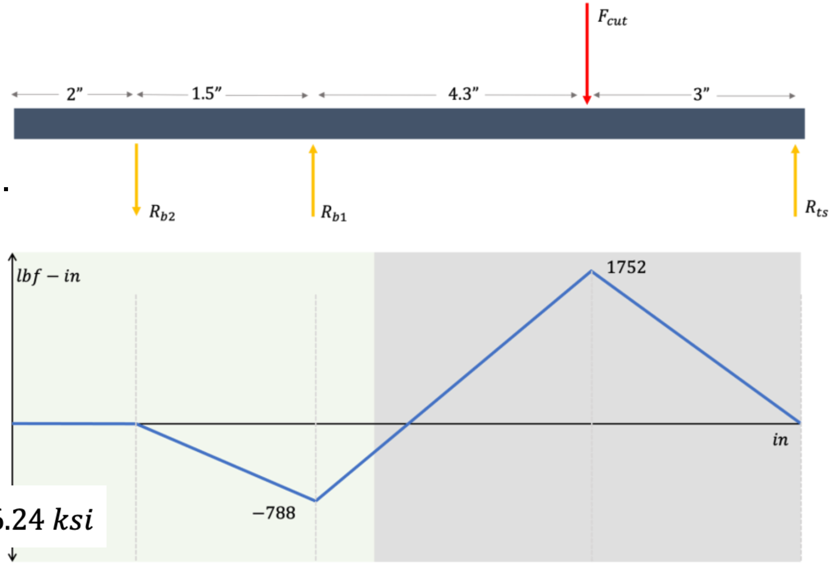
# Spindle Deflection + Tailstock




- Elastic curves with 1.5in bearing spacing

- Several thou from desired accuracy without tailstock. Adding a tailstock significantly improves accuracy to be safely within spec

# Spindle Shaft Fatigue




Assumptions:

- Shaft and workpiece is modeled as one beam with bearings as simple supports
- Worst case roughing pass loading (3" from chuck) on 6 in. workpiece with tailstock
- $\sigma_{max} = \sigma_{alt}$, $\sigma_{VM} \cong \sigma_{bending}$
- Marin factors for machined, 99% reliability

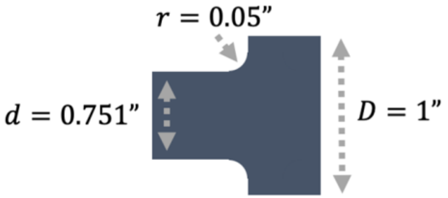
12L14 Steel Test Specimen Endurance Limit

$$S_e = k_a k_b k_c k_d k_e k_f (0.5 S_{UTS}) \qquad S_e = 0.36(310\ MPa) = 112\ MPa = 16.24\ ksi$$

Max Stress

$$\sigma_{VM,max} = K_t \frac{M\frac{D}{2}}{I} = 1.8\frac{(788\ lbf - in)(0.5\ in)}{0.049\ in^4} = 14.47\ ksi$$

$$\boxed{14.47\ ksi < 16.24\ ksi}$$

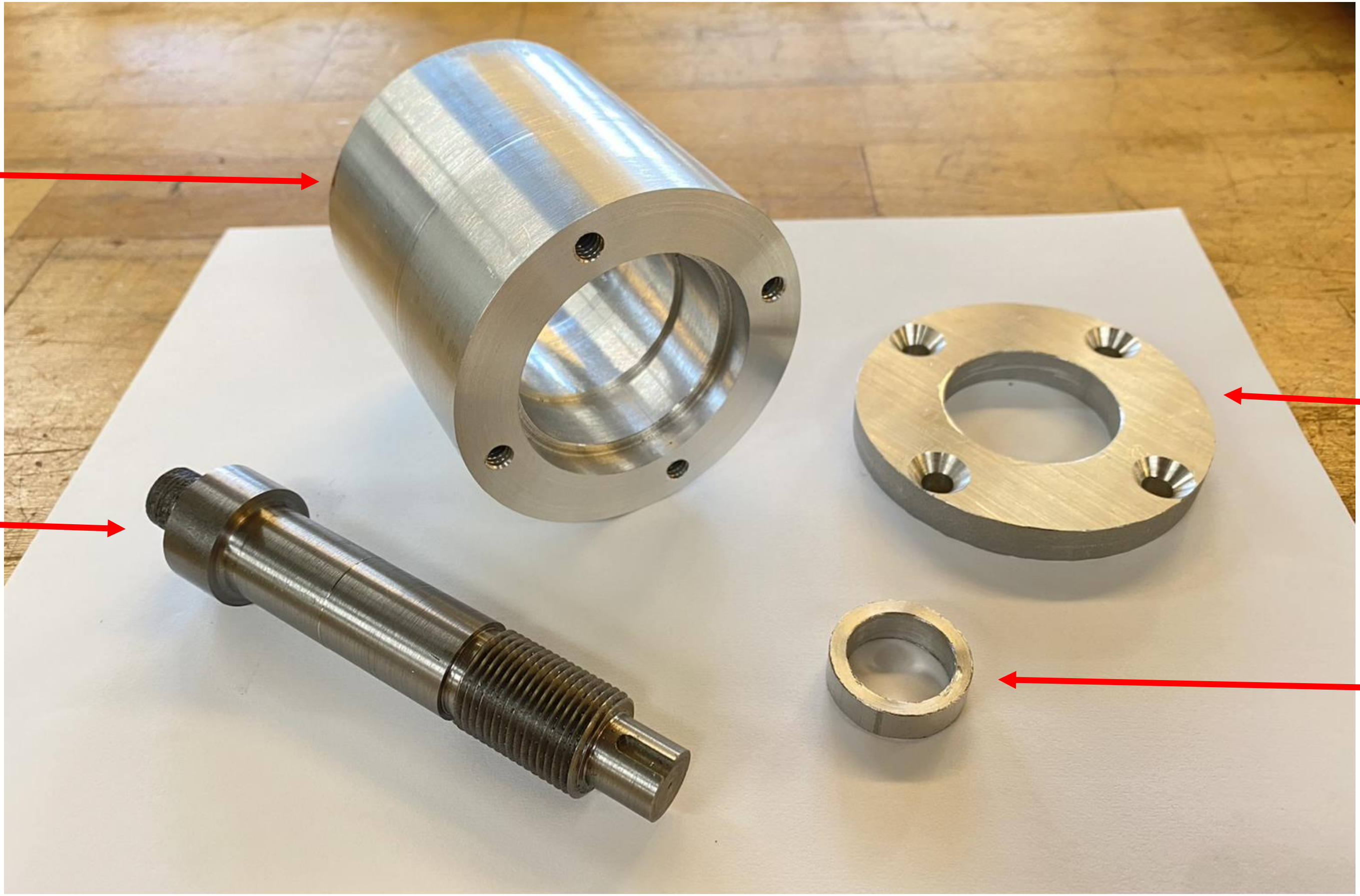



**Max cyclic stress is under the material endurance limit with a safety factor of 1.12.**

# Spindle Manufacturing

Housing

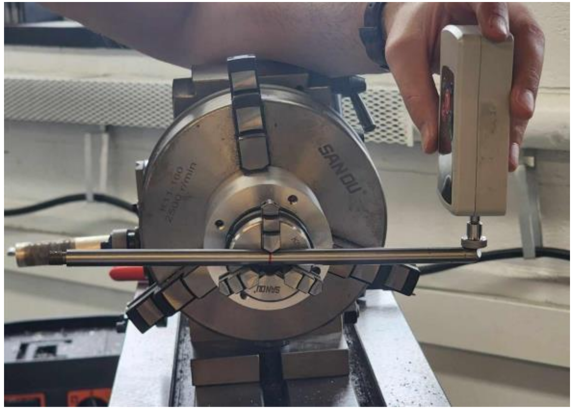
Shaft

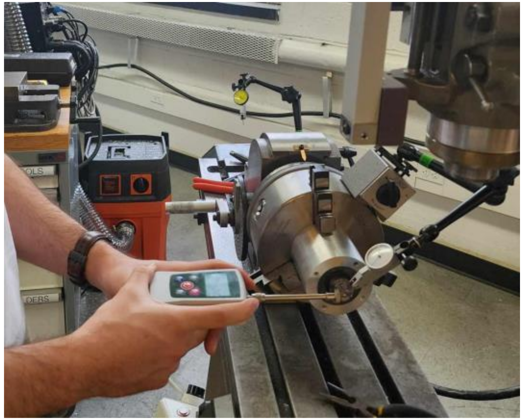


End Cap

Seal
Washer

# Spindle Measurement



**Static torque test:**
(n=10, mean ± 2σ)
1.32 ± 0.11 lbf-in

**~48.5±4.1 W of loss in worst case**

Requirement: 75W

**Deflection at end of spindle due to 100N load:**
(n=8)
**Average:** 0.00065”
**Repeatability (2σ):** 0.00015”

Req. Accuracy: 0.001”
Req. Repeatability: 0.0004”

**Runout measured:**
(n=7)
**Average:** 0.0014”
**Repeatability(2σ):** 0.00015”

Req. Accuracy: 0.003’’
Req. Repeatability: 0.0005”

# Alternative Spindle Proposal

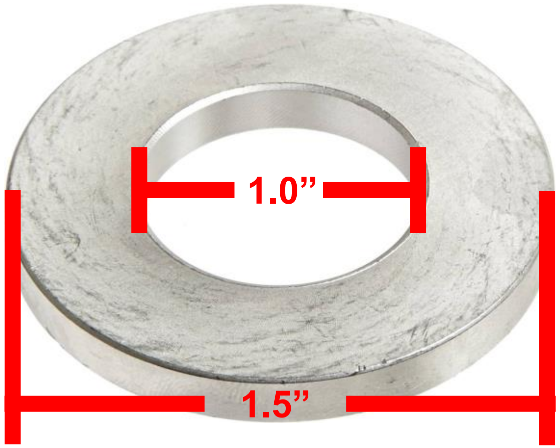
**Goal:** Industrial washers (OD 1.5” ID 1”, 0.125” thick) 304 stainless steel, each washer takes *2 minutes* to machine

**Starting Stock:** OD 2” ID 1” stainless steel tube stock industrial washers

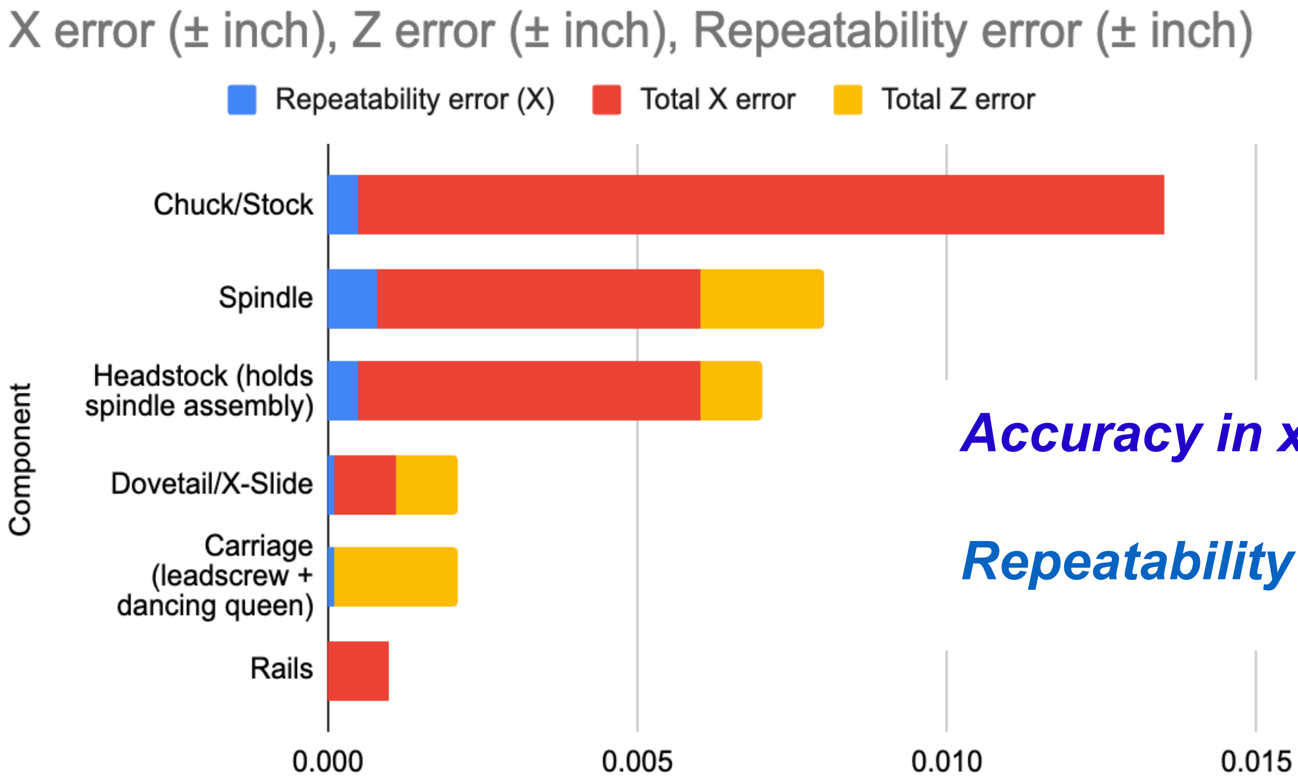
**Resulting MRR:** 0.2 in^3/min
**Optimal Bearing Spacing:** 2.36”
**Bearing Loads:** 10 N (x) and 60 N (y)
**Preload:** 100N still works to achieve $5.8 \times 10^6$ N/m of stiffness

**Considerations:**

- Use same tapered roller bearings to withstand axial and thrust forces
- Bearing spacing increases spacing because deflection is less (thicker and less cantilevered workpiece)



# Error Budget




***Accuracy in x= 0.026”***

***Repeatability in x = 0.002”***

# BACKUP SLIDES

# Pen Process Plan / Customer Needs

| # | Task & Questions | Machine |
|---|---|---|
| 1 | Cut the wood blank into 2 equal pieces | Band saw / Miter saw |
| 2 | Drill the blanks with a 7mm drill bit at a speed of 900 to 1200 RPM. | Mill |
| 3 | Sand 2 barrels, apply glue, insert into through hole of the blank | Handwork |
| 4 | Insert mandrel into PenPalz chuck. Inset start bushing, pen blank, middle bushing, pen blank, end bushing in sequence to the mandrel. Apply tail stock. | Handwork |
| 5 | Turn the wood blank according to design with a tool. End of blank need to be flushed with bushing. | Pen Palz Lathe |
| 6 | Wood finish 1: Sand the wood while spinning the spindle | Pen Palz Lathe |
| 7 | Wood finish 2: apply CA glue while spinning the spindle | Pen Palz Lathe |
| 8 | Press the pen tip, twist mechanism, and pen cap & clip into pen blank. | Press |
| 9 | Assemble pen: slide in decorative middle bushing, insert pen cartrige, top wood blank. | Handwork |

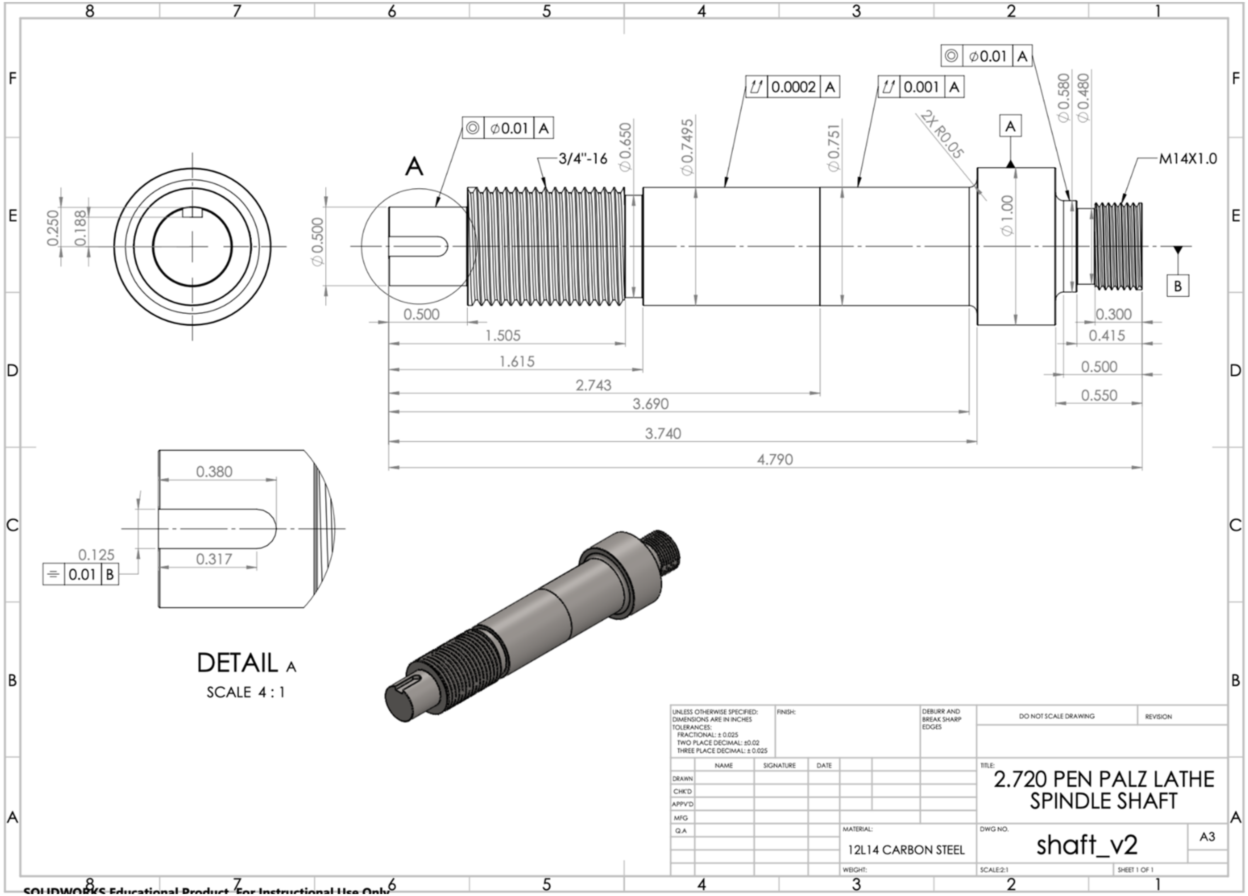
Example Process Plan with Wood Pens

Metal

Wood

⌀7mm standard pen mandrel

# Spindle Shaft GD&T Drawing



# Seals/Grease



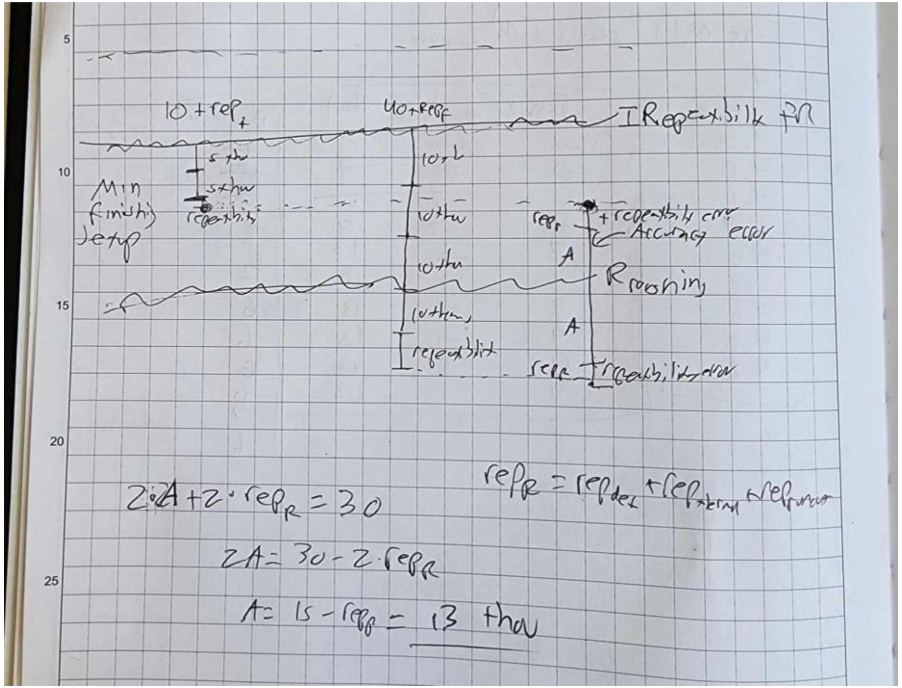
- Reduces friction between seals, bearings, and spindle shaft.
- Chemically inert and compatible with seal materials and metals used.

McMaster-Carr 5154T154

Spring-Loaded Rotary Shaft Seal with Wiper Lip, for 1" Shaft Diameter and 2" Bore Diameter

3800 RPM rating

# Accuracy and Repeatability Breakdown



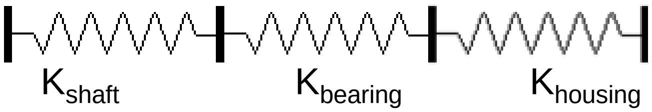
# Bearing Preload

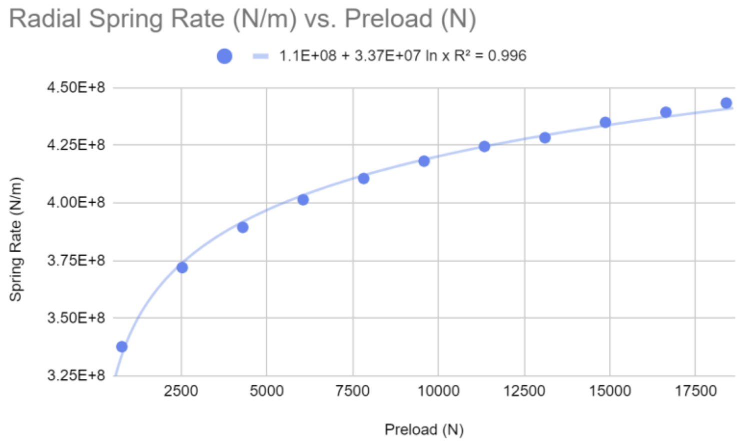
Used the Timken manual and datasheet to plot bearing axial/radial stiffness vs. preload force.

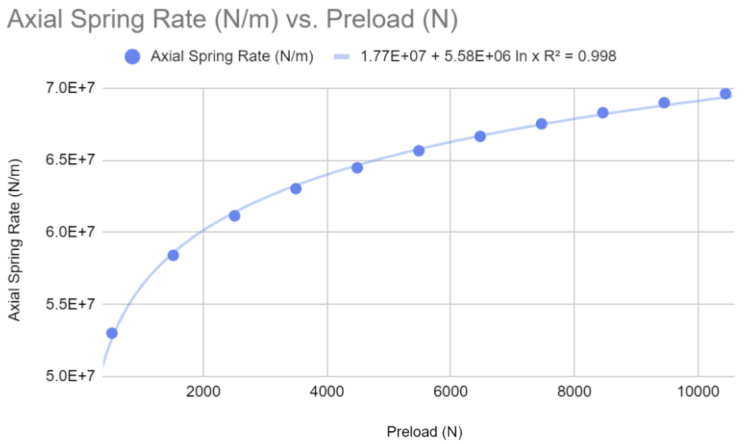
Spindle $K_{axial}$ FR: ~$6.3\times10^4$ N/m
Spindle $K_{radial}$ FR: ~$5\times10^6$ N/m

Find Preload force that gets desired stiffness: ~100N
Lifetime: $1.20\times10^{16}$ revolutions → $10^7$ years

| | Shaft | Bearings | Housing | Spindle |
|---|---|---|---|---|
| $K_{axial}$ (N/m) | ~$10^8$ | ~$10^7$ | ~$10^9$ | ~$3.78\times10^7$ |
| $K_{radial}$ (N/m) | ~$10^8$ | ~$10^8$ | ~$10^{10}$ | ~$1.65\times10^8$ |



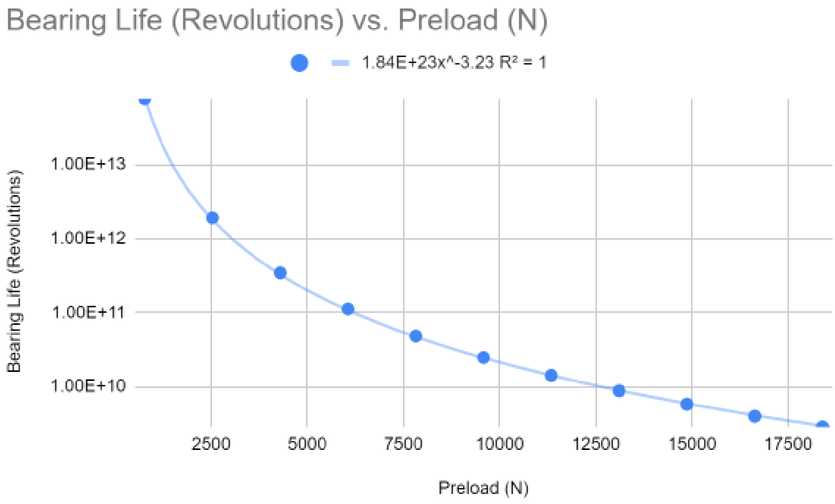
# Bearing Preload

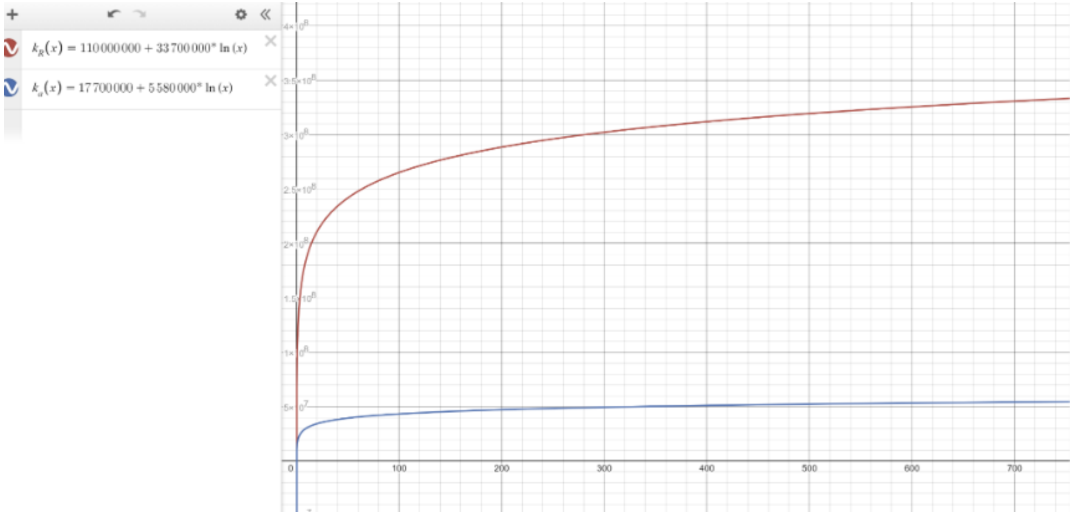
Belleville disc spring needs to be compressed 0.142” to generate the necessary preload force.

Using the lead of ¾”-16 threads, the preload nut must be rotated ~0.45 of a rotation

Experimented when measuring, a higher preload → high friction.

# Bearing Preload



# Spindle Thermal Analysis

Using first-order transient analysis, assume system is ~1.45 kg of steel, taking in ~80 W of power in 8 min (from FRs).

$Q_{in}$ = 1.45 kg · $c_{st}$ · ΔT/ (8 min) → ΔT = 56.5°C

$$\chi_{chips} := 0.8 \qquad \chi_{tool} := 0.125 \qquad t_{cut} := 8\ min$$

$$u_{st} := 5\ \frac{W \cdot s}{mm^3} \qquad u := u_{st}$$

$$MRR := \frac{\pi \cdot \left( \left( \frac{0.5}{2}\ in \right)^2 - \left( \frac{0.415}{2}\ in \right)^2 \right) \cdot 6\ in}{t_{cut}} = \left(1.251 \cdot 10^{-8}\right) \frac{m^3}{s}$$

$$Q_{cut} := \left(1 - \chi_{tool} - \chi_{chips}\right) \cdot u \cdot MRR = 4.692\ W$$

$$m_{sys} := 1.3\ kg + 0.154\ kg = 1.454\ kg$$

$$Q_f := 75\ W \qquad m_{cp\_st} := 466\ \frac{J}{kg \cdot K}$$

$$\Delta T_{sys} := \frac{\left(Q_f + Q_{cut}\right) \cdot t_{cut}}{m_{sys} \cdot m_{cp\_st}} = 56.456\ K$$

→

$$l_{to\_nut} := 2\ in \qquad l_{to\_b} := 1\ in$$

$$\delta_{sh\_tr} := \alpha_{st} \cdot l_{to\_nut} \cdot \Delta T_{sys} = 0.033\ mm$$

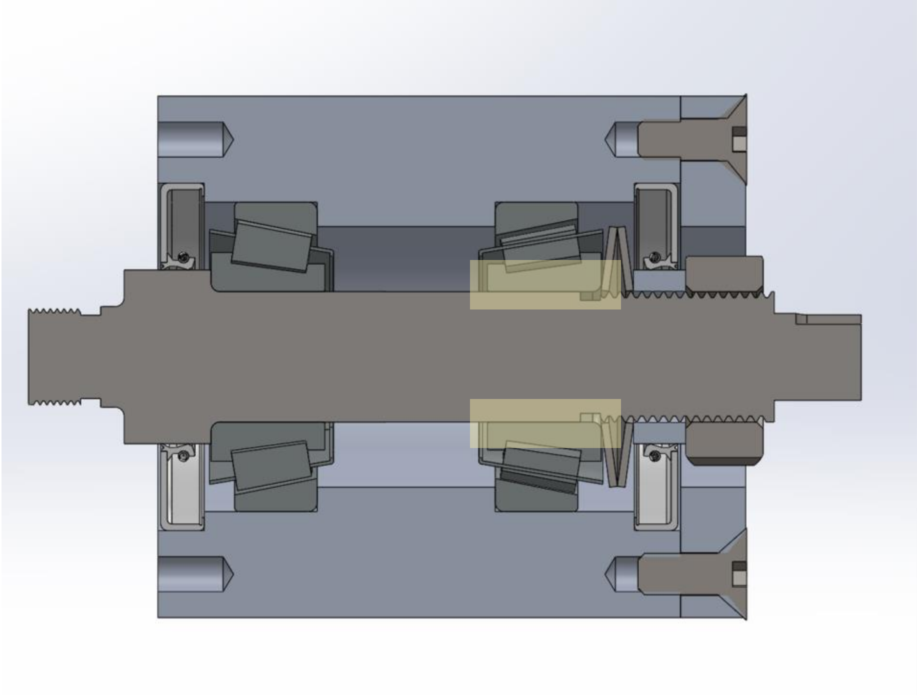
$$\delta_{h\_tr} := \alpha_{al} \cdot l_{to\_b} \cdot \Delta T_{sys} = 0.033\ mm$$

Preload nut (connected to shaft) and bearing outer race (connected housing) move similar amounts), ~33 microns error

*https://www.emerald.com/insight/content/doi/10.1108/00022660510585956/full/pdf*

# Spindle Thermal Analysis

Pulley-side bearing inner race is slip-fit onto the shaft, allowing shaft to expand thermally.



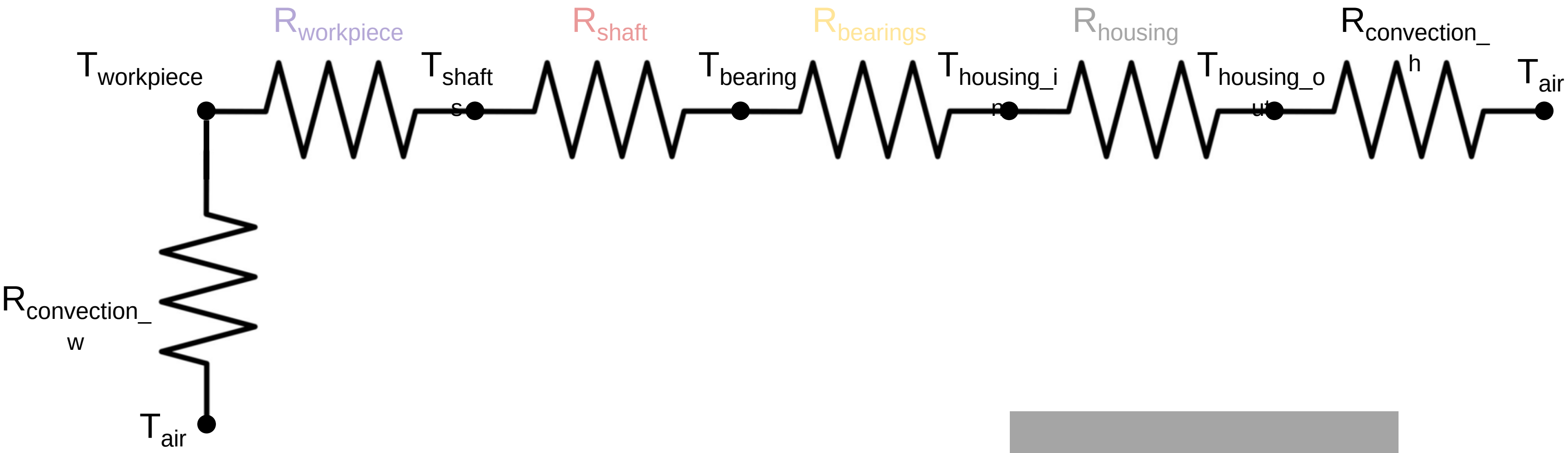
$l_{to\_nut} := 2\ in \qquad l_{to\_b} := 1\ in$

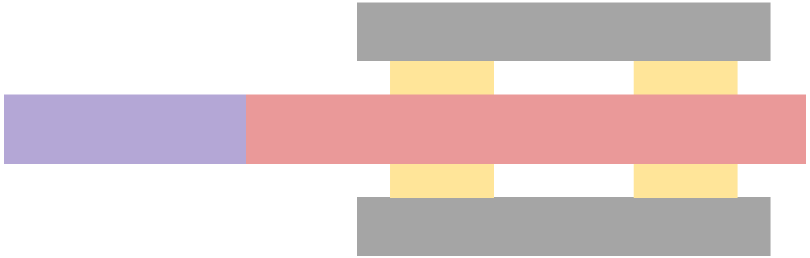
$\delta_{sh\_tr} := \alpha_{st} \cdot l_{to\_nut} \cdot \Delta T_{sys} = 0.033\ mm$

$\delta_{h\_tr} := \alpha_{al} \cdot l_{to\_b} \cdot \Delta T_{sys} = 0.033\ mm$

Expansion by tens of microns, would lead to < 5N of preload lost (with 13.8 kN/m preload washers)

# Spindle Thermal Analysis



Circuit for steady state analysis

# Spindle Thermal Analysis

$$\chi_{chips} := 0.8 \qquad \chi_{tool} := 0.125$$

$$u_{st} := 5 \frac{W \cdot s}{mm^3} \qquad u := u_{st}$$

$$MRR := \frac{\pi \cdot \left(\left(\frac{0.5}{2}\ in\right)^2 - \left(\frac{0.415}{2}\ in\right)^2\right) \cdot 6\ in}{8 \cdot 60\ s} = \left(1.251 \cdot 10^{-8}\right) \frac{m^3}{s}$$

$$Q_{cut} := \left(1 - \chi_{tool} - \chi_{chips}\right) \cdot u \cdot MRR = 4.692\ W$$

$$k_{st} := 51.9 \frac{W}{m \cdot K} \qquad k_{al} := 167 \frac{W}{m \cdot K} \qquad h_h := 2.27 \cdot \frac{W}{m^2 \cdot K} \qquad h_w := 2.35 \cdot \frac{W}{m^2 \cdot K}$$

$$T_w := 1559.589\ °C \qquad T_{air} := 20\ °C$$

$$R_w := \frac{l_w}{k_{st} \cdot \pi \cdot r_w^{\ 2}} = 23.18 \frac{s^3 \cdot K}{kg \cdot m^2} \qquad R_{conv\_st} := \frac{1}{h_w \cdot A_w} = 69.983 \frac{s^3 \cdot K}{kg \cdot m^2}$$

$$R_{sh} := \frac{l_{sh}}{k_{st} \cdot \pi \cdot r_{sh}^{\ 2}} = 8.242 \frac{s^3 \cdot K}{kg \cdot m^2} \qquad R_b := \frac{\ln\left(\frac{r_{bo}}{r_{bi}}\right)}{2 \cdot k_{st} \cdot \pi \cdot l_b} = 0.159 \frac{s^3 \cdot K}{kg \cdot m^2}$$

$$R_h := \frac{\ln\left(\frac{r_{ho}}{r_{hi}}\right)}{2 \cdot k_{al} \cdot \pi \cdot l_h} = 0.009 \frac{s^3 \cdot K}{kg \cdot m^2} \qquad R_{conv\_al} := \frac{1}{h_h \cdot A_h} = 24.15 \frac{s^3 \cdot K}{kg \cdot m^2}$$

$$Q_{dis} := \frac{T_w - T_{air}}{R_{eq}} = 49.66\ W \qquad Q_{spindle} := Q_{dis} - \frac{T_w - T_{air}}{R_{conv\_st}} = 27.66\ W$$

$$T_{ho} := T_{air} + Q_{spindle} \cdot R_{conv\_al} = 687.993\ °C$$

$$T_{hi} := T_{air} + Q_{spindle} \cdot \left(R_h + R_{conv\_al}\right) = 688.233\ °C$$

$$T_{sh} := T_{air} + Q_{spindle} \cdot \left(R_{sh} + 0.5 \cdot R_b + R_h + R_{conv\_al}\right) = 918.412\ °C$$

$$\alpha_{st} := 11.5 \cdot 10^{-6} \frac{1}{K} \qquad \alpha_{al} := 23 \cdot 10^{-6} \frac{1}{K}$$

$$\Delta T_{sh} := T_{sh} - T_{air} \qquad \Delta T_h := \left(\frac{T_{ho} + T_{hi}}{2}\right) - T_{air}$$

$$\delta_{sh} := \alpha_{st} \cdot l_{sh} \cdot \Delta T_{sh} = 1.26\ mm \qquad \delta_h := \alpha_{al} \cdot l_h \cdot \Delta T_h = 1.171\ mm$$

https://www.emerald.com/insight/content/doi/10.1108/00022660510585956/full/pdf