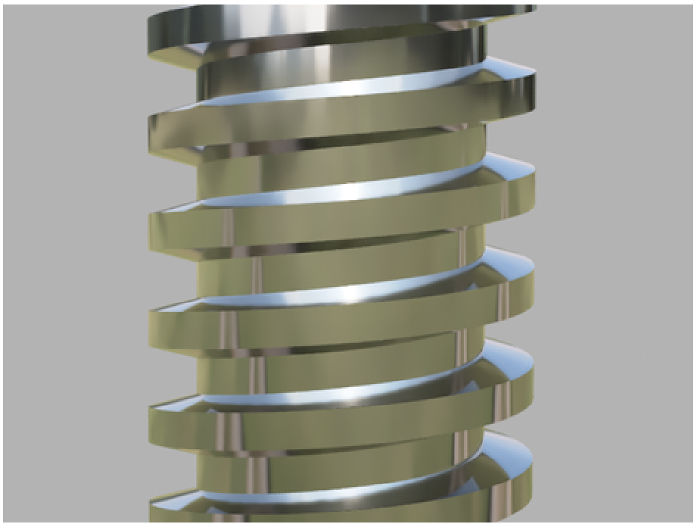
Ahsanullah University of Science and Technology

Department of Mechanical and Production Engineering

Machine Design Sessional (ME 3202)

Design A Lead Screw For Lathe Machine



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1. Introduction

1.1 Main Objective

The lead screw's role in translating rotary motion to controlled linear action is fundamental to threading and turning operations, rendering its meticulous design indispensable. By carefully selecting robust materials, determining parameters such as pitch and thread profile, and addressing challenges like backlash and wear, an adeptly engineered lead screw augments overall lathe performance. Crucially, the incorporation of exhaustive stress analysis using advanced computational tools further enhances this endeavor, enabling a comprehensive assessment of structural integrity under varying loads. Through the fusion of meticulous design and analytical rigor, the project's central objective is to craft a tailored lead screw that seamlessly integrates durability and precision, thereby propelling the lathe's operational efficacy to new heights.

1.2 Methodology

Methodology refers to a number of steps or methods used to do a particular research or project. In this case we were provided a guideline under the term Informed Design Process or IDP. The steps in sequence are provided below,

1. **Problem Specifications and Constraints:** The first step of designing the suspension system was to identify the design specifications as in the measurements and materials which will be our starting point. While doing so the obstructions that may arise were also mentioned.
2. **Research and Investigation:** Several research papers and available data on the internet was gone through by us to get more idea about said project.
3. **Create alternate designs:** For this step some designs of the spring were presented varying based on the wire diameter, mean diameter and pitch. The design was made with the goal to minimize stress and deflection.
4. **Choosing and justifying optimal design:** Among all the design that was done the one with the least stress and deflection. To justify the chosen one hand calculation was done using resources from Shigley's book.
5. **Prototype creation:** The final prototype was designed by altering the measurements here and there.
6. **Testing and Evaluation:** Various simulations was run on the final prototype to figure out how the spring would react under different situations.
7. **Redesign and Solution:** After the previous step a redesigning was required by altering the measurements.
8. **Communicating our achievements:** The last step was to showcase the design which achieved the goal of being a proper suspension system.

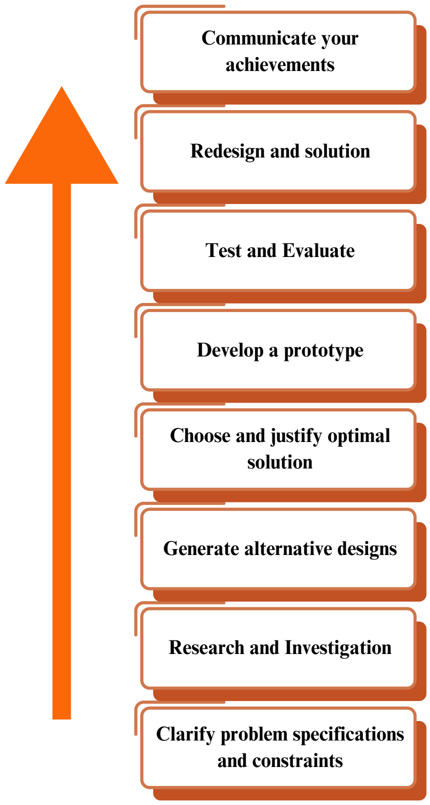


Figure 1: Steps for designing

2. Design specifications and constraints

2.1 Specifications

The first step of this particular project was identifying the specifications and constraints. Specifications refer to what parameters must be considered for the project. In this case the lead screw will be created along with necessary measurements.

The lead screw design integrates pitch and diameter for precision, selects thread profiles to minimize friction, and accounts for material durability. It aligns with the lathe's spindle rotation (900-1500 rpm) for torque calculations, enhancing overall precision and performance.

Coming to the measurement parameters, some constants are,
- Force , P = 6400 N
- Coefficient of friction, f = 0.08

2.2 Constraints

The design of the lathe screw for the lathe machine project is impacted by essential constraints that influence its workability and utility. These comprise:

- **Load Capacity:** The design must ensure that the lathe screw can effectively handle operational loads within defined limits, maintaining structural integrity and precision throughout various machining processes.
- **Vibration and Resonance:** Constraints should be considered to minimize vibration and resonance, ensuring stable operation and precision during machining tasks.
- **Material Availability:** Design choices must align with the availability of suitable materials, facilitating efficient procurement without compromising on mechanical properties and durability.
- **Manufacturing Feasibility:** The design should remain congruent with manufacturing capabilities, favoring processes that can be feasibly employed while maintaining accuracy and efficiency.
- **Lubrication Methods:** Constraints related to lubrication should be accounted for, aiming to integrate efficient lubrication methods that reduce friction, wear, and heat buildup over prolonged use.
- **Cost Effectiveness:** Design choices should be influenced by economic viability, aiming to optimize the design to achieve equilibrium between operational prowess and economical feasibility.

3. Research and investigation

In this step the goal is to attain in-depth information on the lead screw design for lathe machine. Based on three papers, lead screw creation, dynamic characteristics analysis and number of cycles failure were used to evaluate the design.

From paper [1], to create a lead screw, the through-feed rolling process with active rotation (TFRPAR) is used. In this process, the rolling die and workpiece both rotate actively. The lead screw is incrementally formed by the parallel axis rolling dies with a taper angle. The workpiece rotates actively at the initial stage by the mesh between the integrated center and rolling die, and later by the mesh between the formed threaded profile and rolling die. This ensures speed matching and stable motion between the workpiece and rolling die. The process control, die structure, and rolling equipment are relatively simple, and the accuracy of the lead screw pitch can be effectively ensured. The experimental value and designed value of the lead screw pitch were compared based on the major diameter, minor diameter, and pitch. The error between the experimental value and designed value was found to be approximately 0.125%.

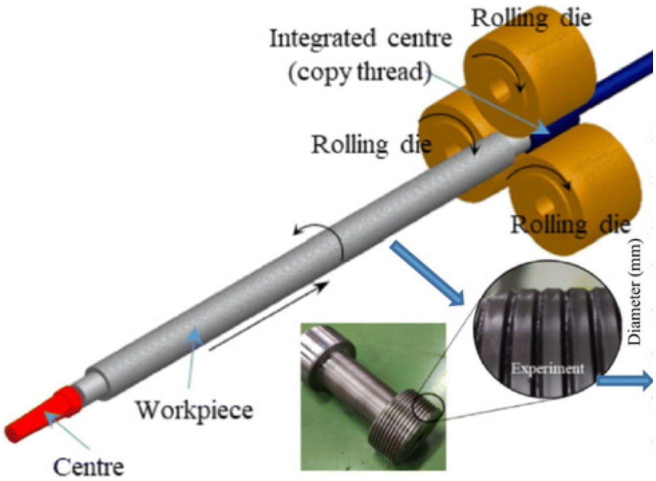
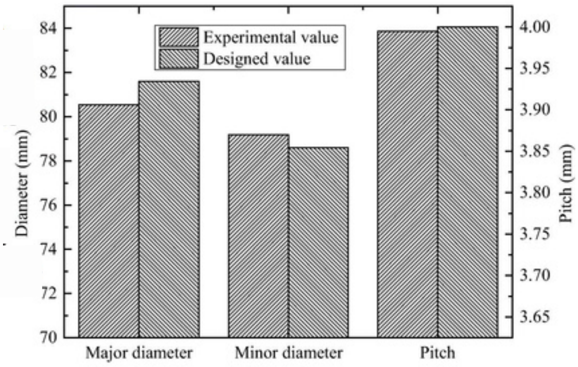


Figure 2: TFRPAR Process
[Zhang, D.-W., Li, D.-H and et al]

Table 1: Diameter and pitch difference when using TFRPAR [Zhang, D.-W., Li, D.-H and et al]



Additionally, the error between the finite element method (FEM) value and the experimental and designed values was less than 1%. These results demonstrate the accuracy and effectiveness of the through-feed rolling process with active rotation in ensuring precise pitch for the lead screw.

From paper [2], in Section 4.5 of the study, the influence of thread pitch variation on stress distribution is investigated. The stress distribution on the lead screw is analyzed for different thread profiles with pitch ranging from 2.5mm to 5.5mm. The results show that the stress values decrease as the nut moves towards the center of the screw and increase as it moves towards the right end support. This trend is observed for all thread profiles.

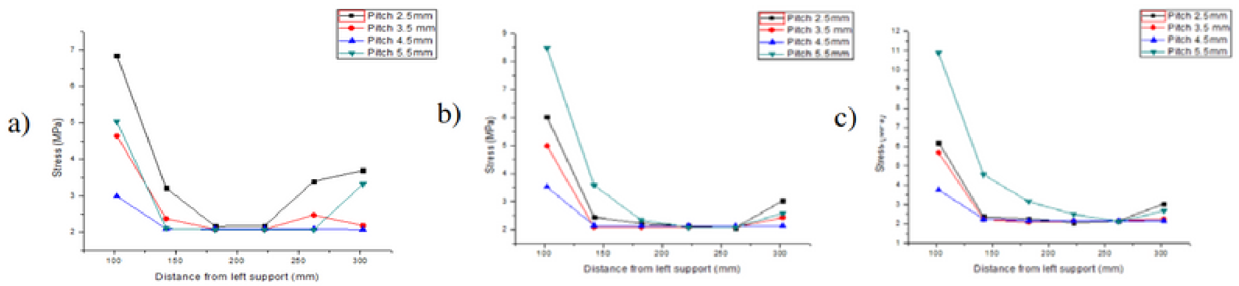


Figure 3. Stress distribution on the lead screw due to variation in pitch in a) square profile b) acme profile c) trapezoidal profile. **[Syriac, Alex & Chiddarwar, Shital.]**

Additionally, it is found that trapezoidal thread profiles generally exhibit higher stress values compared to square and acme profiles at various locations of the nut.

From paper [3], in Section 3.1, the fatigue life of AISI 316L at ambient temperature was investigated. The results showed that AISI 316L exhibited a higher life to failure compared to AISI 1020. The number of fatigue life for AISI 316L was approximately 4 times higher than that of AISI 1020. This indicates that AISI 316L has a longer lifespan and better resistance to fatigue at ambient temperature.

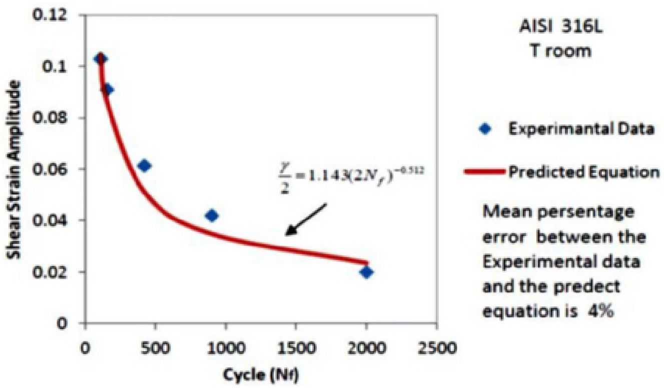


Figure 4: SN curve (linear) of AISI 316L [Hassan, A. D., Nassar, A. A and et al]

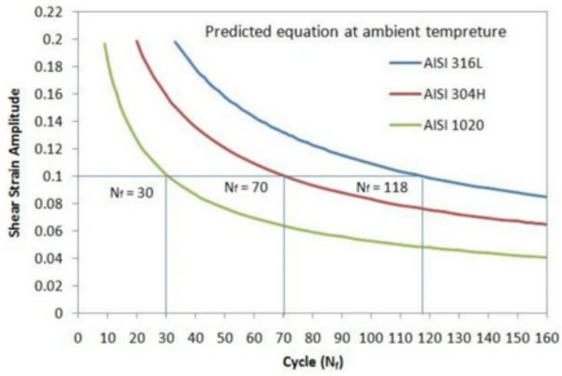


Figure 5: SN curve (linear) comparison of different stainless steel materials [Hassan, A. D., Nassar, A. A and et al]

In Section 3.2, Figure 7 provides a comparison between AISI 316L, AISI 304H, and AISI 1020 at ambient temperature. From the figure 5, it can be observed that AISI 316L exhibited a longer fatigue life compared to AISI 304H and AISI 1020. This further supports the finding that AISI 316L is a superior material in terms of fatigue resistance at ambient temperature.

4. Alternative designs

Based on Shigley's Mechanical Engineering Design by Richard G. Budynas & J. Keith Nisbett (10th Edition) (pg. 408-413), calculations were done using formulas by varying diameter and pitch for Square, ACME and Trapezoidal threaded screws. Two materials: **AISI 304H/304** and **AISI 316L** were selected for the analysis. Based on **paper [2]**, AISI 316L showed suitable results, thus selecting it throughout the **testing and evaluation** section. As there were a handful number of calculation to be done, Google Sheets was used to find torque, stress and efficiency. Down below, color codes are given to make the tables understandable.

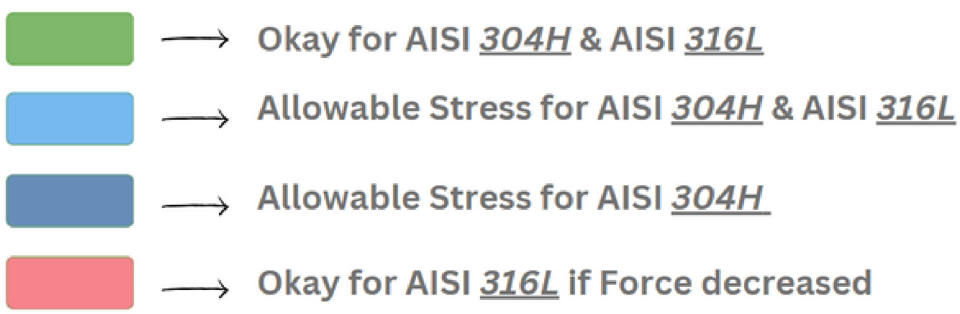


Figure 6: Color codes

4.1 Stress analysis by Varying diameter

Table 2: Stress analysis by varying diameter of (a) Square, (b) ACME and (c) Trapezoidal threaded lead screw

Torsional Shear Stress (MPa)	Axial Stress (MPa)	Bearing Stress (MPa)	Bending Stress (MPa)
266.69	509.30	154.83	580.60
90.95	226.35	110.59	387.06
61.05	166.30	96.77	331.77
43.43	127.32	86.01	290.30
19.63	67.34	64.51	211.13
13.08	48.22	55.29	178.65
6.04	25.15	40.74	129.02

(a)

Torsional Shear Stress (MPa)	Axial Stress (MPa)	Bearing Stress (MPa)	Bending Stress (MPa)
270.17	493.07	149.89	562.10
92.37	219.14	107.07	374.74
62.07	161.00	93.68	321.20
44.19	123.27	83.27	281.05
20.02	65.20	62.46	204.40
13.35	46.68	53.53	172.96
6.18	24.35	39.45	124.91

(b)

Torsional Shear Stress (MPa)	Axial Stress (MPa)	Bearing Stress (MPa)	Bending Stress (MPa)
270.42	491.94	149.55	560.81
92.47	218.64	106.82	373.88
62.14	160.63	93.47	320.47
44.25	122.99	83.08	280.41
20.05	65.05	62.31	203.93
13.37	46.57	53.41	172.56
6.19	24.29	39.36	124.63

(c)

Here, for the analysis, varying diameter, **d: 6, 8, 9, 10, 13, 15, 20 (mm)** and pitch, **p = 2 (mm)** were selected. Then stress analysis was conducted.

4.2 Stress analysis by Varying pitch

Table 3: Stress analysis by varying pitch of (a) Square, (b) ACME and (c) Trapezoidal threaded lead screw

Torsional Shear Stress (MPa)	Axial Stress (MPa)	Bearing Stress (MPa)	Bending Stress (MPa)
43.78	166.30	206.43	663.54
90.95	226.35	110.59	387.06
194.59	325.95	79.40	309.65
454.17	509.30	64.51	290.30
1255.32	905.41	56.30	309.65
4853.93	2037.18	51.61	387.06
43920.37	8148.73	49.15	663.54

(a)

Torsional Shear Stress (MPa)	Axial Stress (MPa)	Bearing Stress (MPa)	Bending Stress (MPa)
44.73	161.00	199.86	642.40
92.37	219.14	107.07	374.74
196.92	315.57	76.87	299.79
458.52	493.07	62.46	281.05
1265.26	876.58	54.51	299.79
4886.65	1972.29	49.96	374.74
44181.31	7889.18	47.59	642.40

(b)

Torsional Shear Stress (MPa)	Axial Stress (MPa)	Bearing Stress (MPa)	Bending Stress (MPa)
44.80	160.63	199.40	640.93
92.47	218.64	106.82	373.88
197.09	314.84	76.69	299.10
458.83	491.94	62.31	280.41
1265.97	874.56	54.38	299.10
4889.02	1967.77	49.85	373.88
44200.19	7871.07	47.48	640.93

(c)

Here, for the analysis, constant diameter, **d = 8 (mm)** and varying pitch, **p: 1, 2, 3, 4, 5, 6, 7 (mm)** were selected. Then stress analysis was conducted.

4.3 Torque analysis :

Table 4: Torque analysis of (a) Square, (b) ACME and (c) Trapezoidal threaded lead screw

T(raise) N.m	T(lower) N.m
3.35	-0.75
3.86	-0.24
4.11	0.01
4.37	0.27
5.13	1.03
5.64	1.54
6.92	2.82

(a)

T(raise) N.m	T(lower) N.m
3.40	-0.71
3.92	-0.18
4.18	0.08
4.44	0.34
5.23	1.13
5.76	1.66
7.08	2.98

(b)

T(raise) N.m	T(lower) N.m
3.40	-0.70
3.92	-0.18
4.19	0.08
4.45	0.35
5.24	1.14
5.77	1.67
7.09	2.99

(c)

Here, for the analysis, varying diameter, **d: 6, 8, 9, 10, 13, 15, 20 (mm)** and pitch, **p = 2 (mm)** were selected. Then torque analysis was conducted. Torque for varying pitch was not calculated because the calculations showed similar results except the 'lower torque' was decreasing. Thus not getting any suitable results. Based on preliminary data, we designed 8 mm ACME lead screw with pitch 2mm using **Fusion 360**.

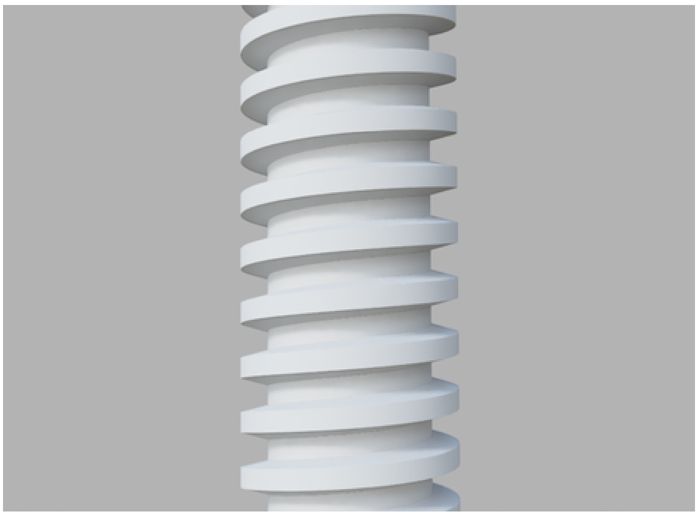


Figure 8: Zoomed in section of 8 mm ACME lead screw

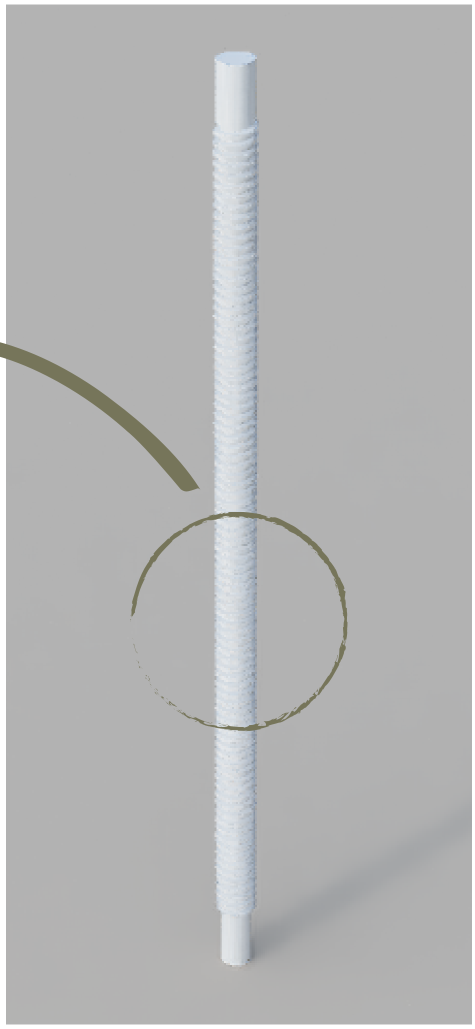


Figure 7: 8 mm ACME lead screw [made with Fusion 360]

5. Choosing and justifying optimal solution

In the pursuit of optimizing the design of a lead screw for integration into a lathe machine, a comprehensive analysis was conducted to evaluate the performance characteristics of three distinct thread profiles: square, ACME, and trapezoidal. This analysis focused on varying thread diameters, pitches, and torques, referring to Table [2], [3], [4], with particular emphasis on axial and bending stresses. The objective was to discern the profile that best balances stress distribution and torque transmission efficiency, ensuring a robust and reliable lead screw solution for the lathe machine.

5.1 Comparison of Thread Profiles on Varying Diameters

Based on Table [2], to hen assessing the effect of varying thread diameters on the square, ACME, and trapezoidal threaded lead screws, it became evident that the trapezoidal profile exhibited superior stress management properties. The trapezoidal thread, characterized by its shallower flanks, facilitated a smoother load transfer across the thread engagement, resulting in reduced axial and bending stresses. The square and ACME threads, while effective in their own right, demonstrated comparatively higher stress concentrations, particularly as the diameter increased. This effect was attributed to the more abrupt transitions between thread flanks in the square and ACME profiles, which hindered stress distribution and contributed to localized stress concentrations.

5.2 Comparison of Thread Profiles on Varying Pitches

From Table [3], in evaluating the performance of the square, ACME and trapezoidal thread profiles under varying pitches, the trapezoidal thread profile once again emerged as the frontrunner. The trapezoidal thread's moderate pitch angle facilitated a smoother load transfer along the thread engagement length. This attribute mitigated the development of excessive axial and bending stresses as compared to the square and ACME profiles. The square thread, characterized by its steep pitch angle, exhibited elevated stress concentrations, particularly evident as the pitch increased. The acme profile, while offering improved stress distribution over the square profile, still displayed higher stress levels compared to the trapezoidal thread due to its sharper pitch angle.

5.3 Comparison of Thread Profiles on Torque Transmission

Referring to Table [4], the consideration of torque transmission capacity among the square, ACME, and trapezoidal thread profiles demonstrated the inherent advantage of the trapezoidal profile. Transitioning from square to acme threads yields a notable 1.5% increase in torque due to the ACME thread's more favorable geometry. Further transitioning from acme to trapezoidal threads leads to an additional 0.22% increase in torque, primarily attributed to the trapezoidal thread's enhanced contact area and stress distribution. Due to trapezoidal thread profile's ability to accommodate higher torque without inducing excessive stresses, it solidified its position as the optimal choice for torque-intensive applications.

Comparing the thread profiles, we can easily discern **Trapezoidal lead screw** as the top selection.

5.4 Justifying The Optimal Design:

Drawing from a comprehensive analysis that encompassed stress distribution and torque transmission assessments, a selection of suitable options has emerged for the lead screw design in the lathe machine. Among the considered diameters—9 mm, 10 mm, 13 mm, 15 mm, and 20 mm—and pitches—2 mm and 3 mm—a discerning engineering evaluation has highlighted diameters 9 mm and 10 mm, accompanied by a 2 mm pitch, as particularly promising choices. Exhibiting efficiencies of 47.02% and 44.23%, respectively, these selections operate in proximity to the pivotal 50% threshold. This intricate decision-making process tactfully navigates the delicate balance between efficient torque transfer and the potential challenge of back drive concerns. Rooted in thorough analysis, this approach reflects a thoughtful stride towards crafting an optimized lead screw configuration that aligns operational performance with mechanical robustness.

6. Developing a prototype

6.1 Prototype creation using CAD software

As part of the development process, we constructed a virtual representation of the refined design as a prototype. The CAD software **Fusion 360** by Autodesk was used. Steps,

- Create a circle of **10 mm diameter** in top plane
- Extrude to 150 mm
- Selecting "Thread" option from drop-down menu of "CREATE"
- Select the cylindrical surface as face
- Select **pitch of 2mm** and click "OK"

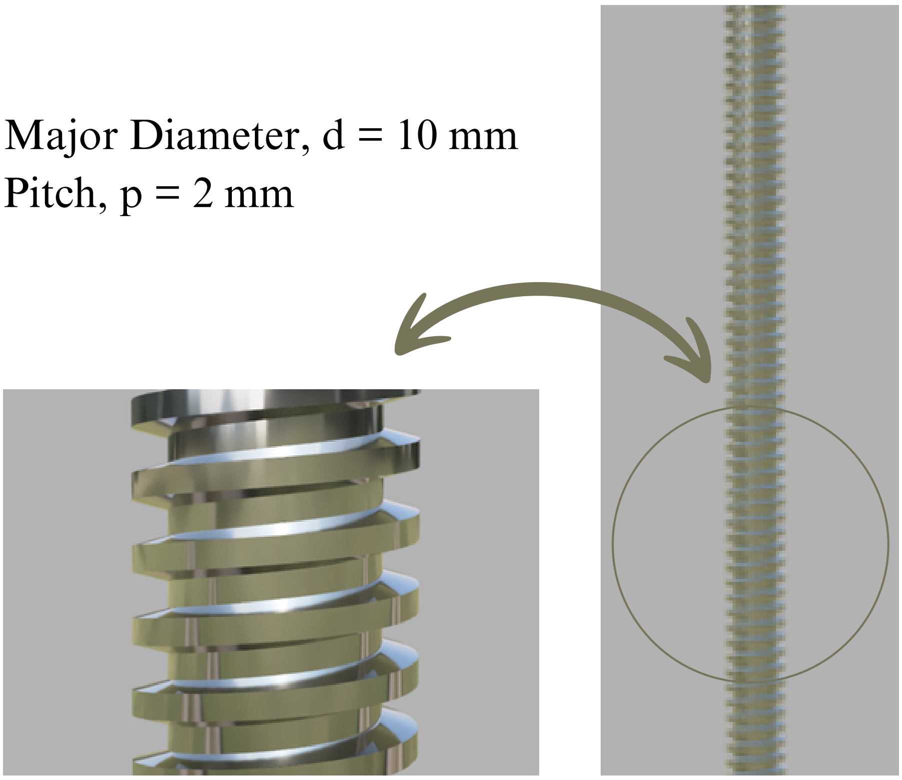


Figure 10: Zoomed in section of 10 mm Trapezoidal lead screw

Figure 9: 10 mm Trapezoidal lead screw [made with Fusion 360]

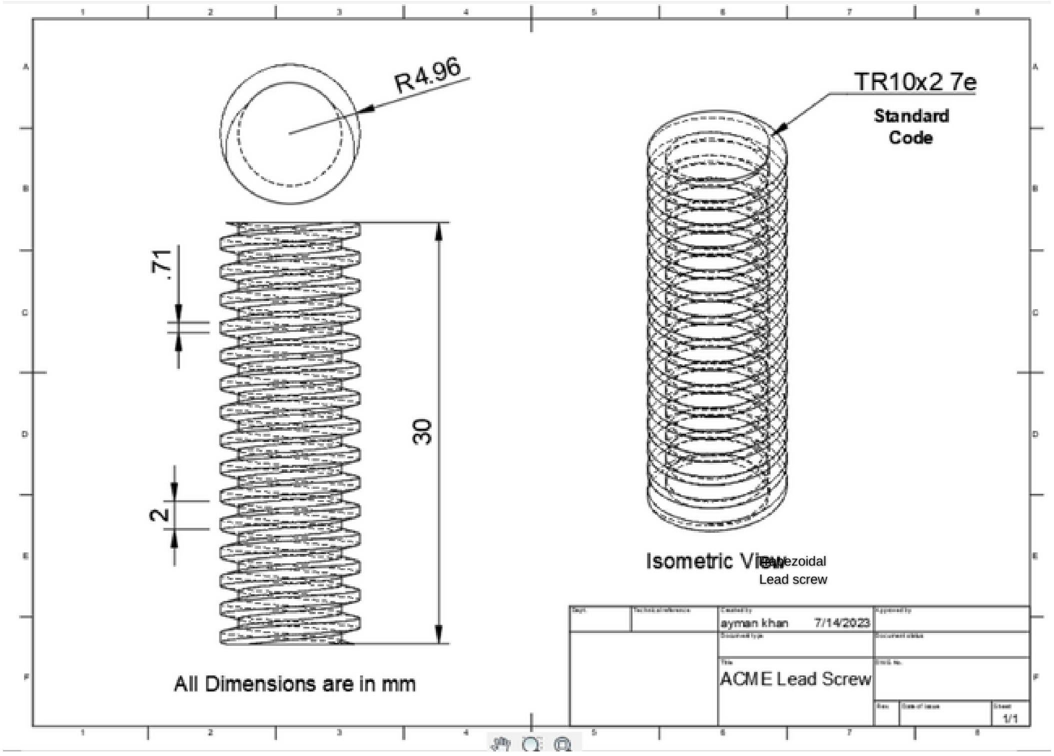


Figure 11: Industrial design of 10 mm Trapezoidal lead screw

6.2 Technical Specification

Following a comprehensive analysis of the trapezoidal lead screw, a concise yet comprehensive technical specification has been formulated. This specification encapsulates critical design parameters, material requirements, tolerances, and performance expectations. Crafted with meticulous attention to detail, this technical specification serves as the cornerstone for the fabrication process, ensuring the translation of analytical insights into a precisely engineered and functional component.

Table 5: Technical Specifications of Trapezoidal lead screw

Specifications	Value
Major Diameter, d	10 mm
Pitch, p	2 mm
Pitch Diameter, Dp	9 mm
Minor Diameter, Dm	8 mm
Force, F	2 kN
Target Tolarence	1.00%
Rasing Torque, Tr	4.44 Nm
Tensile Strength (AISI 316L)	485 MPa
Yield Strength (AISI 316L)	170 MPa
Torsional Shear Stress (MPa)	44.19 MPa
Axial Stress (MPa)	123.27 MPa
Bending Stress (MPa)	224.07 MPa
Efficiency	44.23%

6.3 Fabrication Process

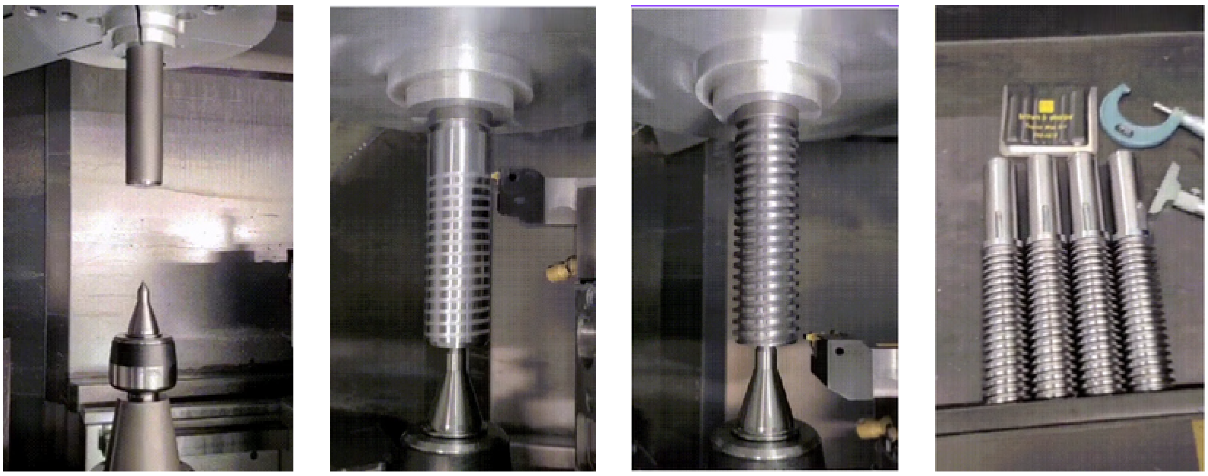


Figure 12: Fabrication of Trapezoidal lead screw using a vertical lathe machine

The fabrication of a trapezoidal lead screw involves a meticulously orchestrated sequence of steps aimed at translating design specifications into a tangible mechanical component.

- A cylindrical bar with a diameter of 10 mm is selected.
- The bar is affixed onto the Chuck.
- The bar's end is secured using the Tailstock.
- The machine is configured to operate with a pitch of 2 mm.
- A cutting tool with a 30º angle is utilized.
- The operation is executed until the thread width aligns with the thread depth.

7.Testing and Evaluation

7.1 Testing of Trapezoidal lead screw

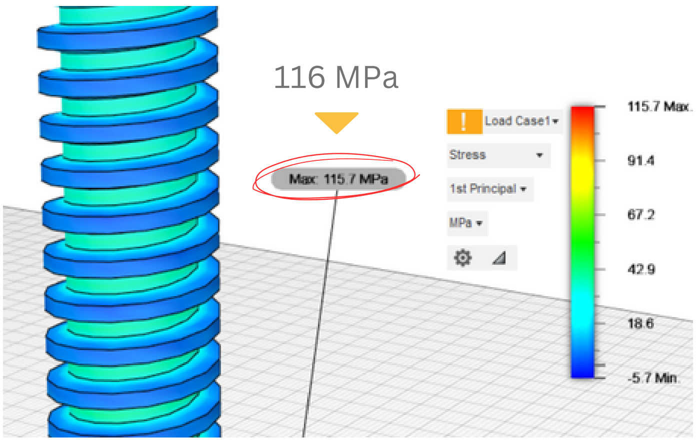


Figure 13: Axial Stress analysis at 2 kN load

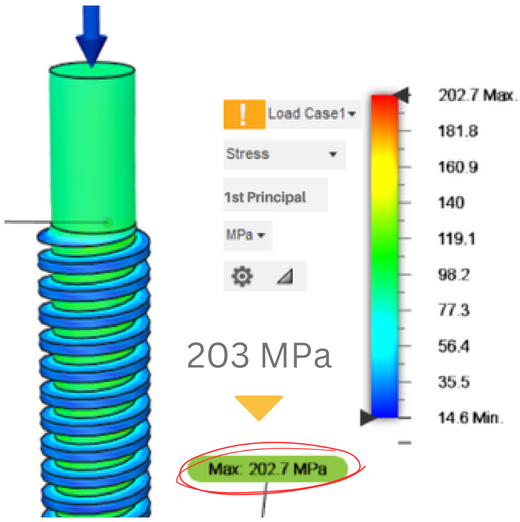


Figure 14: Bending Stress analysis at 2 kN load

In the world of designing lead screws, understanding how they handle both axial and bending stresses is absolutely crucial to ensure they are strong enough to perform well. By simulating these types of stresses in **Fusion 360**, using a specific load scenario of 2 kN, we can unveil how the load is spread out and where potential weak points might be. The numbers we get from these simulations tell us a lot: an axial stress of 116 MPa from figure 13 and a bending stress of 203 MPa from figure 14. These values guide us in choosing the right materials and shapes for the lead screw. Moreover, the fact that the factor of safety is above 1 after the simulation means that the lead screw is strong enough to handle the expected conditions without failing. This kind of stress analysis is really important because it helps us fine-tune the design, ensuring that the lead screw is tough, reliable, and safe in its performance.

7.2 Evaluation

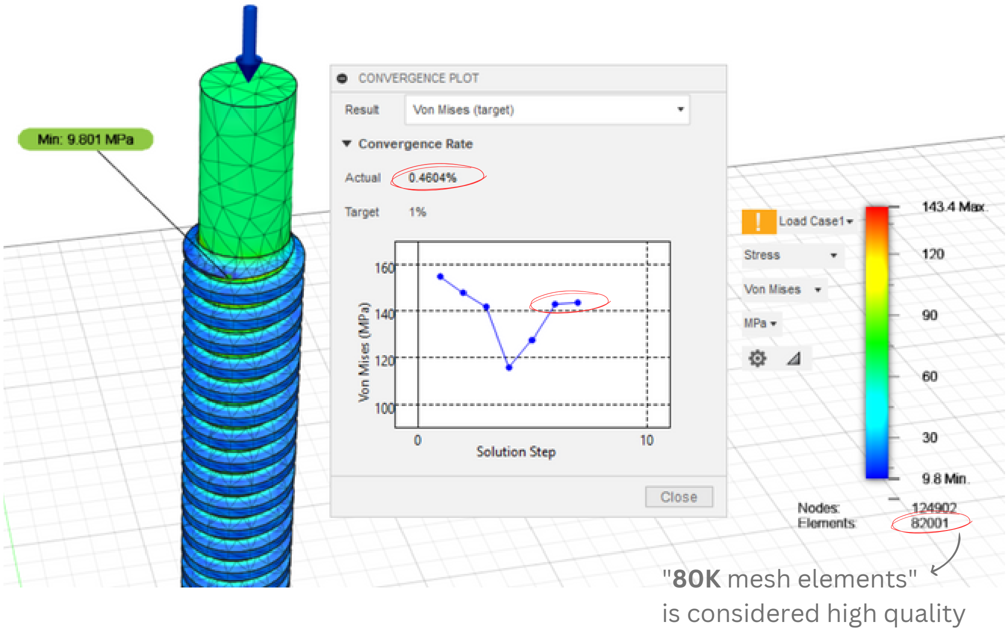


Figure 15: Mesh analysis

In our analysis carried out within **Fusion 360**, we employed a detailed approach known as mesh analysis. This involved simulating the same force configuration as before but with a careful setup of **80,000 mesh** elements to ensure accurate representation. Our goal was to achieve a result within 1% of our target value, and our findings were at 0.46%. Looking at the convergence graph, where stress levels (von Mises) in MPa are on the vertical axis and the analysis steps are on the horizontal axis, we observed an interesting trend: after 7 steps, the graph flattened out, aligning almost parallel to the analysis steps axis. In mesh analysis, this convergence indicates a reliable and accurate representation. This meticulous analysis, conducted with a professional engineer's rigor, provides a clearer picture of how the lead screw behaves under different loads, affirming the strength of our analysis and its close reflection of real-world scenarios.

8.Redesigning and Solution

8.1 Verification

As we delved into the redesign and solution phase, a critical element known as verification and validation (V&V) played a pivotal role. In the verification part, our focus was on ensuring that our simulation outcomes matched up with what we anticipated theoretically. This process involved a meticulous comparison of our calculated values with the expected values, all neatly organized in a **table [6]**. What emerged from this comparison was quite encouraging: our simulated results of axial stress and bending stress were closely aligned with the theoretical ones. It's worth noting that the differences, or errors, were all under 10%, for axial stress indicating a modest variation of 5.7% and bending stress demonstrating a measured divergence of 9.37% which falls well within the acceptable range considering our lead screw design. This thorough verification procedure, carried out with the scrutiny of an experienced engineer, highlights the accuracy of our simulation approach and its effectiveness in affirming the soundness of our lead screw design.

Table 6: Verification chart

Parameters	Axial Stress	Bending Stress
Theoretical value	123	224
Simulated value	116	203
Error	5.70%	9.37%

8.2 Validation

Due to the unavailability of appropriate laboratory machinery designated for testing the mechanical properties of the lead screw, it regrettably resulted in the absence of any empirical data being recorded pertaining to the application of a 2000 N load. This circumstance underscores the criticality of a comprehensive equipment inventory and allocation strategy within research and development environments, ensuring the requisite resources are on hand to enable accurate experimentation and data acquisition, thus contributing to the advancement of precision engineering analyses.

There are two parts: verification and validation, also known as V&V. We completed our verification process, but because of the unavailability of machines, we couldn't get the experimental values, thus not completing the validation process. Still, as long as our verification process is okay, we can assume our design is complete and safe.

9. Concluding Remarks

9.1 Conclusion

A comprehensive exploration of lead screw dynamics has been undertaken, spanning facets encompassing design, stress analysis, simulation, and verification. The culmination of this trajectory highlights the meticulous convergence of theoretical insights and practical outcomes. Through rigorous examination, the viability of the lead screw design is affirmed, as simulation results align within acceptable margins.

Several valuable lessons were acquired throughout this project, including the intricacies of designing an effectively integrated lead screw into the lathe machine. Profound insights were also gained into the realm of Finite Element Analysis (FEA), a pivotal aspect of engineering, as well as the nuances of testing and substantiating design choices. Although the learning curve exhibited fluctuations, the journey proved to be significantly enriching and worthwhile.

9.2 Recommendation

(a) Limitations

1. The use of AISI 316L as a lead screw material for a lathe machine may be constrained by its relatively lower tensile strength, potentially affecting load-bearing capability and durability. Alternatives such as AISI 4140 steel, AISI 1045 steel, AISI 304 can be used.
2. Despite their efficacy, traditional lead screws exhibit comparatively higher friction and lower efficiency than alternative mechanisms, leading to potential compromises in precision and operational smoothness, particularly when subjected to demanding operational conditions.

(b) Suggestions

1. Ball screws offer heightened efficiency, reduced friction, and superior precision compared to traditional lead screws. This translates to smoother motion, increased accuracy, and improved performance in precision applications.

References

[1] Zhang, D.-W., Li, D.-H., Liu, B.-K., Yu, Z.-C., & Zhao, S.-D. **(2022)**. **Investigation and implementation for forming lead screw by through-feed rolling process with active rotation**. Journal of Manufacturing Processes, 82, 96–112.https://doi.org/10.1016/j.jmapro.2022.07.062

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Appendix

Gantt Chart