Design, Analysis, Simulation, and Model Fabrication of CNC Milling and Laser Engraving Machine for PCB Fabrication

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Certificate of Approval

It is certified that the project titled "Design, Analysis, Simulation and Model Fabrication of CNC Milling And Laser Engraving Machine for PCB Fabrication" carried out by Syed Mohammad Hussain Musavi, Reg. No. F19602039, Syed Muhammad Ismail Hussain, Reg. No. F19602042 and Muhammad Haris Sheikh, Reg. No. F19602033. under the supervision of Dr. Kamran Nazir, Assistant Professor, National University of Technology (NUTECH), Islamabad.

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DEDICATED

TO

OUR PARENTS

Preface

In presenting this report, we want to affirm that the contents contained herein are the product of a thorough study. As the authors of this document, we assure the reader that all sources used in the course of this research have been appropriately credited and cited. Furthermore, no section of this report has been copied from any external sources without proper acknowledgment. The findings and conclusions presented are the direct outcome of our own experiments, investigations, and analyses.

Abstract

The traditional methods of PCB fabrication have several drawbacks, including limited resolution and accuracy, high costs, and environmental hazards. CNC milling offers a more efficient and precise alternative for PCB fabrication but requires a specialized machine that can accurately cut the PCB material to the required specifications. This project aims to design and fabricate a CNC milling machine for printed circuit board (PCB) fabrication. The prototype was designed with a combination of computer-aided design (CAD) modelling software and computer-aided manufacturing (CAM). The machine's frame was made from aluminum and assembled using various mechanical components, a lead screw has been used to generate the machine’s linear motion guides. The control system has been developed using a microcontroller and software. The machine has been tested by milling printed circuit board (PCB) prototypes using copper.

The CNC milling machine for PCB fabrication project has the potential to significantly improve the efficiency and accuracy of the PCB fabrication process, while also contributing to the broader goal of advancing manufacturing technology in Pakistan.

Authorship

The project was conceptualized and managed by Syed Muhammad Hussain Musavi, who served as the project lead. He provided guidance, coordinated team efforts, and took overall responsibility for the project. Muhammad Haris Sheikh and Syed Muhammad Ismail Hussain made significant intellectual contributions to the project. All the members have equal contributions included design, fabrication, programming, testing, analysis, and documentation. The faculty advisor Dr. Kamran Nazir (Assistant Professor-Mechanical Department) from National University of Technology (NUTECH), Islamabad, provided significant guidance and mentorship throughout the project and is acknowledged in the report.

Nomenclature

PCBs	Printed Circuit Boards
CNC	Computer Numeric Control
SMEs	Small and Medium-sized Enterprises
NC	Numeric Control
SFM	Surface Feet per Minute
RPM	Revolution Per Minute
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
V_c	Cutting Speed
D_{ap}	Axial Depth of Cut
f_z	Feed per Tooth
v_f	Table feed
$Q_{(MRR)}$	Material Removal Rate
D_c	Radial Depth of Cut
P_c	Cutting Power
k_c	Specific Cutting Force
F_V	Cutting Force
U_t	Specific Energy
ρ	Density
C	Specific Energy
k	Thermal Diffusivity
P_T	Tangential Force on Edge of Lead Screw

W	Total Load on the Screw
$tan\emptyset = \mu_1$	Coefficient of Friction of Lead Screw
α	Helix Angle of Thread
p	Pitch of Screw
d	Mean Diameter
ω	Angular Velocity
μ2	Coefficient of Friction for Collar
F_a	Acceleration Force
F_r	Frictional Force
F_g	External Force due to Gravity
F_t	Total Force
I_{Load}	Moment of Inertia for Load
$I_{Lead-screw}$	Moment of Inertia for Lead Screw
L	Length of Lead screw
m	Mass of Removed Material
V	Volume of Material Removed
ρ	Density of Workpiece
E	Energy
R	Reflectivity
n	Refractive Index
k	Extinction Coefficient
P_{beam}	Power of Beam
M	Molar Mass of Copper

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Chapter 1

1. INTRODUCTION

PCB stands for Printed Circuit Board. It is an insulating board with conductive pathways etched onto its surface. These pathways, tracks, or signal traces are made from copper sheets laminated onto a non-conductive substrate. PCBs serve the dual purpose of mechanically supporting and electrically connecting electronic components.

With the growing use of electrical components and devices, the demand for PCBs has seen a significant rise in recent years. Various techniques are employed for PCB fabrication, ranging from less accurate and time-consuming methods to highly accurate and time-efficient approaches. The quality of PCBs is directly influenced by the fabrication method used. The most common ones include:

- Imaging: In this process, the digital PCB design is transferred onto the physical board, creating a pattern of circuitry and components.
- Etching: It is the method of selectively removing excess metal from the PCB using an industrial solvent, leaving behind the desired circuitry.
- Machining: This technique utilizes a CNC (Computer Numerical Control) machine to precisely remove unwanted copper from the board, shaping it according to the PCB design.
- Plating: During plating, a thin layer of metal is deposited onto the surface of the board, enhancing its conductivity and ensuring proper electrical connections.

Above mentioned techniques, etching is the traditional method of PCB fabrication that involves use of chemicals to etch the circuit pattern onto the substrate. This process is prone to inaccuracy as well as time-consuming, and the chemicals used can be hazardous to the environment and human health. Alternative to the traditional method of PCB fabrication, machining technique has been widely used for PCB fabrication due to its precision and repeatability.

A CNC Milling Machine is a computerized machine that can perform various tasks including milling, drilling, and cutting in order to produce accurate parts with tight tolerances. Because of their precision, speed, and accuracy, CNC machines have become very popular in a wide variety of industries, such as aviation, automotive, and electronics. The ability of CNC machines to produce precise and complex shapes has made them ideal for use in PCB fabrication. A CNC milling machine for PCB fabrication is designed to mill the copper material from the substrate to create the required circuit pattern.

The process of PCB fabrication involves several steps:

1. Designing the circuit pattern.
2. Printing the circuit pattern onto the substrate.
3. Milling the copper material from the substrate to create the circuit pattern.

The use of CNC milling machines for PCB fabrication has become increasingly popular in recent years, with many companies offering CNC milling services for PCB fabrication. However, the cost of CNC milling machines can be high, which may be a barrier for small and medium-sized enterprises (SMEs) that cannot afford to invest in expensive equipment. To overcome this barrier, low-cost CNC milling machines have been developed, which are affordable for SMEs. These machines offer a cost-effective solution for producing high-quality PCBs.

1.1. Consideration for CNC Milling for PCB Fabrication

When considering CNC milling for PCB fabrication there are several factors to take into account. These include:

1.1.1. Accuracy

The accuracy of CNC machine is an important factor that needs to consider, which ensure that the circuit patterns are precisely cut as the width of the traces on a PCB controls the amount of current that may flow through the circuit and can affect the circuit's overall performance.

1.1.2. Speed

In order to increase productivity and efficiency the machine’s speed should be taken into account to ensure that the PCB is ready within the minimum time.

1.1.3. Material compatibility

Different types of materials can be used for PCB fabrication, including copper-clad boards and aluminum. The CNC milling machine should be compatible with the material being used to ensure that the machine can cut through the material effectively.

1.1.4. Cutting tool compatibility

The cutting tool is a critical component of the CNC milling machine, and it is important to ensure that type of cutting tool being used is compatible with the material being removed from PCB board.

1.1.5. Worktable size

The size of PCB boards varies from small to large depending on the system structure where it has to be planted. The worktable should be large enough to accommodate the size of the PCB being fabricated.

1.1.6. Motor to provide a desirable cutting speed

The selection of Motor to provide a desirable cutting speed is also an important factor to be considered for CNC for PCB fabrication to provide a desired speed to make the process more efficient and precise.

1.1.7. Cost

The cost of the CNC milling machine is also an important consideration. The machine should be affordable and provide good value for money.

1.2. Main Components

The machine consists of several components, including the frame, spindle, stepper motors, linear guides, and control system.

1.2.1. Frame

The frame is the main structural component of the machine and provides the foundation for all other components which need to be installed in the machine. It is usually made of aluminum or steel and must be rigid and stable to ensure machine do not vibrate while milling operation.

1.2.2. Motors

Stepper motors are commonly used in CNC milling machines for their precise control and accuracy. They provide the necessary motion to move the milling head and the workpiece in the X, Y, and Z axes.

1.2.3. Control system

The control system is the brain of the CNC milling machine and includes a microcontroller, drivers, and software. The microcontroller reads the G-code instructions from the software and sends signals to the drivers to move the motors.

1.2.4. Spindle

The spindle is the cutting tool used to mill the PCB. It is mounted on the milling head and rotates at high speeds to remove material from the workpiece. A high-speed spindle with a variable speed control is ideal for PCB milling.

1.2.5. Milling bed

The milling bed is the surface on which the workpiece is mounted. It should be flat and level to ensure accurate milling. A vacuum table is commonly used to hold the workpiece securely in place during milling.

1.2.6. Ball screws

Ball screws are used to provide precise linear motion in the X, Y, and Z axes. They consist of a screw and a ball nut that moves along the screw as it rotates.

1.2.7. Linear guides

Linear guides are used to provide smooth and precise motion in the X, Y, and Z axes. They consist of a rail and a carriage that moves along the rail.

1.2.8. Limit switches

Limit switches are used to set the maximum travel limits of the milling machine in the X, Y, and Z axes. They prevent the milling head from moving beyond the safe limits and causing damage to the machine.

1.2.9. Power supply

A power supply is required to provide power to the motors and control system of the CNC milling machine.

1.3. Historical Background

The first numerical control NCN was created in the 1940s, which is when CNC milling machines initially became popular. Punch cards were used in the NC machine, allowing for more accurate and precise control of the tool movement. However, due to the fact that it could only perform simple cutting operations, the NC machine was limited in its capabilities.

In the 1950s, the first computer-controlled machine tool was developed by the Massachusetts Institute of Technology (MIT). The machine used a computer to control the movement of the cutting tool, which allowed for more complex and precise cutting operations. This was the first step towards the development of CNC machines.

In the 1960s, the first commercial CNC machines were introduced by several companies, including Kearney & Trecker and Cincinnati Milling Machine Company. These machines used computers to control the movement of the cutting tool, which allowed for greater accuracy and repeatability.

The development of CNC machines revolutionized the manufacturing industry, as it allowed for the mass production of complex parts with high precision and accuracy. The use of CNC machines in PCB fabrication began in the 1980s, with the introduction of the first CNC milling machines for PCB fabrication.

The first CNC milling machines for PCB fabrication were large and expensive and were mainly used by large electronics companies for in-house PCB fabrication. However, as the technology improved and the cost of CNC machines decreased, small and medium-sized enterprises (SMEs) began to adopt CNC machines for PCB fabrication.

In the early 2000s, the development of low-cost CNC machines revolutionized the PCB fabrication industry. These machines were affordable for SMEs and allowed for the production of high-quality PCBs with complex circuit patterns.

Today, CNC milling machines for PCB fabrication are widely used in the electronics industry. They offer high precision and repeatability, which is essential for producing high-quality PCBs. They are also faster and more efficient than the traditional method of PCB fabrication, which reduces production time and increases the overall efficiency of the PCB fabrication process.

In conclusion, the development of CNC milling machines for PCB fabrication has revolutionized the electronics industry. It has allowed us to produce high-quality PCBs with complex circuit patterns and has increased the overall efficiency of the PCB fabrication process. Technology continues to evolve, with the development of new materials and processes that further improve the capabilities of CNC milling machines for PCB fabrication.

1.4. Motivation

PCBs are an essential component of modern electronic devices, and their demand is increasing globally due to the growing electronics industry. Traditional PCB fabrication techniques rely heavily on chemical etching, which can be costly and time-consuming. CNC milling, on the other hand, eliminates the need for chemical etching and can significantly reduce the cost of PCB production, especially for small production runs. Moreover, the ability to program CNC machines enables to produce complex and intricate boards that meet specific requirements, such as multi-layer boards or miniaturized components. Additionally, the ability to quickly produce a prototype PCB enables manufacturers to test and refine the design before moving forward with full-scale production. CNC milling can reduce the overall lead time for producing a PCB, helping to meet tight deadlines and get products to market faster. By leveraging the flexibility, versatility, and cost-effectiveness of CNC milling, PCB manufacturers can stay competitive in today's fast-paced manufacturing environment.

1.5. Problem Statement

The problem addressed in this design project is the need for an efficient and cost-effective CNC milling machine specifically designed for PCB (Printed Circuit Board) fabrication. PCBs are crucial components in electronic devices, and their production often relies on traditional manufacturing methods that are inefficient, time-consuming, labor-intensive, and generate substantial waste.

1.6. Purpose of Project

1.6.1. Enhance Efficiency

The machine should streamline the fabrication process, automating tasks such as drilling, etching, and soldering to minimize human error and improve production efficiency.

1.6.2. Reduce Costs

The CNC milling machine should be designed to minimize production costs by optimizing material usage, reducing waste generation, and utilizing cost-effective manufacturing techniques.

1.6.3. Improve Design Flexibility

The machine should allow for greater design flexibility, enabling the production of intricate PCB layouts, finer traces, and smaller component footprints.

1.6.4. Promote Sustainability

The CNC milling machine should incorporate sustainable design principles, aiming to minimize energy consumption, reduce waste generation, and utilize environmentally friendly materials and processes.

1.7. Applications

1.7.1. Electronics Prototyping

The CNC milling machine allows engineers, researchers, and hobbyists to quickly prototype PCBs in-house, reducing the turnaround time for testing and iterating designs. It enables rapid fabrication of PCB prototypes with complex designs, allowing for faster validation and refinement of electronic circuits.

1.7.2. Small-Scale PCB Production

The CNC milling machine provides a cost-effective solution for small-scale electronic product development and manufacturing. It allows small businesses and startups to produce custom PCBs in-house, reducing dependence on external fabrication services and enabling faster time-to-market.

1.7.3. Educational Institutions

The CNC milling machine can be used in educational institutions to teach students about PCB design, fabrication processes, and CNC machining. It offers hands-on learning opportunities and facilitates practical training in electronics manufacturing.

1.7.4. Research and Development

The CNC milling machine supports research and development activities in the field of electronics by enabling quick fabrication of custom PCBs for experimental setups, prototypes, and proof-of-concept demonstrations. It allows researchers to iterate designs and test ideas in a timely and cost-efficient manner.

1.8. Project Management

Throughout the project, effective project management strategies were employed to keep the project on track, meet deadlines, and achieve the desired outcomes. The project begins with a comprehensive planning phase, including defining the project scope, objectives, and deliverables, as well as creating a detailed project plan with clear timelines and milestones. Each member has been assigned specific roles and responsibilities based on their expertise. We ensure that everyone understands their tasks and how they contribute to the overall project goals. Regular team meetings have been held to foster communication, collaboration, and decision-making.

We closely monitor project progress, track tasks, and manage resources effectively. This involves weekly progress updates, task tracking, closely monitored milestones to ensure they are achieved as planned and budget monitoring.

We identify potential risks and develop strategies to mitigate them. This involves conducting thorough risk assessments and establishing contingency plans. By being proactive in identifying and addressing risks, we minimize the impact of unforeseen events and ensure project continuity.

Finally, proper documentation of each phase of the project has been maintained. This practice aids us in delivering a final project report, summarizing the design process, outcomes, and recommendations for future work.

By following these project management practices, our team ensures effective coordination, timely completion, and successful delivery of the "CNC Milling for PCB Fabrication" project.

1.9. Sustainable Development Goals

The development of a CNC Milling Machine for the Fabrication of PCBs has the potential to contribute to several sustainable goals, particularly those related to innovation and environmental sustainability.

1.9.1. SDG 9: Industry, Innovation, and Infrastructure

Develop innovative technology for efficient and sustainable PCB fabrication. Promoting manufacturing processes to minimize waste and enhance productivity.

1.9.2. SDG 12: Responsible Consumption and Production

Sustainable manufacturing of PCB board by ensuring minimum utilization of resources and minimal impact on the environment.

1.9.3. SDG 17: Partnerships for the Goals

Collaborate with industry partners, academia, and research institutions to develop sustainable PCB fabrication techniques.

1.10. Objectives

Following are the listed objectives of the project:

- To design and fabricate a CNC milling machine that can accurately and efficiently design PCBs.
- To test and optimize the CNC milling machine's performance to ensure that it designs clean PCBs with smooth traces and well-defined tracks.
- To promote local entrepreneurship and self-sufficiency in the electronics industry by producing locally fabricated CNC milling machines.

1.11. Scope

Here are key aspects within the scope of the project:

1.11.1. Design Requirements

- Define the specifications and performance parameters for the CNC milling machine, considering factors such as accuracy, repeatability, speed, and compatibility with various PCB materials.
- Determine the size and working area of the machine to accommodate different PCB sizes and complexities.

1.11.2. Machine Development

- Design the mechanical structure of the CNC milling machine, including the frame, linear motion system, spindle system, and work holding mechanisms.
- Select appropriate components and materials to ensure the machine's robustness, precision, and longevity.
- Integrate the mechanical components with the electrical and electronics systems, including stepper motor drivers, controller boards, limit switches, and sensors.

1.11.3. Performance Optimization

- Conduct testing and calibration to optimize the machine's performance in terms of accuracy, speed, and repeatability.
- Evaluate the machine's capabilities through test runs and benchmarking against industry standards.

1.11.4. Sustainability Considerations

- Implement measures to minimize material wastage during PCB fabrication, such as optimizing tool paths and reducing the need for chemicals.
- Assess and mitigate the machine's energy consumption by considering energy-efficient components and system optimization.
- Consider the environmental impact of the project by promoting the use of eco-friendly materials and reducing reliance on external PCB fabrication services.

1.12. Deliverables

Our project deliverables are summarized below:

1.12.1. CNC Milling Machine Prototype

A fully functional scaled prototype of the CNC milling machine designed specifically for PCB fabrication. The prototype will include the mechanical structure, linear motion system, spindle system, work holding mechanisms, and control electronics.

1.12.2. Project Report

A comprehensive project report that outlines the design process, methodologies, summary of the project objectives, achievements, and outcomes.

1.13. Bill of Material

Table 1-1 Bill of Material

#	Component Name	Quantity	Unit price	Total
01	Stepper motor NEMA 17	3	750	2250
02	Motors wire	3	200	600
03	Mount Flat Bracket Alloy Plate	2	250	500
04	Rotor (DC motor)	1	650	650
05	Motor cable	1	200	200
06	Aluminum profile 2020	0.36 m x 5	500	3000
07	Aluminum profile 2020	0.33 m	500	1100
08	Aluminum profile 2020	0.22 m	500	800
09	Stainless steel rod (supporting rod)	0.4 m x 2	275	550

10	Stainless steel rod (supporting rod)	0.33 m x 2	275	500
11	T8 Lead screw	0.4 m	1200	1200
12	T8 Lead screw	0.32 m	1200	1200
13	M3x6 hexagon screw	8	10	40
14	M5x8 hexagon screw	4	15	60
15	M5x10 hexagon screw	59	20	1180
16	M6x12 hexagon screw	10	25	250
17	M5 T nut	63	30	1890
18	M6 Slide nut	10	30	300
19	Lead screw Nut	3	230	690
20	2020 L bracket	16	120	1920
21	10 mm rod Support	8	300	2400
22	Bearing holder	1	350	350
23	T nut holder	1	200	200
24	Linear bearing	4	350	1400
25	Coupling	3	350	1050
26	M5 Gasket	35	2	70
27	Power supply (24v 5A)	1	950	950
28	Drill bit (30 degree 0.1mm)	1	1050	1050

29	Drill bit (20 degree 0.1mm conical)	1	1242	1242
30	Drill bit (15 degree 0.1mm conical coated)	1	1402	1402
31	Drill Bit (0.3-1.2 mm)	1	880	880
32	Collet ER11	1	1578	1578
33	Support holder L shape	2	350	700
34	Micro controller GRBL 1.1	1	9000	9000
35	1518 CNC table	1	16650	16650
36	X Axis bearing Holder (3d printed)	1	600	600
37	Z Axis holder (3D printed)	1	5900	5900
38	Table Holder (3D printed)	6	600	3600
39	5.5w Laser Module	1	30500	30500

Total Shipping Cost	14520 Pkr
Total	112,922 Pkr

1.14. Work Division

It is important that the work should be divided between members of group so as to maximize each member's knowledge and expertise in order to achieve an efficient execution of a project with title "CNC Milling Machine for PCB Fabrication". Based on the three group members' skills and interests, we distributed the work among them.

The CAD modeling and computations has been done by Syed Muhammad Hussain Musavi. This entails developing a 3D model of the product using computer-aided design software and running calculations to make sure it complies with the specifications.

Syed Muhammad Ismail and Muhammad Haris Sheikh has done Calculations for the important parameters which are required for proper functioning of machine according to our design requirements.

We all three members have managed the components and manufacturing phase. This entails assembly of machine and testing for its proper functioning.

Finally, the product testing will involve all three members. This entails doing a number of tests on the assembled prototype to make sure that it complies with the desired objectives. The entire team will address any problems that come up during testing and make any necessary adjustments.

We have also involved our supervisor and co-supervisors in addition to the division of work among the three group members for successful completion of project. Throughout the project, they will be constantly informed, and meetings were held to discuss any challenges or issues that arise.

Overall, by keeping the entire members, supervisor, and co-supervisor in the loop throughout the project, we have successfully completed the project smoothly and any issues were addressed promptly.

1.15. Standard Operating Procedures

Here are SOPs that must be implemented to ensure smooth working of the machine:

1.15.1. Machine Operation SOP

1.15.1.1. Start-up Procedure

This includes:

- Perform a visual inspection to ensure no obstructions or safety hazards are present.
- Power on the CNC milling machine and associated control systems.

1.15.1.2. Workpiece Setup

This includes:

- Secure the workpiece using appropriate work holding mechanisms, such as clamps or vacuum systems.
- Ensure the workpiece is properly aligned and positioned on the machine bed.

1.15.1.3. Tool Selection and Setup

This SOP includes:

- Choose the appropriate cutting tools based on the desired PCB design and material.
- Install and secure the cutting tools in the spindle system.

1.15.1.4. Program Loading

This SOP covers:

- Load the appropriate tool paths and G-code programs into the machine's control system.
- Verify the program's compatibility and review it for any potential errors or collisions.

1.15.1.5. Machine Operation

The machine operation SOP contains:

- Execute the CNC program, carefully monitoring the machine's movements and performance.
- Remain attentive to any unusual noises or vibrations during operation.

- Maintain a safe distance from moving parts and cutting tools.

1.15.1.6. Post-Operation

This SOP covers after machine operation actions:

- Power off the machine and clean the work area of debris and waste materials.
- Conduct routine maintenance, such as lubrication, to ensure the machine's longevity and optimal performance.

1.15.2. Safety SOP

1.15.2.1. Personal Protective Equipment (PPE)

Ensure all individuals operating or working near the CNC milling machine wear appropriate PPE, including safety glasses, gloves, and closed-toe shoes.

1.15.2.2. Emergency Procedures

Establish clear procedures for responding to emergencies, such as equipment malfunction or personal injury.

1.15.2.3. Machine-Specific Safety Guidelines

Communicate and enforce safety protocols specific to the CNC milling machine being used. Provide training on safe machine operation, handling of cutting tools, and proper workpiece setup.

1.15.2.4. Material Handling and Waste Disposal

Follow guidelines for handling and storing PCB materials and chemicals, if applicable. Implement proper waste disposal procedures for PCB waste and any other hazardous materials.

1.16. Organization of Report

This report contains Chapter 1 which is related to the introduction, which includes What is CNC Milling, Purpose of CNC Milling Machine for PCB Fabrication, Components used for the Fabrication of CNC Milling, advantages related to the project, Sustainable Development Goals which are mapped against our Project, Historical Background, Motivation for the project, Problem Statement and Objectives which we have to achieved during the whole working of project.

The Literature review has also been done. It contains the Process and Parameters which are required for the Fabrication of CNC Milling for PCB Fabrication, what is Traditional Method of PCB Fabrication, Drawbacks of Traditional Ways of PCB Fabrication, Causes and Effects of Vibrations and ways to Control Vibrations.

In Chapter 3 project design and implementation is Presented. It includes proposed design of our project, Specifications, Software which we used for guiding the machine to perform the tasks and Features Added for making the working efficient.

Chapter 4 covers all the calculations which includes Torque of Spindle, Design of Lead Screw, Rise in Temperature during Milling Operation and the Torque of Lead Screw due to Acceleration.

Chapter 5 covers the improvement in the project, which is usig of Laser technology for fabrication of PCBs, all of its calculation, how it will work.

Finally, Chapter 6, titled "Conclusion and Future Recommendations," delves into the analysis of the project's impact on various aspect. It examines the outcomes and implications of the project and offers recommendations for future enhancements or initiatives.

1.17. Project Considerations

1.17.1. Economic Considerations

In this we have considered the economic feasibility of the project, including cost analysis, return on investment, and potential cost savings compared to alternative PCB fabrication methods. Assess the affordability and market competitiveness of the CNC milling machine.

1.17.2. Environmental Considerations

In this we have considered environmental impact of the CNC milling machine's fabrication and operation. Choose materials and manufacturing processes that minimize resource consumption, waste generation, and carbon emissions. Consider the machine's energy efficiency and the potential for recycling or repurposing at the end of its lifecycle.

1.17.3. Sustainability

In this we have considered the design of the CNC milling machine with sustainability in mind. Integrate energy-saving features and explore ways to reduce material waste during the milling process. Incorporate eco-friendly practices throughout the machine's lifecycle.

1.17.4. Manufacturability

In this we have considered the manufacturability of the CNC milling machine. Ensure that the chosen materials and components are readily available and can be sourced reliably. Simplify assembly processes and minimize production complexities to enhance efficiency and reduce costs.

1.17.5. Ethical Considerations

In this we have adherence to the ethical guidelines and practices throughout the project. Ensure responsible sourcing of materials, respecting labor rights and fair-trade principles. Avoid any potential conflicts of interest or unethical practices that may arise during the fabrication process.

1.17.6. Health and Safety

In this we have prioritized the health and safety of individuals involved in the fabrication, operation, and maintenance of the CNC milling machine.

1.17.7. Social Considerations

In this we have assessed the social impact of the CNC milling machine, considering its potential to create employment opportunities or enhance productivity in PCB fabrication. Ensure that the machine's design and functionality align with the needs and expectations of end-users.

1.17.8. Political Considerations

In this we have aware ourselves of any political factors that may affect the project, such as regulations or policies related to manufacturing, environmental protection, or industry standards. Ensure compliance with relevant laws and regulations to avoid legal complications.

Chapter 2

2. LITERATURE REVIEW

CNC (Computer Numerical Control) milling has emerged as a popular method for fabricating Printed Circuit Boards (PCBs) due to its flexibility, precision, and cost-effectiveness. This literature review aims to provide an overview of the existing research and developments related to CNC milling for PCB fabrication. The review encompasses various aspects, including machine configurations, tooling, material selection, process parameters, surface finish, and challenges associated with CNC milling for PCB fabrication.

One of the significant advantages of CNC milling for PCB fabrication is its high precision and accuracy. Several studies have demonstrated the effectiveness of CNC milling for PCB fabrication. For instance, in a study conducted by Liu et al. (2017), a CNC milling machine was used to fabricate PCBs with a line width of 0.15 mm and a spacing of 0.15 mm, which met the requirements of high-frequency circuits. The study concluded that CNC milling was an effective method for producing high-quality PCBs with high precision and accuracy.

Another study conducted by Zhang et al. (2018) evaluated the performance of a CNC milling machine for PCB fabrication. The study found that the CNC milling machine could produce PCBs with a line width of 0.1 mm and a spacing of 0.1 mm with high precision and accuracy. The study concluded that CNC milling was a suitable method for fabricating PCBs with high precision and accuracy.

In recent years, there has been a significant development in the use of AI and machine learning algorithms in CNC milling for PCB fabrication. These technologies have the potential to improve the precision and accuracy of CNC milling machines, enabling them to produce high-quality PCBs with minimal human intervention. In a study conducted by Li et al. (2019), an AI-based CNC milling machine was developed for PCB fabrication. The machine was able to learn from the fabrication process and optimize its performance, leading to a reduction in errors and improved precision and accuracy.

Additionally, researchers have explored various methods to improve the efficiency of CNC milling machines for PCB fabrication. For example, in a study conducted by Singh et al. (2021), a new toolpath optimization method was proposed to improve the CNC milling machine's performance.

The method reduced the milling time and improved the surface finish of the PCBs, leading to more efficient and effective PCB fabrication.

Overall, the existing research and developments in CNC milling for PCB fabrication demonstrate that this method is effective in producing high-quality PCBs with high precision and accuracy. Furthermore, the integration of AI and machine learning algorithms has the potential to improve the precision and accuracy of CNC milling machines, making them more efficient and effective. The development of new methods and technologies to improve the performance of CNC milling machines for PCB fabrication will continue to advance the field and enhance its capabilities.

2.1. Process and parameters for CNC milling for PCB fabrication

Various process parameters, such as spindle speed, feed rate, depth of cut, and step-over, have a direct impact on the milling process. Researchers have investigated the effects of these parameters on PCB quality, focusing on aspects such as dimensional accuracy, surface roughness, and feature resolution. Here we have discussed the process involved in PCB fabrication and process parameters that impact the machine operation.

2.1.1. Process

2.1.1.1. PCB Layout Design

The first step in CNC milling for PCB fabrication is designing the PCB layout using software such as Proteus. The software allows the user to create the desired circuitry pattern and place components on the board.

2.1.1.2. Generating Toolpath

Once the PCB layout is designed, the next step is to generate the toolpath. The toolpath defines the movement of the milling machine's cutting tool as it removes unwanted copper from the PCB substrate. This is done using CAM software.

2.1.1.3. Milling the PCB

After generating the toolpath, the next step is to mill the PCB. The milling process involves clamping the copper-clad PCB substrate to the milling machine's worktable and lowering the cutting tool onto the surface of the PCB substrate. The machine then moves the cutting tool along the defined toolpath, removing unwanted copper and leaving behind the desired circuitry pattern.

2.1.2. Process Parameters

2.1.2.1. Cutting Speed

The cutting speed refers to the speed at which the cutting tool moves along the toolpath. The cutting speed should be optimized based on the material being cut and the cutting tool being used. It is typically measured in surface feet per minute (SFM) or meters per minute (m/min).

2.1.2.2. Spindle Speed

Spindle speed refers to the rotational speed of the milling tool during the cutting process. The selection of an appropriate spindle speed is crucial to achieve optimal cutting conditions. Higher spindle speeds generally result in faster material removal rates, but they may also lead to increased tool wear and decreased tool life. Conversely, lower spindle speeds may reduce tool wear but may result in longer machining times. The choice of spindle speed depends on factors such as the material being milled, tooling characteristics, and desired surface finish. Optimization techniques, such as empirical testing and mathematical modeling, can aid in determining the optimal spindle speed for specific PCB milling applications.

2.1.2.3. Depth of Cut

The depth of cut refers to the distance between the initial and final positions of the cutting tool along the Z-axis during each milling pass. It directly affects the amount of material removed in each pass and influences the cutting forces and heat generation. A deeper cut can increase material removal rates but may result in higher cutting forces, increased tool wear, and potentially compromise the stability of the milling process. Conversely, shallower cuts may reduce these issues but can extend machining times. The appropriate depth of cut is determined by factors such as the material properties, tooling characteristics, and desired surface finish. Experimental studies and simulation techniques can aid in optimizing the depth of cut for specific PCB milling requirements.

2.1.2.4. Feed Rate

The feed rate refers to the linear speed at which the cutting tool moves along the workpiece during the milling process. It determines the amount of material removed per unit of time. Selecting an appropriate feed rate is crucial to achieve efficient material removal while maintaining dimensional accuracy. Higher feed rates can increase productivity, but they may also result in higher cutting forces, increased tool wear, and potential damage to the PCB substrate. Lower feed rates can mitigate these issues but may lead to longer machining times. Factors influencing the choice of feed rate include the material properties, tooling characteristics, and desired surface quality. Experimental approaches and machining simulations can aid in optimizing the feed rate for specific PCB milling operations.

2.1.2.5. Tool Selection

The selection of appropriate tools is crucial for achieving high-quality PCBs. The cutting tool should be selected based on the material being cut, the depth of cut, and the desired surface finish. Literature suggests the use of specialized end mills, such as carbide or diamond-coated tools, with small diameters to achieve fine traces and small drill holes.

Spindle speed, feed rate, and depth of cut are critical process parameters in CNC milling for PCB fabrication. The selection and optimization of these parameters significantly impact the quality, efficiency, and productivity of the milling process. Achieving the desired dimensional accuracy, surface finish, and tool life require careful consideration of the material properties, tooling characteristics, and specific requirements of the PCB design.

2.2. Traditional Method of PCB fabrication

Traditional methods of PCB fabrication have been widely used for many years and have undergone significant developments to meet the demands of electronic manufacturing. The traditional way of manufacturing PCBs is through the use of chemicals to etch the desired circuit pattern onto a copper-clad board. However, this process can be time-consuming and error prone.

2.2.1. Etching

Etching is a widely used technique in PCB fabrication. It involves selectively removing the copper layer from the PCB substrate using chemical solutions like ferric chloride or ammonium persulfate. A resist mask is employed to protect areas that should not be etched. Etching offers cost-effective solutions for low-volume production, rapid prototyping, and simple PCB designs. However, it may have limitations in achieving fine features, tight tolerances, and high-density circuitry.

2.3. Advancements and Current Trends

Traditional methods of PCB fabrication have evolved over time to meet the demands of miniaturization, increased complexity, and higher reliability in electronic devices. Recent advancements include the development of advanced etching techniques, such as plasma etching and laser ablation, which offer improved precision and control. Furthermore, hybrid approaches combining traditional methods with additive manufacturing techniques, such as 3D printing or inkjet printing, are being explored to enable rapid prototyping, customized designs, and heterogeneous integration. Furthermore, CNC Milling Engraving Machine is being explored that uses material removal technique, for the fabrication of Printed Circuit Board.

2.4. Work Flow for the Fabrication of PCB Through Etching Process

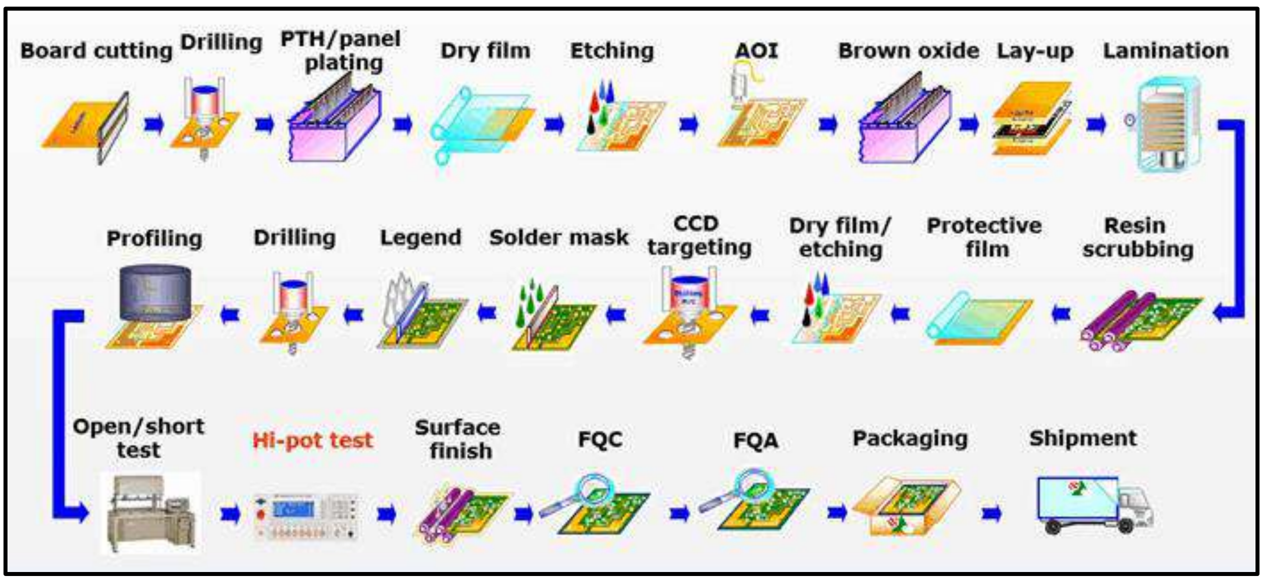

Figure 2-1 Work Flow for the Fabrication of PCB through Etching Process

Traditional methods of PCB fabrication, including etching, screen printing, and photoengraving, have been instrumental in the production of PCBs for various applications. These methods offer cost-effective solutions, rapid prototyping capabilities, and the ability to produce simple to moderately complex circuit designs. However, they may have limitations in terms of achieving high-density interconnects, fine feature resolution, and complex multilayer structures. Advancements in traditional methods, as well as the integration of additive manufacturing techniques, are expected to enhance the capabilities and address the limitations of traditional PCB fabrication processes.

2.5. Drawbacks of Traditional Method of PCB fabrication

The traditional methods of PCB fabrication, such as etching, screen printing, and photoengraving, have certain drawbacks that limit their applicability and effectiveness in certain scenarios. Here are some common drawbacks associated with the traditional methods:

2.5.1. Limited Resolution

Traditional methods may struggle to achieve high-resolution features and fine traces, especially for complex and high-density circuit designs. The limitations arise from the inherent constraints of the processes, such as the minimum line width and spacing achievable.

2.5.2. Design Flexibility

Traditional methods may have limitations when it comes to designing intricate circuit patterns and complex PCB layouts. The processes may not easily accommodate designs with tight spacing, irregular shapes, or three-dimensional structures.

2.5.3. Multilayer PCB Fabrication

Fabricating multilayer PCBs using traditional methods can be challenging and time-consuming. Aligning and bonding multiple layers with precision can be difficult, leading to potential issues like misalignment, warping, or delamination.

2.5.4. Time and Cost

Traditional methods may involve multiple steps and longer production times compared to modern PCB fabrication techniques. The processes often require manual labor and multiple iterations, resulting in increased costs and longer lead times for PCB production.

2.5.5. Waste Generation

Traditional methods generate a significant amount of waste, particularly in processes like etching where excess copper and chemical solutions are involved. Proper disposal of waste materials, such as etchants and inks, is necessary to minimize environmental impact.

2.5.6. Limited scalability

Traditional methods may face challenges in scaling up production or achieving consistent results across large production runs. Variations in manual processes and limitations in controlling process parameters can lead to inconsistencies in PCB quality and performance.

2.5.7. Limitations in Complex Structures

Traditional methods may struggle to fabricate PCBs with complex structures, such as embedded components, advanced interconnects, or flexible substrates. These methods are better suited for simpler PCB designs and may not fully address the requirements of modern electronic devices.

2.5.8. Surface Finish and Coating

Achieving uniform surface finishes and applying conformal coatings using traditional methods can be difficult. Inconsistent coating thickness, uneven coverage, and limited options for specialized coatings may impact the PCB's reliability and performance.

2.5.9. Repair and Rework Challenges

Traditional methods may present difficulties when it comes to repairing or reworking PCBs. Soldering or modifying circuitry can be more challenging due to the nature of the fabrication processes and the risk of damaging adjacent components.

2.5.10. Lack of Automation

Traditional methods often rely on manual labor and craftsmanship, leading to higher dependence on skilled operators. The lack of automation can limit scalability, increase production costs, and introduce the potential for human errors.

It's worth noting that while traditional methods have drawbacks, they have also served as foundational techniques in PCB fabrication and continue to be utilized in specific applications where their advantages outweigh the limitations. However, advancements in modern fabrication technologies, such as CNC milling, additive manufacturing, and advanced lithography, have addressed many of these drawbacks and offer enhanced capabilities for PCB fabrication in terms of complexity, precision, scalability, and flexibility.

2.6. Benefits of CNC Milling for PCB fabrication

Figure 2-2 PCB Being Fabricated by CNC Milling

CNC (Computer Numerical Control) milling has revolutionized the process of PCB fabrication, offering numerous benefits over traditional methods. Here are some key advantages of CNC milling for PCB fabrication:

2.6.1. Precision

CNC milling provides exceptional precision and accuracy in fabricating PCBs. The computer-controlled milling machine follows precise instructions to cut and shape the PCB according to the design specifications. This ensures consistent and accurate results, even for complex circuitry and fine features.

2.6.2. Design Flexibility

CNC milling offers greater design flexibility compared to traditional methods. It can accommodate complex circuit layouts, irregular shapes, and three-dimensional structures with ease. The ability to precisely control the milling tool's movement allows for the fabrication of intricate designs and customized PCB shapes.

2.6.3. Faster Production

CNC milling allows for faster production times compared to traditional methods. Once the design is programmed into the CNC machine, it can quickly and efficiently mill the PCB. This reduces lead times, making it ideal for prototyping, small-scale production, and time-sensitive projects.

2.6.4. Multilayer PCBs

CNC milling is well-suited for fabricating multilayer PCBs. It can accurately drill and mill each layer, ensuring proper alignment and interconnectivity. This enables the creation of complex multilayer structures with high precision and reliability.

2.6.5. Reproducibility

CNC milling ensures high reproducibility of PCBs. Once a design is programmed, the CNC machine can consistently produce identical copies of the PCB, ensuring uniformity across multiple units. This is particularly important for large-scale production and maintaining quality standards.

2.6.6. Material Compatibility

CNC milling supports a wide range of PCB materials, including standard substrates like FR-4, as well as specialized materials like flex PCBs and metal-based PCBs. This versatility allows for the fabrication of PCBs suitable for diverse applications and requirements.

2.6.7. Automation and Efficiency

CNC milling is an automated process that reduces manual labor and improves production efficiency. Once the design is programmed, the CNC machine can work autonomously, minimizing human errors and increasing productivity. This enables operators to focus on other tasks, leading to improved overall efficiency.

2.6.8. Scalability

CNC milling is highly scalable, making it suitable for both small-scale and large-scale production. The same CNC program can be used to fabricate a single prototype or thousands of PCBs, ensuring consistent quality, and reducing the need for retooling or additional setup.

2.6.9. Quality Control and Inspection

CNC milling allows for integrated quality control and inspection processes. The precise milling ensures the final PCBs meet the required specifications and standards. Additionally, CNC machines can be equipped with automated inspection systems to detect any defects or anomalies during the milling process, ensuring higher product quality.

2.6.10. Integration with CAD/CAM Software

CNC milling seamlessly integrates with CAD/CAM software, enabling efficient design-to-fabrication workflows. Design files can be directly imported into the CNC machine, eliminating the need for manual conversions and reducing the chances of errors. This integration streamlines the entire fabrication process, improving productivity and accuracy.

Overall, CNC milling offers precision, design flexibility, automation, scalability, and efficiency, making it a highly advantageous method for PCB fabrication. Its ability to meet the demands of modern electronic devices, complex circuit designs, and various production requirements positions CNC milling as a preferred choice in the industry.

2.7. Factor of Selection of Motor for CNC for PCB Fabrication

Selecting the right motor for a CNC (Computer Numerical Control) machine used in PCB fabrication is crucial for ensuring accurate and efficient operation. Several factors should be considered when choosing a motor for a CNC machine specifically tailored for PCB fabrication:

2.7.1. Torque Requirements

PCB milling involves cutting through the PCB substrate and copper layers. Therefore, the motor should provide sufficient torque to drive the milling tool through the material without stalling or losing accuracy. Consider the torque requirements based on the PCB material, thickness, and complexity of the milling operations.

2.7.2. Speed Range

The motor should offer a suitable speed range to accommodate the different cutting requirements of PCB fabrication. Higher speeds may be necessary for efficient material removal, while lower speeds are beneficial for precise milling of intricate circuit patterns. Look for a motor with a wide speed range and the ability to maintain consistent speed under varying loads.

2.7.3. Motor Type

The two common motor types used in CNC machines are stepper motors and servo motors. Stepper motors are often preferred for PCB fabrication due to their affordability, simplicity, and high torque at low speeds. Servo motors offer greater precision and faster response but tend to be more expensive. Consider the specific requirements of the PCB fabrication process to determine the most suitable motor type.

2.7.4. Motor Power and Size

The power rating of the motor should be sufficient to handle the demands of PCB fabrication, including cutting through the PCB material and driving the milling tool. Consider the power requirements based on the size and complexity of the PCB designs. Additionally, ensure that the motor's physical dimensions and weight are compatible with the CNC machine's design and structural requirements.

2.7.5. Control System Compatibility

The motor should be compatible with the CNC machine's control system. Ensure that the motor can be seamlessly integrated into the control system architecture and communicate effectively with the CNC software for precise positioning and movement control.

2.7.6. Durability and Reliability

The motor should be robust and reliable to withstand the demands of continuous operation in PCB fabrication. Look for motors with a proven track record of reliability and durability, as well as suitable protection mechanisms against overheating or overload conditions.

2.7.7. Maintenance and Serviceability

Consider the ease of maintenance and availability of spare parts for the selected motor. A motor that is easy to access, inspect, and maintain will help minimize downtime and ensure smooth operation in the long run.

2.7.8. Cost

Evaluate the cost-effectiveness of the motor, considering its performance, durability, and suitability for PCB fabrication. Compare different motor options and consider the overall value and return on investment provided by each option.

Selecting the appropriate motor and determining the optimal cutting speed is essential for ensuring the quality and efficiency of the PCB fabrication process. This requires careful consideration of the material being cut, the size of the milling bit, and the desired level of precision, among other factors. By optimizing the cutting speed, designers can ensure that the CNC milling process is as efficient and effective as possible.

2.8. Causes of Vibration during Milling Process

Vibration during the milling process can significantly affect the quality of the machined surface, accuracy of the dimensions, and overall productivity. Several factors can contribute to vibration in milling operations. Here are some common causes of vibration during the milling process:

2.8.1. Improper Tool Selection

Using an incorrect or poorly suited tool for the milling operation can lead to excessive vibrations. Factors such as tool geometry, material composition, and cutting parameters should be carefully considered to ensure optimal tool performance and minimize vibration.

2.8.2. Insufficient Rigidity of the Setup

The stability and rigidity of the milling machine setup, including the workpiece, toolholder, and machine structure, play a crucial role in minimizing vibration. Inadequate clamping, poor fixturing, or flexible workpiece or toolholder setups can result in vibration during the milling process.

2.8.3. Excessive Cutting Forces

When the cutting forces generated during milling exceed the machine's capacity or the tool's capability, vibrations can occur. This can happen due to aggressive cutting parameters, improper feeds and speeds, or inadequate tool geometry for the material being machined. High cutting forces can lead to tool chatter and workpiece vibrations.

2.8.4. Improper Tool Path Strategies

The tool path strategy used during milling can impact vibration levels. Continuous engagement of the tool without proper considerations for chip evacuation and tool engagement can lead to vibrations. Inefficient tool paths that cause sudden changes in direction or excessive tool engagement can also contribute to vibration.

2.8.5. Material Properties

The properties of the workpiece material, such as hardness, brittleness, and internal stresses, can influence vibration levels during milling. Hard and brittle materials may generate higher cutting forces and vibrations, requiring special tooling and machining strategies to minimize vibration.

2.8.6. Tool Wear or Damage

Worn or damaged cutting tools can cause irregular cutting forces and vibrations. Dull or damaged tool edges may not efficiently shear the material, resulting in increased forces and vibrations during milling. Regular tool inspection, maintenance, and replacement are essential to minimize vibration issues.

2.8.7. Inadequate Coolant or Lubrication

Proper coolant or lubrication is crucial for reducing friction, heat, and vibration during milling. Insufficient coolant flow or poor lubrication can lead to increased friction and heat generation, causing vibrations and reducing tool life.

2.8.8. Resonance and Natural Frequencies

Every machine and its components have natural frequencies at which they can vibrate more easily. Milling operations that match these natural frequencies can result in significant vibration amplitudes. Identifying and avoiding resonant conditions through proper tool selection, tool path optimization, and machine design can help mitigate vibration issues.

To minimize vibrations during milling, it is important to address these causes through proper tool selection, machine setup, cutting parameters optimization, regular maintenance, and adherence to best practices for milling operations. Experimentation, analysis of cutting conditions, and consultation with experts can help identify and mitigate specific vibration sources in a milling process.

2.9. Effects of Vibrations

Vibrations during machining processes can have several detrimental effects, impacting the quality of the machined surface, dimensional accuracy, tool life, and overall productivity. Here are some common effects of vibrations in machining operations:

2.9.1. Poor Surface Finish

Vibrations can lead to surface irregularities and roughness on the machined surface. The unstable cutting forces and tool vibrations can cause chatter marks, waviness, or scalloping, resulting in an unsatisfactory surface finish. This can affect the aesthetics, functionality, and performance of the machined part.

2.9.2. Dimensional Inaccuracy

Vibrations can cause dimensional deviations in the machined part. The inconsistent cutting forces and tool movements can lead to variations in the dimensions and tolerances of the workpiece, resulting in parts that do not meet the desired specifications. This can lead to assembly issues, functional problems, and increased rework or scrap rates.

2.9.3. Reduced Tool Life

Excessive vibrations accelerate tool wear and reduce tool life. The repeated impact and friction between the vibrating tool and workpiece can cause tool chipping, edge rounding, and premature wear. This not only increases tool replacement costs but also affects the consistency and accuracy of the machining process.

2.9.4. Increased Risk of Tool Breakage

Vibrations can subject the cutting tool to excessive stress and strain, increasing the risk of tool breakage. The dynamic forces generated by vibrations can cause tool fractures, particularly in brittle or worn-out tools. Tool breakage interrupts the machining process, necessitates tool change, and can lead to workpiece damage or injury to operators.

2.9.5. Reduced Machining Speed and Efficiency

Vibrations restrict the maximum achievable cutting speeds and feed rates. To avoid excessive vibrations, operators often have to reduce cutting parameters, resulting in slower machining speeds and lower productivity. This can lead to longer machining times, decreased throughput, and reduced overall efficiency.

2.9.6. Impact on Machine and Structural Integrity

Vibrations can affect the integrity and lifespan of the machining equipment. The dynamic forces generated by vibrations can cause wear, fatigue, and stress concentrations in machine components, leading to premature failure. Additionally, continuous vibrations can loosen bolts, degrade machine alignment, and negatively impact the overall performance and reliability of the machine.

2.9.7. Increased Noise Levels

Vibrations produce additional noise during machining operations. The impact and resonance of vibrating components can generate high levels of noise, causing discomfort for machine operators and increasing the risk of noise-induced hearing loss. Excessive noise levels also impact on the working environment and may require additional noise control measures.

2.9.8. Safety Risks

Vibrations can pose safety hazards in machining operations. Excessive machine vibrations can lead to unstable workpieces, tool ejection, or unintended collisions between the tool and workpiece. These incidents can result in injuries to operators, damage to equipment, and compromised workplace safety.

To mitigate the negative effects of vibrations, it is important to identify and address the root causes through proper machine setup, tool selection, cutting parameter optimization, and maintenance practices. Damping techniques, vibration absorbers, and enhanced machine designs can also help reduce vibrations and improve the overall machining process. Regular monitoring, analysis, and control of vibrations can contribute to better surface finish, dimensional accuracy, tool life, and operational efficiency.

2.10. Ways to Control Vibrations

Controlling vibrations in machining operations is crucial for achieving optimal surface finish, dimensional accuracy, tool life, and overall productivity. Here are some effective ways to control vibrations during machining:

2.10.1. Machine Stability and Rigidity

Ensure that the machining equipment, including the machine structure, work holding systems, and tooling, is properly designed and rigid enough to minimize vibrations. Stiffer machines with enhanced damping characteristics help dampen vibrations and improve machine stability.

2.10.2. Proper Machine Alignment

Ensure proper alignment of machine components, such as axes, spindles, and toolholders. Misalignment can lead to vibrations and reduced machining accuracy. Regularly check and adjust the machine's alignment to maintain optimal performance.

2.10.3. Optimize Cutting Parameters

Adjust cutting parameters, such as cutting speed, feed rate, and depth of cut, to minimize vibrations. Finding the right balance between productivity and stability is essential. High cutting forces and aggressive cutting parameters should be avoided to prevent excessive vibrations.

2.10.4. Select Suitable Cutting Tools

Choose cutting tools that are specifically designed for vibration control. Tools with advanced geometries, coatings, and dampening features can help reduce vibrations and improve tool performance. Select tools that match the machining requirements and material properties.

By implementing these control measures, operators can effectively minimize vibrations during machining operations, ensuring improved surface finish, dimensional accuracy, tool life, and overall machining performance.

Chapter 3

3. PROJECT DESIGN AND IMPLEMENTATION

In this section of our report we have presented an overview of the methodology that we have adopted for completing our project of "CNC Milling for PCB Fabrication". We try our best to follow the engineering design process throughout the project.

3.1. Planning process of Fabrication

3.1.1. Define Project Objectives

We thoroughly understand the project requirements and objectives. This involves clarifying the scope of the project, identifying the specific goals, and determining the desired outcomes.

3.1.2. Conduct Research

A literature review has been conducted in which each team member has read several research papers and articles to gain knowledge about CNC milling for PCB fabrication. This helps us understand the existing techniques, challenges, and advancements in the field. It provides a foundation for designing the project methodology.

3.1.3. Conceptual Design

A conceptual design for the CNC milling machine has been made using SolidWorks. Then assembly was performed on the parts designed to visualize the final prototype of our machine.

3.1.4. Detailed Design

Once the conceptual design is deemed feasible, we proceed with the detailed design phase. This involves designing the machine's structure such as the frame, spindle, control system, and tooling mechanism.

3.1.5. Assembly and Integration

In this phase we assembled the fabricated components according to the design specifications. Integrate the mechanical, electrical, and control systems to ensure seamless operation and functionality.

3.1.6. Testing and Validation

Conduct thorough testing and validation of the completed CNC milling machine. Verify its performance, accuracy, stability, and reliability. Address any issues or deviations from the design specifications.

3.2. Project Analysis

Project analysis for the Final Year Design Project of "CNC Milling Machine for PCB Fabrication" involves a comprehensive evaluation of various aspects to assess the project's feasibility, effectiveness, and potential impact.

3.2.1. Technical Feasibility

It is a key consideration, as it involves evaluating the viability of developing a CNC milling machine specifically designed for PCB fabrication.

In the technical analysis, we have assessed the market to know the availability of materials for the fabrication of machine. And whether our fabricated model will be compatible with CAD/CAM model to validate our machine’s performance. And we reached a conclusion that all the required materials and components are readily available in Market of Pakistan.

3.2.2. Economic Analysis

In economic analysis, we made an estimate for components and raw materials required for the fabrication of machine. And also consider how this technology helps in growing economy of our country Pakistan. And we reach towards a point that our project will be in benefit for economy of Pakistan as this will produce less waste and it is eco-friendly technology.

3.2.3. Market Demand Analysis

It helps evaluate the potential market for the CNC milling machine. In market analysis, we have evaluate whether there is potential in market for such machine. And whether we have larger number of customers to gain their interest in precise and cost-effective milling machines for PCB fabrication. And we come to know that there is much demand of such machine not only in Pakistan but all over the world as such technology makes the PCB fabrication easy and more precise.

Understanding the market demand ensures that the project aligns with market needs and has the potential for commercial success.

3.2.4. Environmental Impact

We have Assessed the environmental impact of the project. This analysis considers the entire lifecycle of the CNC milling machine, including material sourcing, manufacturing processes, and energy consumption. Exploring sustainability measures, such as using eco-friendly materials or implementing energy-efficient components, helps minimize the environmental footprint of the machine and aligns with the principles of sustainable development.

3.2.5. Risk Assessment

We have also worked on identifying potential risks and challenges that could impact the project's success. This analysis involves identifying technical hurdles, resource constraints, or regulatory compliance issues.

3.3. Design Specifications

3.3.1. Motor Specification

Motor type: Stepper Motor (NEMA 17)

Step Angle: 1.8° (200 steps/revolution)

Shaft Dimensions: Ø 5 x 22 mm (4mm flat spot)

Motor power: 30 watts

Motor torque: 0.59 Nm

Number of Phases: 2

Rated Voltage: 12 V DC

Rated Current: 1.8 A

Rotational Inertia: 0.0082 gm^2

Dimensions: 42 x 42 x 48 mm

Weight: 420 g

3.3.2. Tool Specification

Tool holder type: ER collet (Collet ER 11)

Tool diameter(shank) range: Typically 1 mm to 7 mm

Tool length range: Typically up to 40 mm

Tool change mechanism: It requires manual insertion and removal of the tool from the collet.

3.3.3. Torque and Speed Range

Spindle torque range: 0.12 Nm to 1.35 Nm

Spindle speed range: 1 rpm to 12000 rpm

3.3.4. Feed Rate

Maximum cutting feed rate: 127 mm/min

3.3.5. Plunge

Maximum Plunge: 240 mm/min

3.3.6. Working Area

X-axis travel: 240 mm

Y-axis travel: 140 mm

Z-axis travel: 35 mm

Maximum workpiece dimensions: 220mm x 120mm x 20mm

3.3.7. Frame

Frame material: Aluminum (6063)

Poisson’s Ratio: 0.33

Ultimate Tensile Strength: 186 MPa

Modulus of Elasticity: 68.9 GPa.

Shear Modulus: 25.8 GPa.

Shear Strength: 117 MPa.

Fatigue Strength: 68.9 MPa.

3.3.8. Software Specification

3.3.8.1. CNC control software

3.3.8.1.1. Candle Software

- Candle is an open-source CNC control software.
- It is compatible with GRBL-based controllers and Arduino-based CNC systems.
- Candle provides a graphical user interface (GUI) for controlling CNC operations.
- It supports loading and executing G-code files.
- The software offers manual control features for precise positioning and setup.
- Spindle control functions may be available depending on the machine's capabilities.
- File management features allow for loading and managing G-code files.
- Homing functionality may be supported for accurate referencing.
- Candle is open-source, allowing customization and modification by users and developers.

3.3.8.2. CAD/CAM software compatibility

3.3.8.2.1. Proteus

- Proteus is a popular PCB design software that provides a comprehensive set of tools for creating electronic circuit designs and PCB layouts.
- It offers a user-friendly interface with a wide range of features specifically designed for PCB design and simulation.
- Proteus supports schematic capture, allowing users to create circuit diagrams and connect components.
- It provides a vast library of electronic components and symbols that can be easily accessed and used in the design process.
- The software offers automatic routing capabilities, enabling efficient and accurate placement of traces on the PCB.
- Proteus allows for 3D visualization of the PCB layout, providing a realistic representation of the final product.

- It supports the generation of manufacturing files, such as Gerber files, which are commonly used in PCB production.
- Proteus includes simulation features for analyzing and testing circuit behavior, including interactive simulation and SPICE simulation.
- The software supports the import and export of industry-standard file formats, allowing compatibility with other PCB design tools.
- Proteus provides collaboration features, enabling multiple designers to work on the same project simultaneously.
- It offers a range of analysis tools, such as signal integrity analysis and thermal analysis, to ensure the reliability of the PCB design.

3.3.8.3. File format compatibility

Ares Software and Aspire Software.

3.3.8.3.1. Ares Software

- Ares is a software tool commonly used for PCB (Printed Circuit Board) design and layout.
- While Ares focuses primarily on PCB design, it may provide features for exporting PCB designs to bitmap file formats.
- Ares allows users to convert their PCB designs into bitmap image formats, such as BMP (Bitmap) or PNG (Portable Network Graphics).
- Bitmap export functionality may be useful for creating visual representations or documentation of the PCB layout.
- The software may offer options to customize the resolution, color depth, and other settings of the exported bitmap image.
- Ares may support exporting both the top and bottom layers of the PCB design, providing a comprehensive visual representation.
- Bitmap files can be easily viewed, shared, and printed using standard image viewers or editing software.
- It is important to verify the specific capabilities of Ares regarding bitmap export functionality, as features may vary based on the software version and updates.
- Ares is primarily intended for PCB design, and for advanced image manipulation or conversion tasks, dedicated image editing software may be more suitable.

3.3.8.3.2. Aspire Software

- Aspire is a powerful software tool used for 2D and 3D modeling, design, and machining operations.
- Aspire supports importing bitmap files, such as BMP or JPEG, allowing users to work with raster images.
- The software provides tools for converting bitmap images into vector-based designs suitable for CNC machining.
- Aspire offers automatic tracing and vectorization features, allowing bitmap images to be converted into scalable vector graphics (SVG) or other vector formats.
- Once the bitmap image is converted to vectors, Aspire provides tools for editing, manipulating, and optimizing the resulting vectors.
- Aspire enables users to define machining operations, such as toolpaths and cutting strategies, based on the vectorized image.
- The software supports generating G-code, which is a machine-readable language used to control CNC machines, from the vector design.
- Aspire offers customization options for specifying machining parameters, such as feed rates, tool sizes, and cutting depths.
- It provides simulation and visualization tools to preview the machining process and ensure accuracy before generating the final G-code.
- Aspire may have additional features for multi-sided machining, rotary machining, or 3D relief carving, depending on the specific version and capabilities of the software.

3.3.9. Micro controller GRBL 1.1

3.3.9.1. Compatibility

GRBL 1.1 is designed to work with various Arduino-compatible microcontrollers, such as Arduino Uno, Arduino Nano, and Arduino Mega, making it versatile and widely compatible.

3.3.9.2. Stepper Motor Control

GRBL 1.1 supports up to three axes (X, Y, and Z) for controlling stepper motors. It provides precise step and direction control signals to drive the motors accurately.

3.3.9.3. Spindle Control

The microcontroller can also control the spindle motor for PCB milling. It supports both on/off control and variable speed control, allowing you to adjust the spindle speed according to your requirements.

3.3.9.4. G-Code Interpreter

GRBL 1.1 includes a G-code interpreter, which enables the microcontroller to understand and execute G-code commands. G-code is the standard language used to communicate with CNC machines, including milling machines.

3.3.9.5. Real-Time Status Reporting

The microcontroller continuously monitors the machine's status and provides real-time feedback. This includes reporting the current position, feed rate, and spindle speed, which helps in tracking the progress of the milling operation.

3.3.9.6. Limit Switch Support

GRBL 1.1 supports limit switches for each axis to ensure safe operation. Limit switches are used to detect the physical boundaries of the machine, preventing it from moving beyond its designated workspace.

3.3.9.7. Homing Functionality

The microcontroller includes homing functionality, allowing you to define a home position for the machine. Homing involves moving each axis to a known reference point, ensuring accurate positioning and repeatability.

3.3.9.8. Software Control

GRBL 1.1 can be configured and controlled using various software applications, such as Universal Gcode Sender (UGS), Grbl Controller, and other compatible software. These applications provide a user-friendly interface to send G-code commands, adjust machine settings, and visualize the milling process.

3.3.9.9. Customization and Configuration

The microcontroller offers a range of configurable parameters, allowing you to customize the machine's behavior to suit your specific requirements. This includes step pulse timing, acceleration settings, and various other parameters that affect motion control.

3.4. Machine’s Feature

3.4.1. Homing

Homing is the process of relocating a motor attached to a mechanism to a designated position on the machine known as "home." This established home position serves as the reference point for all subsequent absolute movements.

3.4.1.1. How to do Auto Homing?

To achieve this, the system moves each axis towards one end of its track until a switch, commonly known as an "end stop," is triggered. When all the end stops have been activated, the machine's position is determined and marked as the "home position."

To initiate homing for one or more axes, the G28 command is utilized. By default, when no parameters are specified, all axes are homed. For enhanced positional accuracy, the homing procedure can be executed at a reduced speed.

3.4.1.2. Importance of Homing

3.4.1.2.1. Position Accuracy

Homing ensures that the machine starts from a known and accurate position. By returning the machine's axes to their home positions, any potential accumulated errors or drifts in positioning are eliminated or minimized. This allows for precise and repeatable positioning of the machine's components, ensuring accuracy in subsequent operations.

3.4.1.2.2. Safety

Homing is crucial for ensuring the safety of the machine, the operator, and the surrounding environment. When the machine is homed, it helps prevent accidental collisions or crashes. By establishing a reliable home position, the machine's control system can set limits and prevent movements beyond those limits, thus avoiding potential damage to the machine and ensuring operator safety.

3.4.1.2.3. Tool and Workpiece Protection

Homing is particularly important in machines that use interchangeable tools or workpieces. By homing the machine, the control system can accurately position the tools or workpieces relative to the machine's reference point. This ensures that the tools or workpieces are properly aligned and protected, reducing the risk of collisions and damage.

3.4.1.2.4. Workflow Efficiency

Homing a machine streamlines the operational workflow. By starting from a known position, the machine can quickly and accurately move to the desired work area, reducing setup time and increasing productivity. This is especially beneficial when performing repetitive tasks or when multiple tools or workpieces need to be used in a coordinated manner.

3.4.1.2.5. Error Detection

The homing process can also serve as a mechanism to detect any mechanical or electrical issues with the machine. If the homing routine consistently fails or produces unexpected results, it can indicate problems such as faulty sensors, misalignment, or damaged components. Identifying such issues early on allows for timely maintenance or troubleshooting, minimizing downtime and preventing further damage to the machine.

3.4.2. Auto Levelling

Auto-leveling on a Machine typically involves using sensors to measure the distance between the bed and the cutting tool. This information is used to adjust the height of the bed, ensuring that it is evenly leveled and properly aligned with the tool.

Auto leveling feature is ability to probe user-defined areas for detect curved surface in your material.

This is especially useful for engraving metal surfaces with V-shaped cutters where any deviation in the Z-direction will result in wider or narrower traces.

3.4.2.1. How to do Auto Levelling?

a. Install the probing system on the CNC milling machine. The probing system typically consists of a touch probe or a probe with a stylus that can make contact with the work surface.
b. Connect the probing system to the CNC machine's controller. This may involve connecting cables or using a wireless connection, depending on the specific probing system and CNC machine setup.
c. Calibrate the probing system to ensure accurate measurements. This may involve setting the probe's offset, determining its contact point, or performing other calibration procedures as per the manufacturer's instructions.
d. In the CNC machine's control software, define the auto leveling routine. This involves specifying the probing points or the grid pattern to be used for surface mapping. The software should also have the capability to calculate and adjust the toolpath based on the surface irregularities detected.
e. Run the auto leveling routine by executing the probing cycle. The probing system will make contact with the work surface at each designated point or grid location, collecting data on the surface variations.
f. Once the probing cycle is complete, the data collected from the surface probing is analyzed by the control software. The software calculates the variations in the work surface and generates compensation data.
g. The control software adjusts the toolpath based on the compensation data to compensate for the surface irregularities. This ensures that the milling tool maintains a consistent depth of cut across the entire work surface.
h. Verify the auto leveling results by milling a test PCB. Inspect the PCB for uniformity of trace and pad thickness, as well as overall surface flatness. Fine-tune the auto leveling parameters if necessary to achieve the desired results.
i. Auto leveling can be performed before each PCB fabrication job to ensure accurate and consistent milling results.

3.4.2.2. Importance of Auto Levelling a Machine

3.4.2.2.1. Uniform PCB Thickness

PCBs (Printed Circuit Boards) require precise and consistent thickness throughout the fabrication process. Auto leveling ensures that the milling tool maintains a consistent distance from the work surface, resulting in uniform PCB thickness. This is essential for ensuring the proper functioning of electronic components and maintaining signal integrity.

3.4.2.2.2. Accurate Traces and Pads

Auto leveling compensates for any unevenness or variations in the work surface, which could affect the accuracy of the milled traces and pads. By detecting and adjusting for surface irregularities, it ensures that the milling tool follows the desired toolpath accurately. This results in precise and well-defined traces and pads on the PCB, minimizing the risk of short circuits or connectivity issues.

3.4.2.2.3. Surface Flatness Compensation

PCB substrates, such as copper-clad laminates, can exhibit slight variations in flatness. Auto leveling detects these variations and adjusts the toolpath accordingly. This compensation ensures that the milling tool maintains a consistent depth of cut, regardless of any irregularities in the substrate surface. As a result, the milled PCB surface remains flat and even, facilitating proper component placement and soldering.

3.4.2.2.4. Improved Yield and Quality

Auto leveling contributes to higher yield and improved PCB quality. By compensating for uneven surfaces, it reduces the likelihood of errors, such as over-cutting or under-cutting, that can lead to damaged traces or pads. The consistent and accurate milling achieved through auto leveling minimizes the risk of defects and ensures that the PCBs meet the required specifications.

3.4.2.2.5. Time and Material Savings

Auto leveling optimizes the PCB fabrication process, resulting in time and material savings. It reduces the need for manual adjustments, rework, or scrap caused by variations in the work surface. The milling process can proceed with minimal operator intervention, leading to improved efficiency and productivity. Additionally, auto leveling helps to minimize tool wear, prolonging the tool's lifespan and reducing tooling costs.

3.4.2.2.6. Consistency in Copper Thickness

Auto leveling helps maintain consistency in the copper thickness during PCB milling. By compensating for variations in the substrate surface, it ensures that the copper layer is milled to the desired thickness across the entire PCB. This is important for achieving consistent electrical properties and signal integrity in the finished PCB.

3.4.2.2.7. Ease of Operation

Auto leveling simplifies the operation of the CNC milling machine for PCB fabrication. It reduces the dependency on the operator's skill in manually adjusting the work surface or substrate flatness. The automatic detection and compensation of surface irregularities make the machine more user-friendly and accessible to operators with varying levels of experience.

3.4.3. Installing End Stoppers

End stoppers, also known as limit switches or proximity sensors, are commonly used in machines for various purposes.

Figure 3-1 Limit switch

3.4.3.1. How to Install End Stoppers?

1. Determine the appropriate locations for installing the end stoppers on your CNC milling machine. Typically, these are placed at the extreme ends of each axis (X, Y, and Z) to define the machine's working limits.
2. Select the type of end stoppers you want to install. Common options include mechanical limit switches, optical sensors, or proximity sensors.

3. Connect the end stopper wires to the appropriate terminals on the CNC machine's control board or breakout board. Refer to the machine's wiring diagram or user manual for guidance. Ensure that the wiring is secure and properly insulated.
4. Securely mount the end stoppers at the designated locations on the machine. This may involve attaching them to the machine frame or other fixed parts using screws or brackets. Ensure that the end stoppers are positioned to be triggered by the moving components, such as spindle carriage, when they reach their respective limits.
5. Fine-tune the position of each end stopper to ensure that it is triggered at the desired limit of each axis. This may involve adjusting the physical position of the end stopper or adjusting the trigger mechanism (e.g., the actuator arm on a mechanical limit switch).
6. Once the end stoppers are installed and adjusted, test their functionality. Move the machine's axes manually or using the CNC control software and observe if the end stoppers are triggered when the moving components reach their limits. Ensure that the machine halts or changes direction correctly when the end stoppers are triggered.
7. Configure the CNC control software to recognize and respond to the end stopper signals. This typically involves specifying the type and location of the end stoppers in the software settings.
8. Verify that the end stoppers are correctly recognized and functioning within the CNC control software. This can be done by manually triggering the end stoppers or using the software's homing function to automatically move the machine towards the limits and observe if the end stoppers are detected.

3.4.3.2. Importance of Using End Stoppers

3.4.3.2.1. Position Sensing

End stoppers are often employed to determine the precise position of a moving component within a machine. By placing the end stopper at the extreme ends of the desired travel path, the machine can detect when the component reaches these limits. This information helps the machine control system ensure accurate positioning and prevent overtravel.

3.4.3.2.2. Safety and Collision Prevention

End stoppers play a crucial role in ensuring machine safety by preventing collisions and damage. By detecting when a moving part reaches the predetermined limit, the machine's control system can halt or redirect the motion, avoiding potential collisions with other objects or machine components.

3.4.3.2.3. Home Positioning

Many machines require a reference or home position for their moving parts. End stoppers are used to establish this reference point. When the machine is initialized or powered on, the moving part moves until it triggers the end stopper, indicating the home position. This allows the machine to start operations from a known and consistent starting point.

3.4.3.2.4. Process Control

In certain manufacturing processes, the use of end stoppers helps in controlling the production cycle. For example, in a conveyor system, end stoppers can be positioned to trigger specific actions like stopping, diverting, or sorting products based on their position. This enables precise control over the workflow and enhances efficiency.

3.4.3.2.5. Calibration and Alignment

End stoppers are useful for calibration and alignment purposes. By using precision end stoppers at specific positions, the machine can be calibrated or aligned accurately during setup or maintenance. This ensures that the machine operates within the desired specifications and achieves the desired outcomes.

3.4.4. Installing of Vibration Damper

Vibration dampers are employed to mitigate and absorb vibrations generated by machinery, primarily aimed at reducing the noise resulting from these vibrations and creating a more comfortable environment.

Figure 3-2 Vibration Dampers

3.4.4.1. Importance of Vibration Dampers

3.4.4.1.1. Vibration Isolation

Machines can generate significant vibrations during operation, especially those with rotating or reciprocating components. These vibrations can be transmitted to the floor and adjacent structures, leading to discomfort, noise, and potential damage. Dampers installed under the machine foundation help isolate these vibrations by absorbing or dissipating the energy generated, thereby reducing the transmission to the surrounding environment.

3.4.4.1.2. Structural Protection

Excessive vibrations can cause fatigue failure, cracking, or loosening of structural elements. By installing dampers, the impact of vibrations on the machine's structure can be minimized, thus protecting it from potential damage.

3.4.4.1.3. Equipment Performance and Lifespan

Vibrations can negatively affect the performance and lifespan of the machine itself. Excessive vibrations can lead to increased wear and tear on the machine's components, reduced accuracy, and decreased overall efficiency. By using dampers, the vibrations are dampened or absorbed, providing a stable and vibration-free environment for the machine to operate optimally, ensuring better performance and extended lifespan.

3.4.4.1.4. Operator Comfort and Safety

Excessive vibrations can cause discomfort and fatigue for machine operators working in close proximity to the equipment. Prolonged exposure to vibrations can have health implications, such as decreased productivity. Dampers help reduce vibrations, creating a more comfortable and safer working environment for the operators.

3.4.4.1.5. Noise Reduction

Vibrations often generate noise that can be disruptive and lead to noise pollution. By isolating the vibrations through dampers, the transmission of noise to the surrounding area can be reduced, creating a quieter environment.

3.5. CAD Modeling of The Machine

3.5.1. CAD Model Number 1

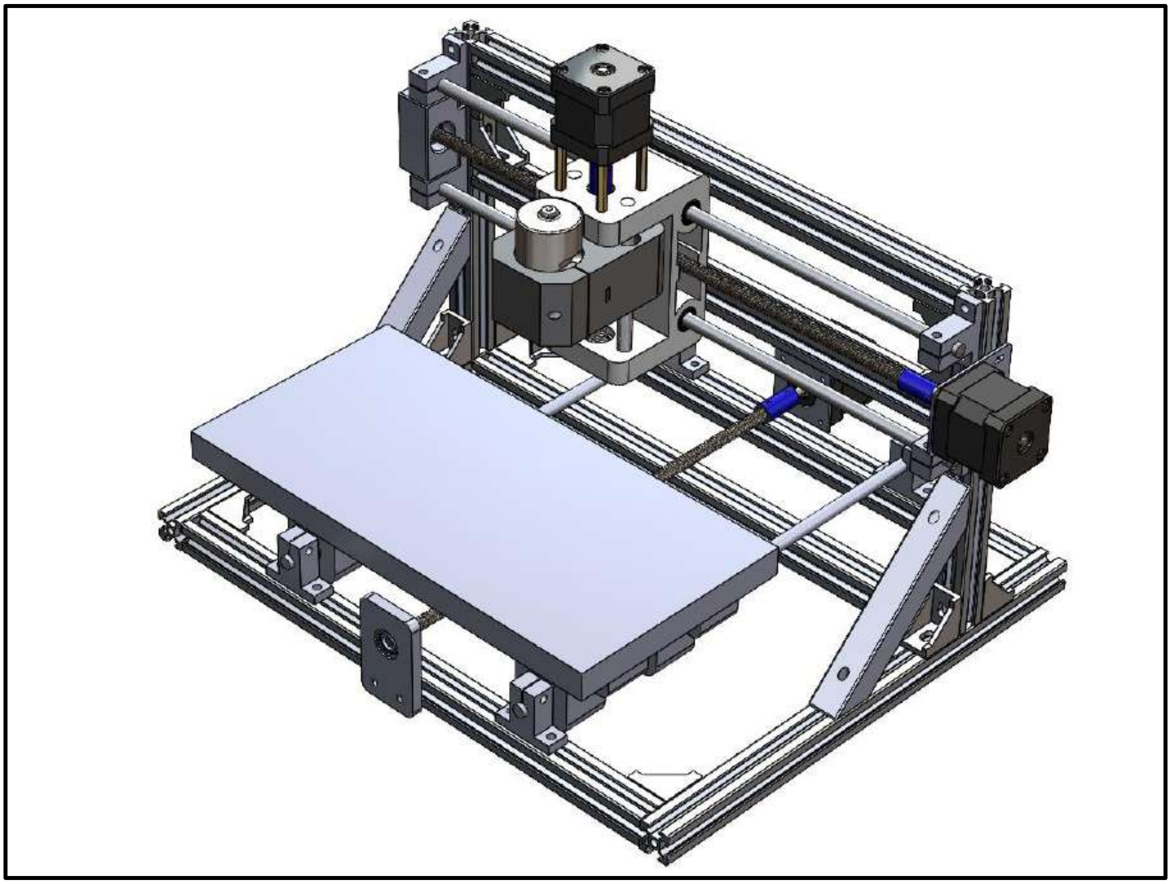

Figure 3-3 CAD Model Number 1

Spindle is on X-Axis and Z-Axis.

Table on Y-Axis.

Compact design.

Reasonable cost.

3.5.2. Cad Model Number 2

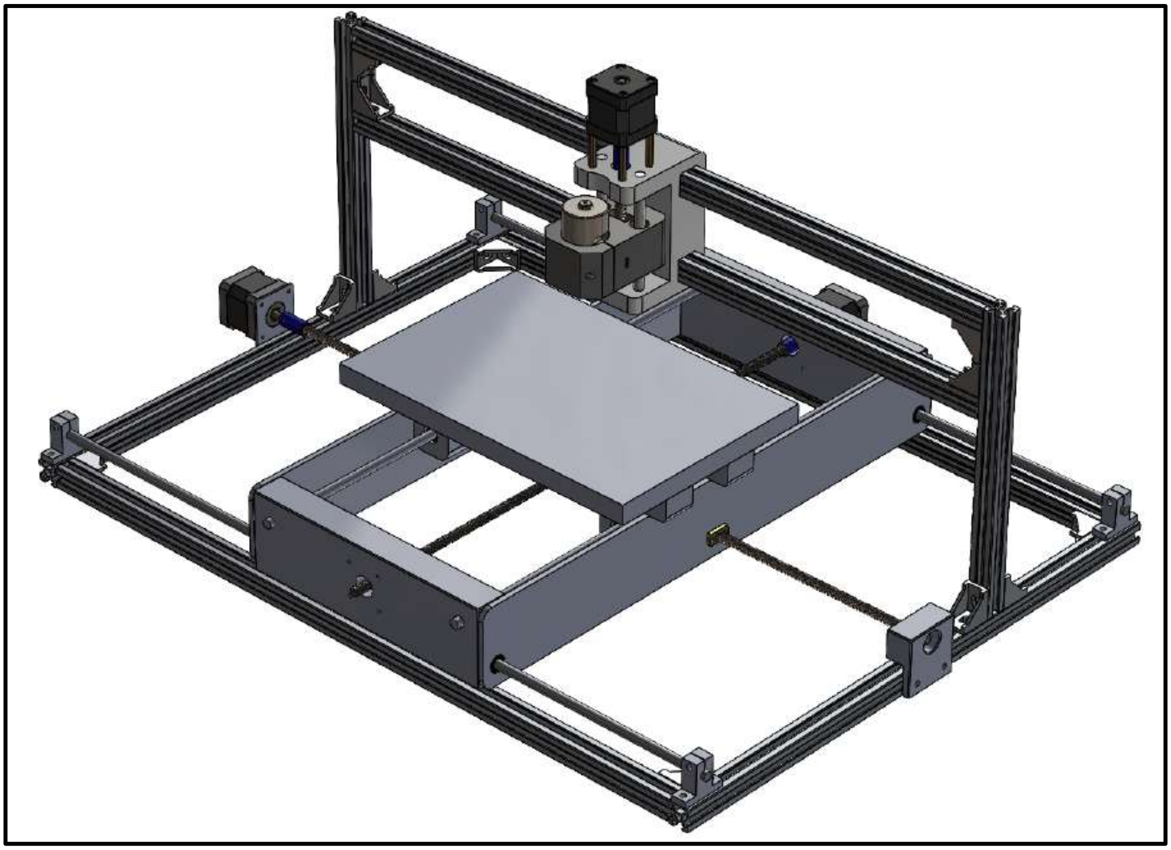

Figure 3-4 CAD Model Number 2

X-Axis and Y-Axis motion on table.

Z-axis on Spindle.

It is more accurate.

It is expensive.

3.5.3. Selection of Model

Considering the budget allocation and project assessment, the team has opted to proceed with the proposed Model Number 1. This decision is rooted in a notable disparity in manufacturing costs between the options, coupled with the realization that the cost of Model Number 2 outweighs its corresponding scope. Consequently, Model Number 1 has been chosen as the prototype design. It's pertinent to note that the adoption of Model Number 2's production remains feasible for potential future investigations. It's essential to emphasize that the design process for both models adheres to the principles of DFMA (Design for Manufacturing and Assembly).

3.5.4. Axis of Motion

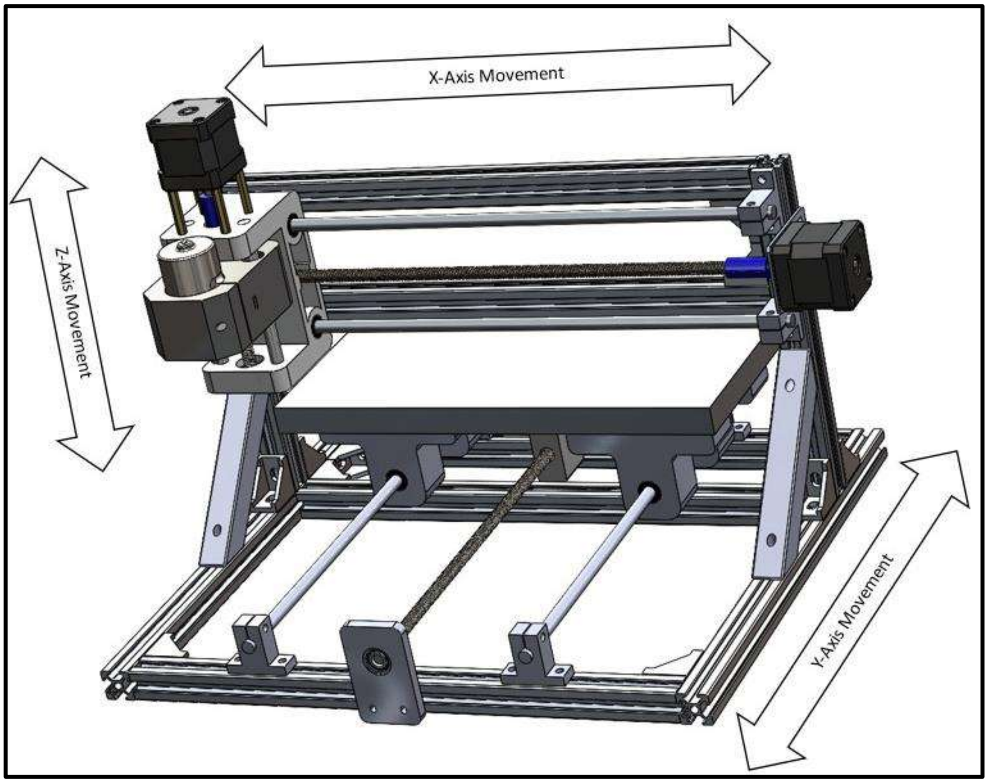

Figure 3-5 Axis of Motion of Machine

3.5.5. Disassembled Model With Table Of Components

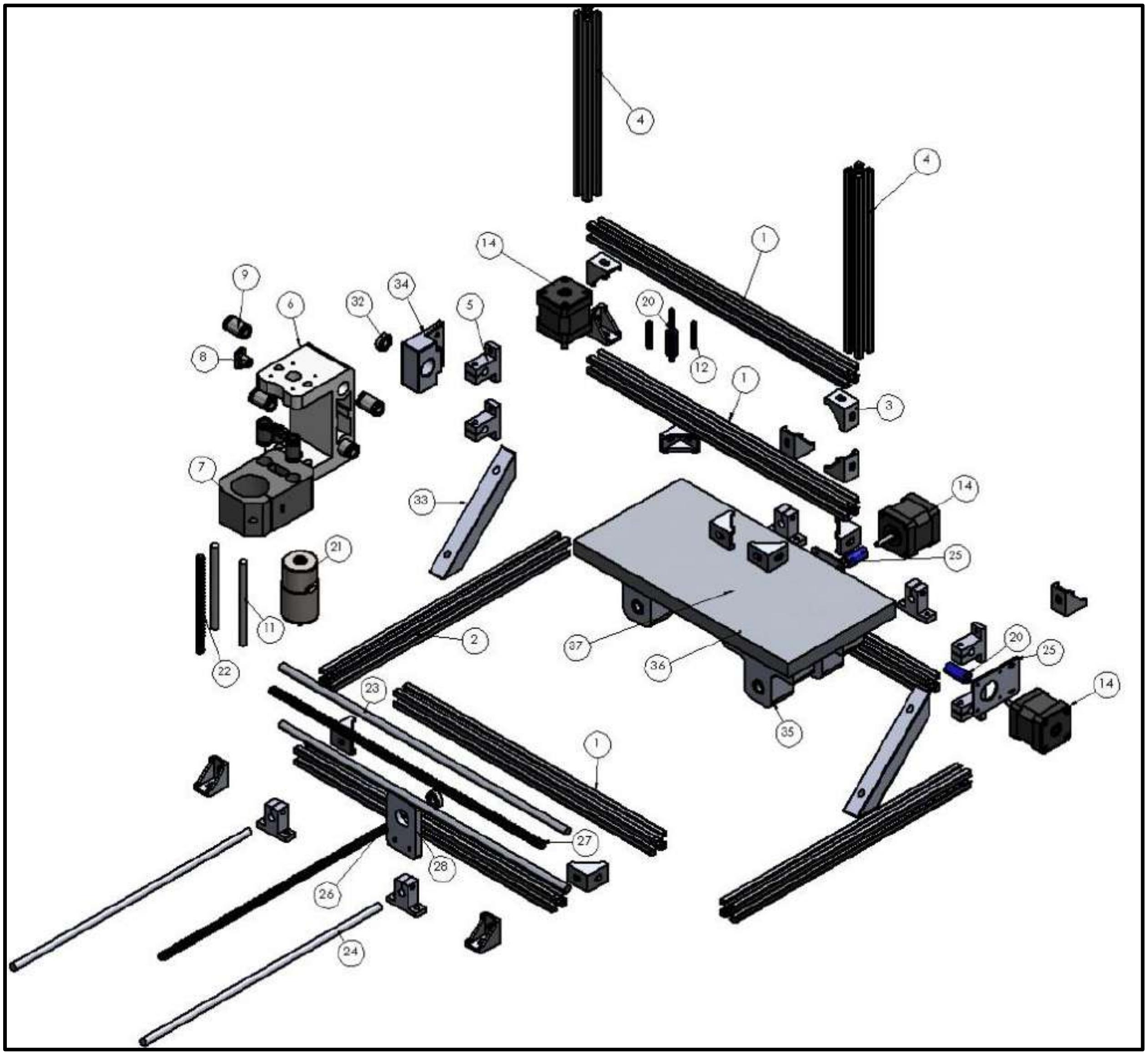

Figure 3-6 Disassembled of Machine Components.

Table 3-1 Disassembled Machine Components

NO.	FILE NAME OF PART	DESCRIPTION	QTY.
1	beam width	lower Support of X axis	5
2	beam Length	Lower Support of Y axis	2
3	2020 cast corner bracket		14
4	height	Side Support for Z axis	2
5	rod holder	Supporting Rod Holder	8
6	Z axis	Z-axis Assembly Holder	1
7	spindle holder		1
8	lead screw nut		3
9	lm8uu	8mm Linear Bearing	10
11	supporting rod	Supporting Rod for Linear Motion Z-axis	2
12	spacer	Spacer For Stepper Motor to set the height of motor for coupling	4
13	Assem	Stepper Motor Assembly (Nema 17)	3
14	coupling	Coupling for Stepper motor and Lead screw	3
15	DC motor	24v 3.75A DC Motor for Spindle	1
16	Z axis lead screw		1
17	X axis rod	Supporting rod for Linear Motion X-axis	2
18	Y axis rod	Supporting rod for Linear Motion Y-axis	2
19	stepper motor holder		2
20	Y axis lead screw		1
21	X axis lead screw		1
22	bearing holder for lead screw		1
23	bearing 8mm	8mm Dia Rotational Bearing For Lead screw	3
24	structure support		2
25	X axis lead screw holder		1

26	table holder		4
27	table x motion	Working Space Table	1
28	Lead Screw Nut Holder	Lead screw Nut Holder for Y axis	1

3.6. Controller Board Diagram

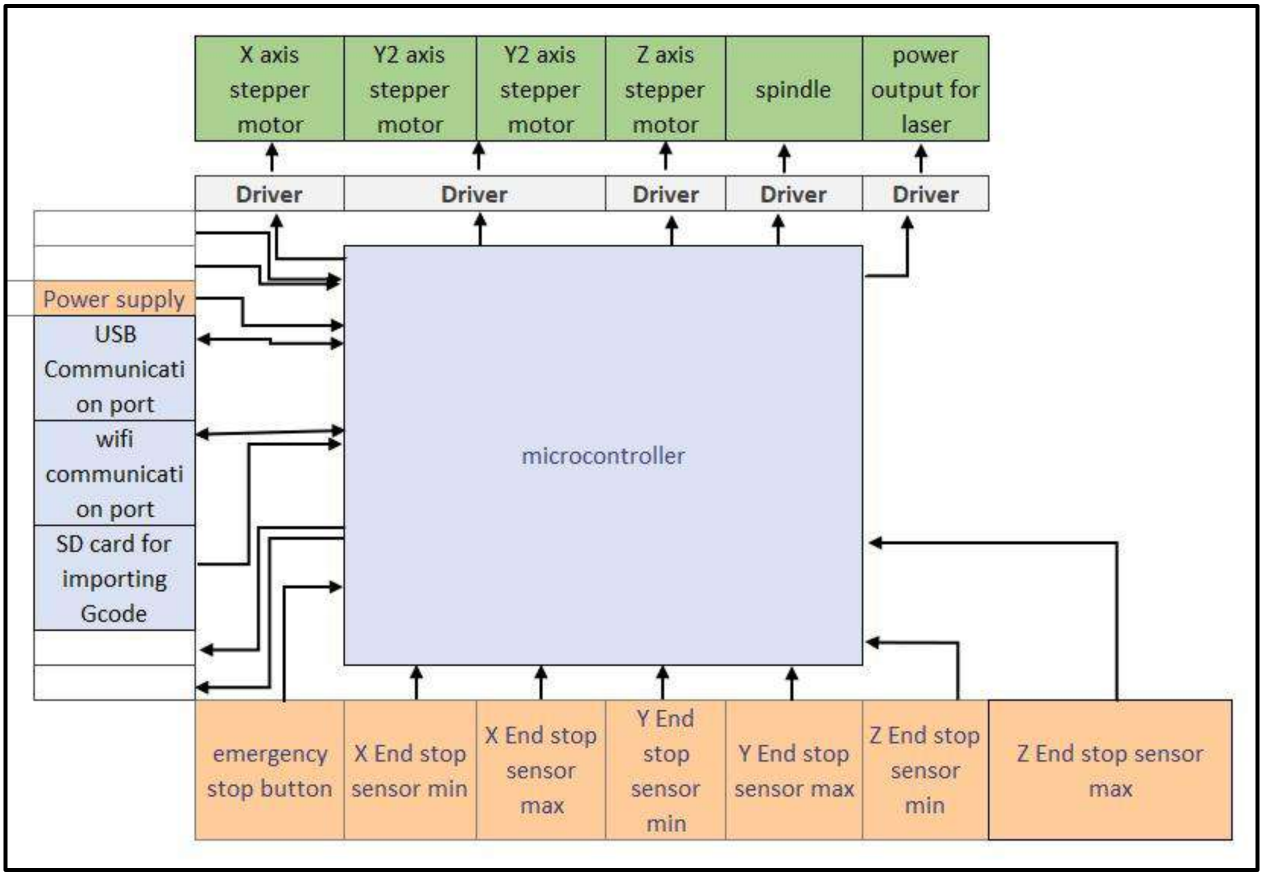

Figure 3-7 Controller Board Diagram

3.7. Hardware Setup

3.7.1. Design the Machine

Begin by designing the machine structure using computer-aided design (CAD) software. Determine the dimensions, material requirements, and necessary components such as linear motion systems, stepper motors, lead screws, and spindle. This design phase includes creating 3D models and assembling the various parts to ensure proper fit and functionality.

Figure 3-8 Spindle

Figure 3-9 Linear Guide

Figure 3-10 Lead Screw

Figure 3-11 Stepper Motor

3.7.2. Gather Materials and Components

Once the design is finalized, gather all the materials and components required for the fabrication. This includes the frame material (e.g., aluminum extrusions or steel), linear rails, stepper motors, lead screws, nuts, bearings, spindle, electronics (motor drivers, controller board, power supply), cables, connectors, and any other necessary hardware.

3.7.3. Frame Fabrication

Start with fabricating the frame of the CNC milling engraving machine. Cut the frame material to the desired dimensions based on the CAD design. Use appropriate cutting tools such as saws or CNC routers to achieve accurate cuts. Ensure proper alignment and securely fasten the frame components together using fasteners such as screws or bolts.

Figure 3-12 Aluminum Frame

3.7.4. Mount Linear Motion Systems

Install the linear motion systems, such as linear rails and carriages, onto the frame according to the CAD design. Use appropriate mounting brackets and fasteners to ensure stability and smooth motion.

3.7.5. Assemble Motor and Lead Screw System

Mount the stepper motors on designated motor mounts or brackets. Connect the lead screws to the motor shafts and install the corresponding nuts or ball screws. Ensure the motor and lead screw assembly is aligned and securely fastened to the machine frame.

3.7.6. Install Spindle and Tool Holder

Mount the spindle onto the machine frame, following the manufacturer's instructions. Attach the tool holder or collet chuck to the spindle, which will hold the cutting tools for PCB fabrication.

Figure 3-13 Tool Holder

3.7.7. Wiring and Electronics

Connect the various electrical components, including the stepper motors, motor drivers, limit switches, controller board, and power supply. Follow the wiring diagram and instructions provided by the manufacturer. Ensure proper grounding and secure cable management to prevent interference or accidents.

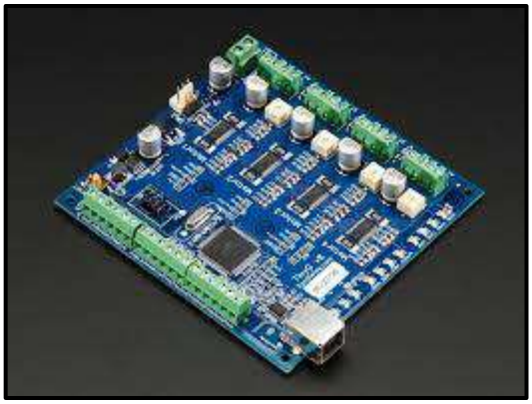

Figure 3-14 GRBL Controller

3.7.8. Test and Calibration

Before using the machine, perform thorough testing and calibration. Check the movement of the linear motion systems, the functionality of the motors, and the accuracy of the spindle rotation. Calibrate the machine's movement by adjusting motor steps, micro stepping, and acceleration settings in the CNC control software.

3.7.9. PCB Worktable

Design and fabricate a suitable worktable for PCB fabrication. This could include a vacuum table, clamps, or fixtures to securely hold the PCB during milling and engraving processes. Ensure proper alignment with the machine's spindle.

Chapter 4

4. CALCULATIONS

Our Calculations includes:

- Torque of Spindle Calculations.
- Heat Generation Calculations.
- Lead screw Calculations.

4.1. For Torque of Spindle

For calculating torque of spindle, we have first calculated the following parameters:

1. Cutting Speed
2. Feed per tooth
3. Material Removal Rate
4. Net Power
5. Net Torque

4.1.1. Spindle Speed

$$N = \frac{V_c \times 60}{\pi \times D_{ap}}$$

Equation 4.4.1

4.1.2. Cutting Speed

$$V_c = \frac{\pi \times D_{ap} \times N}{60}$$

Equation 4.4.2

V_c = Cutting speed (m/s)

Cutting speed is defined as the relative velocity between the surface of the work piece and the cutting tool.

D_{ap} = Axial depth of cut (m)

Axial Depth of cut is the length that the tool engages a work piece in its axis direction as it moves perpendicular to it.

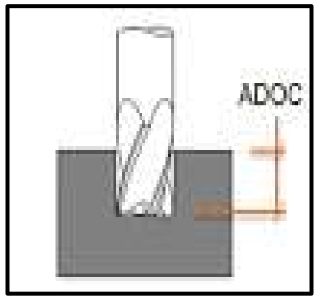

Figure 4-1 Axial Depth of Cut

N = Spindle speed (rpm)

Spindle speed is the number of revolutions the milling tool on the spindle makes in unit time.

4.1.3. Feed per tooth

$$f_z = \frac{v_f \times 60}{N \times Z \times \pi}$$

Equation 4.4.3

f_z= feed per tooth (m)

Feed per tooth is defined as the amount of material that should be removed by each tooth of the cutter as it revolves and advances into the work.

v_f= Table feed (m/sec)

The linear velocity of the cutting tool relative to the work piece is known as the table feed.

Z = number of tool teeth

The cutting edges on the cutting tool is known as number of tool teeth.

4.1.4. Material Removal Rate

$$Q = D_{ap} \times D_e \times v_f$$

Equation 4.4.4

Q = material removal rate

The quantity (amount) of material removed per unit time is known as Material removal Rate

D_e= radial depth of cut (m)

The Radial depth of cut or width of cut is known as the length that the cutting tool engages a work piece perpendicular to its axis direction.

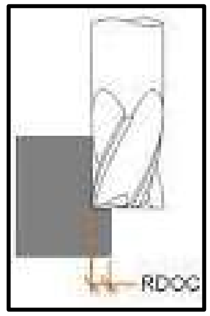

Figure 4-2 Radial Depth of cut

4.1.5. Net Power

$$P_C = (D_{ap} \times D_e \times v_f \times G)$$

Equation 4.4.5

Pc = cutting power (Watt)

The cutting power of a milling machine refers to its ability to remove material from a workpiece during the milling process.

G = Shear Modulus (N/m^2)

The Shear Modulus, also known as Modulus of Rigidity, is a fundamental material property that quantifies the rigidity or resistance of a material to shear deformation. It is defined as the ratio of the shear stress to the shear strain experienced by a material.

4.1.6. Net Torque

$$T = \frac{P_c}{2\pi N}$$

Equation 4.4.6

T = Net torque (Nm)

The net torque produced determines the machine's ability to overcome resistance and rotate the cutter through the workpiece material.

Summarization of Results

Input Parameters

Table 4-1 Input Parameters for Torque of Spindle

D_{ap} (Axial Depth of Cut)	0.0001 m.
N (Spindle Revolution)	10000 rpm.
v_f (Table Feed)	0.01 m/sec
Z (Number of Cutting Edges)	2
D_e (Radial Depth of Cut)	0.0003 m
G (Shear Modulus)	45×10^9 N/m^2

Calculations

a) $V_c = \frac{\pi \times D_{ap} \times N}{60}$

$$\boldsymbol{V_c} = \mathbf{0.05\ m/sec.}$$

b) $f_z = \frac{v_f \times 60}{N \times Z \times \pi}$

$$\mathbf{f_z = 9.5 \times 10^{-6}\ m = 9.5 \times 10^{-3}\ mm}$$

c) $Q = D_{ap} \times D_e \times v_f$

$$\mathbf{Q = 3 \times 10^{-10}\ \frac{m^3}{sec}.}$$

d) $P_C = (D_{ap} \times D_e \times v_f \times G)$

$$\boldsymbol{P_C} = \mathbf{13.5\ W}$$

e) $T = \frac{P_c}{2\pi N}$

$$\mathbf{T = 2.15 \times 10^{-4}\ N\text{-}m = 0.215\ N.mm}$$

Output Parameters

Table 4-2 Output Parameters for Torque of Spindle

V_c (Cutting Speed)	0.05 m/sec.
f_z ($Feed\ per\ tooth$)	9.5×10^{-6} m
Q (Material Removal Rate)	$3\times10^{-10}\ \frac{m^3}{sec}$.
P_C (Net Power)	13.5 W
T (Net Torque)	2.15×10^{-4} N.m

4.1.2. For Heat Generation

For calculation of heat generation following parameters were calculated first:

1. Cutting Force.
2. Energy Required to Remove a Unit Material.
3. Temperature Rise.

4.1.2.1. Cutting Force

$$\boldsymbol{F_V = \frac{F_s cos(\beta - \alpha)}{cos(\varphi + \beta - \alpha)}}$$

Equation 4.4.7)

$F_V =$ Cutting Force (N)

Cutting force is the resistance of the material against the intrusion of the cutting tool.

F_s= Shear Force (N)

In milling, shear force refers to the force acting parallel to the surface of the workpiece during the cutting process. It is the force that causes the material to deform and eventually be removed.

β = Friction Angle (Degrees)

The friction coefficient or frictional resistance angle is the angle between the resultant force and the normal force at the interface between the cutting tool and the workpiece material.

α = Rake Angle (Degrees)

It is the angle at which the cutting edge is inclined with respect to the direction of the feed motion.

A positive rake angle means the cutting edge is tilted in the direction of the feed motion.

A negative rake angle means it is tilted opposite to the feed motion. The rake angle affects the cutting action, chip formation, and the forces acting on the tool.

φ = Shear Angle (Degrees)

Shear angle is the angle between the shear plane (the plane along which the material is sheared) and the normal to the machined surface.

4.1.2.2. Friction Angle

$$\mu = \tan(\beta)$$

Equation 4.4.8

μ = Coefficient of Friction Cutting Tool and Workpiece Material.

It represents the resistance to relative motion between the two surfaces.

4.1.2.3. Shear Angle

$$\varphi = 45° + \frac{\alpha}{2} - \frac{\beta}{2}$$

Equation 4.4.9

4.1.2.4. Shear Force

$$F_S = S \times A_S$$

Equation 4.4.10

S = Shear Strength (MPa)

Shear strength refers to the maximum stress that a material can withstand before it fails in shear. In milling, shear strength represents the resistance of the workpiece material to shear deformation and fracture.

A_s = Area of Shear (m^2)

The area of shear, also known as the shear plane area, is the cross-sectional area of the material that undergoes shear deformation during the milling process. It is the area over which the shear force acts.

4.1.2.5. Area of Shear

$$A_S = \frac{t \times w}{\sin(\varphi)}$$

Equation 4.4.11

4.1.2.6. Energy Needed for the removal of one unit volume of material.

$$U_t = \frac{Cutting\ Power}{MRR}$$

Equation 4.4.12

$$U_t = \frac{F_v \times Vc}{Vc \times w \times t}$$

Equation 4.4.13

$$U_t = \frac{F_V}{w \times t}$$

Equation 4.4.14

U_t = Specific Energy (J/m^3)

The specific cutting energy is energy consumed to remove a unit volume of material.

w = width (m)

Width of cut is the width of material that is removed by a cutting process.

4.1.2.7. Temperature Rise

$$\triangle T = \frac{0.4 \times U}{\rho \times C} \, x \, (\frac{Vc \times t}{k})^{0.333}$$

Equation 4.4.15

$\triangle$ T = Temperature Rise (°C)

Temperature rise during a machining operation refers to the increase in temperature experienced by the workpiece, cutting tool, and the surrounding environment as a result of the machining process. When material is removed from the workpiece through cutting or grinding, the energy transferred to the material generates heat, causing the temperature to rise.

ρ = density of copper (kg/m^3)

Density, mass of a unit volume of a material substance.

C = Specific Energy for copper (J/kg.K)

Specific energy is energy per unit mass.

k = Thermal Diffusivity of Copper ($\frac{m^2}{sec}$)

Thermal diffusivity is a parameter that quantifies the speed at which heat propagates through a specific material. It characterizes how efficiently and rapidly a material can conduct heat, taking into account the effects of stored or internal heat within the material..

Summarization of Results

Input Parameters

Table 4-3 Input Parameters for Heat Generation

V_f (Table Feed)	0.01 m/sec
α (Rake Angle)	30°
w (width of cut)	0.0003 m
t (chip thickness)	0.0001 m
V_c (Cutting Velocity)	0.05 m/sec
S (Shear Strength of Copper)	172×10^6 Pa
C (Specific Heat for Copper)	385 J/kg.K,
k (Thermal Diffusivity)	$1.11 \times 10^{-4} \frac{m^2}{sec}$
ρ (Density of Copper)	8960 kg/m^3

Calculations

a) $\beta = \tan^{-1}(\mu)$

$$\beta = \tan^{-1}(0.2)$$

$$\boldsymbol{\beta = 11°}$$

b) $\varphi = 45° + \frac{\alpha}{2} - \frac{\beta}{2}$

$$\varphi = 45° + \frac{30}{2} - \frac{11.3}{2}$$

$$\boldsymbol{\varphi = 54°}$$

c) $A_S = \frac{t \times w}{\sin(\varphi)}$

$$A_S = \frac{0.0001 \times 0.0003}{\sin(54)}$$

$$\mathbf{A_S = 3.7\ X\ 10^{-8}\ \boldsymbol{m^2}}$$

d) $F_S = S \times A_S$

$$F_S = 172 \times 10^6 \times 3.7\ \ X\ 10^{-8}$$

$$\boldsymbol{F_S} = \mathbf{6.38\ N}$$

e) $F_V = \frac{F_S cos(\beta - \alpha)}{cos(\varphi + \beta - \alpha)}$

$$F_V = \frac{6.38 \times cos(11 - 30)}{cos(54 + 11 - 30)}$$

$$\mathbf{F_V = 7.36\ N}$$

f) $U_t = \frac{F_V}{w \times t}$

$$U_t = \frac{7.36}{0.0003 \times 0.0001}$$

$$\boldsymbol{U_t} = \mathbf{2.4 \times 10^8\ N/m^2}$$

or

$$\boldsymbol{U_t} = \mathbf{2.4 \times 10^8\ J/m^3}$$

g) $\triangle T = \frac{0.4 \times U}{\rho \times C}\ x\ (\frac{Vc \times t}{k})^{0.333}$

$\triangle T = \frac{0.4 \times 2.4 \times 10^8}{8960 \times 385}\ x\ (\frac{0.05 \times 0.0001}{1.11 \times 10^{-4}})^{0.333}$

$$\triangle \boldsymbol{T generated} = \mathbf{10℃}$$

$$\mathbf{T_{total} = 10+25 = 35℃}$$

Output Parameters

Table 4-4 Output Parameters for Heat Generation

β (Friction Angle)	11°
φ (Shear Angle)	54°
A_S (Area of Shear)	$3.7 \text{ X } 10^{-8}$ m^2
F_s (Shear Force)	6.38 N
F_V (Cutting Force)	7.36 N
U (Specific Energy)	2.4×10^8 J/m^3
$\triangle Tgenerated$	10 ℃
Temperature Rise	35 ℃

4.1.3. For Lead Screw

The lead screw following calculations were involved:

1. Tangential force which is required at the circumference of screw to move the load
2. Calculating Torque required to overcome friction between nut and screw
3. Calculating Torque required to overcome friction between collar and screw so that load does not rotate with screw
4. Total torque required at lead screw to move the combined load without rotating
5. Power of motor
6. Efficiency of lead screw

4.1.3.1. For Helix Angle

$$\boldsymbol{tan\alpha = \frac{lead}{\pi d}}$$

Equation 4.4.16

Lead (mm)

The linear travel the nut makes per one screw revolution.

d = Mean Diameter (mm)

Mean diameter is the average diameter of the screw surface. It is twice the average distance from the center line of the thread to the screw surface.

Putting

Lead= 8 mm

d= 8 mm

4.1.3.2. For Maximum bearing Load (W)

$$\boldsymbol{W = \left(\frac{\pi}{16}\right) \times d^3 \times \frac{Yield\ Strength\ of\ Material}{Lead}}$$

Equation 4.4.17

Yield Strength (N/m^2)

It is the maximum stress which a material will bear before plastic deformation begins.

4.1.3.3. For Tangential Force P

$$P_T = W \times tan(\alpha + \emptyset)$$

Equation 4.4.18

$$lead = pitch \times number\ of\ starts$$

Equation 4.4.19

$$tan\alpha = \frac{lead}{\pi d}$$

Equation 4.4.20

P_T= Tangential force on edge of lead screw.(N)

The force that operates on a moving object in the direction of the tangent to the curved path.

$tan\emptyset$= μ_1= coefficient of friction of lead screw and nut.

A measure of the amount of friction existing between two surfaces (screw and nut).

α= helix angle of thread. (Degree)

Helix angle refers to the angle formed by the screw flight concerning a plane that is perpendicular to the screw plane.

p = pitch of screw. (m)

The distance (spacing) between adjacent threads.

W= total load on the screw. (N)

The total load on a lead screw refers to the combined force exerted on the screw due to the weight or resistance being lifted or moved by the screw.

4.1.3.4. Torque Calculation to overcome friction between nut and screw

$$T_1 = P_T \times \frac{d}{2}$$

Equation 4.4.21

T_1 =Torque requirement for overcoming friction between nut and lead screw

The torque required to overcome the friction between a nut and a lead screw refers to the rotational force needed to move the nut along the length of the screw against the resistance caused by friction.

It represents the effort required to overcome the frictional forces acting between the mating surfaces of the nut and the lead screw.

4.1.3.5. Torque Calculation to overcome friction between collar and screw so that load does not rotate with screw

$$\boldsymbol{T_2 = \mu_2 \times W \times R}$$

Equation 4.4.22

T_2 = Torque required to overcome friction between collar and screw

The torque required to overcome the friction between a collar and a screw refers to the rotational force needed to rotate the collar along the screw's axis against the resistance caused by friction.

It represents the effort required to overcome the frictional forces acting between the collar and the screw, enabling the collar to move freely.

μ_2= coefficient of friction for the collar and screw

A measure of the amount of friction existing between two surfaces (collar and screw).

R= mean radius (m)

4.1.3.6. Total torque required at lead screw to move the combined load without rotating

$$\boldsymbol{T = T_1 + T_2}$$

Equation 4.4.23

T = Total Torque Required at lead screw to move the combined load without rotating

The total torque required at a lead screw to move a combined load without rotating refers to the rotational force needed to overcome the resistance and initiate linear motion of the load without causing the lead screw itself to rotate.

This torque is necessary to generate sufficient axial force to move the load along the length of the screw without rotation.

4.1.3.7. Power of motor

$$Required\ Power = T \times \omega$$

Equation 4.4.24

T= total torque required at lead screw to move the combined load without rotating. (N-m)

ω= angular velocity (rpm)

4.1.3.8. Efficiency of lead screw

$$\boldsymbol{\eta} = \frac{\boldsymbol{W tan\alpha} \times \frac{\boldsymbol{d}}{\boldsymbol{2}}}{\boldsymbol{P_T} * \frac{\boldsymbol{d}}{\boldsymbol{2}} + \boldsymbol{\mu_2} \times \boldsymbol{W} \times \boldsymbol{R}} = \frac{\boldsymbol{T0}}{\boldsymbol{T}}$$

Equation 4.4.25

$$\eta = \frac{\text{Torque required to move load neglecting friction}}{\text{Torque required to move the load including screw and collar friction}}$$

η =efficiency of lead screw

It is a parameter that tells how well a screw converts rotary energy (torque) into linear motion.

W = load applied (N)

α = helix angle of thread (degree).

d = mean diameter (mm)

P_T= Tangential force (N)

μ_2= coefficient of friction for collar

Summarization of Results

Input Parameters

Table 4-5 Input Parameters for Lead Screw

Lead	8 mm
d (Diameter of Lead Screw)	8 mm
Yield Strength for stainless steel	$170 \times 10^6 N/m^2$
W (Weight on Lead Screw)	40 N
$tan\emptyset = \mu_1$ (coefficient of friction of lead screw)	0.3

μ_2 (coefficient of friction for the collar and screw)	0.2
ω (Angular velocity)	7.854 rad/sec

Calculations

a) $tan\alpha = \frac{lead}{\pi d}$

$$\boldsymbol{\alpha = 17.6°}$$

b) $W = \left(\frac{\pi}{16}\right) \times d^3 \times \frac{Yield\ Strength\ of\ Material}{Lead}$

W = 2136 N > 40N So it's safe

c) $P = W \times tan(\alpha + \emptyset)$

$$\tan(\alpha + \emptyset) = \frac{\tan\alpha + \tan\emptyset}{1 - tan\alpha \times \tan\emptyset}$$

$$\tan(\alpha + \emptyset) = 0.32$$

$$\mathbf{P_T = 12.8\ N}$$

d) $T_1 = P_T \times \frac{d}{2}$

$$\boldsymbol{T_1} \mathbf{= 0.0512\ N\text{-}m = 51.2\ N\text{-}mm}$$

e) $T_2 = \mu_2 \times W \times R$

$$\boldsymbol{T_2} \mathbf{= 0.032\ N\text{-}m = 32N\text{-}mm}$$

f) $T = T_1 + T_2$

$$\mathbf{T = 0.0832\ N\text{-}m = 83.2\ N\text{-}mm}$$

g) $Power = T \times \omega$

$$\boldsymbol{Power = 12\ W}$$

h) $\eta = \frac{W\tan\alpha \times \frac{d}{2}}{P_T * \frac{d}{2} + \mu_2 \times W \times R} = \frac{T0}{T}$

$$\boldsymbol{\eta = 61\%.}$$

Output Parameters

Table 4-6 Output Parameters for Lead Screw

α $(Helix\ Angle)$	$\alpha = 17.6°$
W (Maximum Bearing Load)	2136 N
Tangential Force	12.8 N
Torque required to overcome friction between nut and screw	0.0512 N-m
Torque required to overcome friction between collar and screw	0.032 N-m
(Total Torque)	0.0832 N-m
$Power$ (Power of Motor)	12 W
(Efficiency of Lead Screw)	$\eta = 61\%$.

4.1.4. For Torque due to Acceleration

This includes following calculations.

1. Acceleration Force
2. Frictional Force
3. External Force due to Gravity
4. Total Force
5. Torque Due to Acceleration for lead screw
6. Moment of Inertia for load
7. Moment of Inertia for lead screw

4.1.4.1. Force Calculations for lead screw

4.1.4.1.1. Acceleration Force

$$\boldsymbol{F_a = \frac{W}{g} \times a}$$

Equation 4.4.26

F_a = Acceleration Force (N)

The acceleration force for a lead screw refers to the force required to accelerate the load being moved along the screw at a desired rate of acceleration.

a= Linear Acceleration (m/s^2).

The linear acceleration of a lead screw refers to the rate at which the load being moved along the screw experiences a change in velocity.

W= Load on Lead Screw (N)

g= Gravitational Acceleration (m/s^2).

4.1.4.1.2. Frictional Force

$$F_r = \mu \ x \ N$$

Equation 4.4.27

F_r = Frictional Force (N)

The frictional force of a lead screw refers to the resistance encountered between the screw and the nut or collar as they interact during linear motion.

N= Normal Force (N)

The normal force is the force exerted perpendicular to the contact surfaces between the screw and the nut or collar.

μ = Coefficient of Friction between Lead Screw (Stainless Steel) and nut (bronze).

4.1.4.1.3. External Force due to Gravity

$$F_g = W$$

Equation 4.4.28

F_g = Gravitational Force (N)

F_g = Gravitational Force (N)

The gravitational force acting on a lead screw refers to the force exerted on the load being lifted or moved due to the effect of gravity.

It is the force that pulls the load downward and opposes the motion or upward force applied by the lead screw.

4.1.4.1.4. Total Force

$$F_t = F_a + F_r + F_g$$

Equation 4.4.29

F_T = Total Force (N)

The total force on a lead screw refers to the combined axial force exerted on the screw due to various factors, such as the weight of the load, applied forces, and friction. It represents the overall force that needs to be overcome or transmitted by the lead screw to achieve the desired linear motion.

4.1.4.2. Torque Calculations for lead screw

4.1.4.2.1. Total Torque (without considering supports)

$$\boldsymbol{T} = \frac{\boldsymbol{F_t} \times \mathrm{L}}{\mathbf{2} \times \boldsymbol{\pi} \times \boldsymbol{\eta}}$$

Equation 4.4.30

4.1.4.2.2. Torque Due to Acceleration for lead screw without support

$$\boldsymbol{T} = (\boldsymbol{I_{Load}} + \boldsymbol{I_{LeadScrew}}) \times \boldsymbol{\alpha}$$

Equation 4.4.31

T = Torque due to Acceleration of lead screw (Nm)

The torque due to the acceleration of a lead screw refers to the rotational force required to accelerate the screw and the load being moved along its axis.

I_{Load}= Moment of Inertia for load (kg.m^2)

The load torque is the torque required to accelerate the load being moved along the lead screw.

It depends on the mass of the load, the angular acceleration, and the effective radius or lever arm distance between the center of the screw and the point of application of the force.

$I_{Lead\ screw}$= Moment of Inertia for lead screw (kg.m^2)

the torque required to overcome the inertia of the lead screw itself. It depends on the mass and distribution of mass along the length of the screw, as well as the angular acceleration of the screw.

α= Angular Acceleration

The angular acceleration refers to the rate at which the screw undergoes rotational acceleration as a result of an applied torque.

4.1.4.2.2.1. Moment of Inertia for load

$$\boldsymbol{I_{Load}} = \frac{\boldsymbol{W}}{(\mathbf{2}\boldsymbol{\pi p})^{\mathbf{2}}}$$

Equation 4.32

W = Load applied on lead screw

p = Pitch of lead screw

4.1.4.2.2.2. Moment of Inertia for lead screw

$$I_{Leadscrew} = \frac{\pi L \rho R^4}{2}$$

Equation 4.33

L= Length of Lead screw (m)

The overall measurement of the screw's axial extent from one end to the other is known as length of lead screw.

ρ = Density of Stainless steel (kg/m^3)

Summarization of Results

Input Parameters

Table 4-7 Input Parameters for Torque due to Acceleration

W (Weight)	W= 40 N
g (Gravitational Acceleration)	g= 9.8 m/s^2
a (Linear Acceleration)	a= 0.0082 m/s^2
α (Angular Acceleration)	α = 7.854 rad/s^2
N (Normal Force)	40 N
μ (Coefficient of Friction between Lead Screw (Stainless Steel) and nut (bronze))	0.2
L (Lead)	0.0008 m
η (Efficiency)	61%
Pitch of Lead screw	15.63 threads per inch = 1.625 mm
L (Length of Lead screw)	0.36 m
ρ (Density of Stainless Steel)	7.6 kg/m^3

Calculations

a) $F_a = \frac{W}{g}$x a

$$\mathbf{F_a = 0.03\ N}$$

b) $F_r = \mu$ x N

$$\mathbf{F_r = 8\ N}$$

c) $F_g = W$

$$\mathbf{F_g = 40\ N}$$

d) $F_t = F_a + F_r + F_g$

$$\mathbf{F_t = 48.03\ N}$$

e) $T = \frac{F_t \times L}{2 \times \pi \times \eta}$

T=0.01 N-m=10 N-mm

f) $I_{Load} = \frac{W}{(2\pi p)^2}$

$$\mathbf{I_{Load} = 0.013\ kg.m^2}$$

g) $I_{Leadscrew} = \frac{\pi L \rho R^4}{2}$

$$\boldsymbol{I_{Leadscrew} = 1.1 \times 10^{-9}\ kg.m^2}$$

h) $T = (I_{Load} + I_{LeadScrew}) \times \alpha$

$$\boldsymbol{T = 0.1\ N.m = 102\ N.mm}$$

Output Parameters

Table 4-8 Output Parameters for Torque due to Acceleration

Acceleration Force	0.03 N
Gravitational Force	40 *N*
Friction Force	8 N

Total Force	48.03 N
$Moment\ of\ Inertia\ for\ Load$	$0.013\ \text{kg.m}^2$
$Moment\ of\ Inertia\ for\ Lead\ Screw$	$1.1 \times 10^{-9}\ \text{kg.m}^2$
Torque due to Acceleration	$102\ N.mm$

4.1.4.2.3. Calculation of Total Torque (with considering supports)

Figure 4-21 and 4-22

$$I_{Load} = \frac{W}{(2\pi \text{p})^2}$$

$$I_{Load} = \frac{0.08}{(2\pi * 15.63)^2}$$

$$\boldsymbol{I_{Load} = 8.2 \times 10^{-6} \text{kg.} m^2}$$

$$\text{T} = I_{Load} + I_{LeadScrew} * \alpha$$

$$\boldsymbol{T = (8.2 * 10^{-6}) + (1.1 * 10^{-9}) \times 7.854 = 6.7 * 10^{-6}\ N.m}$$

$$\boldsymbol{T = 6.7 * 10^{-5} N.m = 0.067\ N.mm}$$

4.2. Results

4.2.1. Numerical Results

4.2.1.1. For Spindle Torque

Table 4-9 Numerical Data and Calculations for Spindle Torque

Cutting diameter at cutting depth ap (m)	Spindle speed rpm	Table feed (m/s)	number of tool teeth	Axial depth of cut (m)	radial depth of cut (m)
D_{cap}	n	v_f	Z	Dp	De
0.0003	10000	0.001	2	0.0001	0.0003
0.0003	11000	0.002	2	0.0001	0.0003
0.0003	12000	0.003	2	0.0001	0.0003
0.0003	13000	0.004	2	0.0001	0.0003
0.0003	14000	0.005	2	0.0001	0.0003
0.0003	15000	0.006	2	0.0001	0.0003
0.0003	16000	0.007	2	0.0001	0.0003
0.0003	17000	0.008	2	0.0001	0.0003
0.0003	18000	0.009	2	0.0001	0.0003
0.0003	19000	0.01	2	0.0001	0.0003

Shear Modulus (N/m^2)	Feed Per Tooth (m/sec)	MRR (m^3/sec)	Cutting Speed (m/s)	Net Power (W)	Net Torque (N.m)
G	fz	Q	Vc	Pc	T
$4.50x10^{10}$	0.000001	$3x10^{-11}$	0.053	1.35	$2.15x10^{-5}$
$4.50x10^{10}$	0.000002	$6 x10^{-11}$	0.058	2.70	$3.91 x10^{-5}$
$4.50x10^{10}$	0.000002	$9 x10^{-11}$	0.063	4.05	$5.37 x10^{-5}$
$4.50x10^{10}$	0.000003	$1.2 x10^{-10}$	0.069	5.40	$6.61 x10^{-5}$
$4.50x10^{10}$	0.000003	$1.5 x10^{-10}$	0.074	6.75	$7.67 x10^{-5}$
$4.50x10^{10}$	0.000004	$1.8 x10^{-10}$	0.079	8.10	$8.59 x10^{-5}$
$4.50x10^{10}$	0.000004	$2.1 x10^{-10}$	0.084	9.45	$9.40 x10^{-5}$
$4.50x10^{10}$	0.000004	$2.4 x10^{-10}$	0.09	1.08	$1.01 x10^{-5}$
$4.50x10^{10}$	0.000005	$2.7 x10^{-10}$	0.095	1.22	$1.07 x10^{-5}$
$4.50x10^{10}$	0.000005	$3 x10^{-10}$	0.1	1.35	$1.13 x10^{-5}$

4.2.1.2. For Heat Generation

Table 4-10 Data and Calculation for Heat Generation during Operation

Area of Shear(m^2)	Shear Strength (N/m^2)	Shear Force (N)	Table feed (m/s)	Cutting Speed (m/s)	Cutting Force (N)	Energy required to Remove a unit volume of material. (J/m^3)	Temperature Rise (degree)	Total Temperature (ΔT+25)
As	S	Fs	V_f	V_c	Fv	U_t	ΔT	T
$3.71x10^{-8}$	$1.72x10^8$	6.38	0.01	0.053	7.4	$2.47\ x10^8$	10.10	35.1
$3.71x10^{-8}$	$1.72x10^8$	6.38	0.02	0.058	7.4	$2.47\ x10^8$	10.41	35.41
$3.71x10^{-8}$	$1.72x10^8$	6.38	0.03	0.063	7.4	$2.47\ x10^8$	10.7	35.7
$3.71x10^{-8}$	$1.72x10^8$	6.38	0.04	0.069	7.4	$2.47\ x10^8$	11	36
$3.71x10^{-8}$	$1.72x10^8$	6.38	0.05	0.074	7.4	$2.47\ x10^8$	11.3	36.3
$3.71x10^{-8}$	$1.72x10^8$	6.38	0.06	0.079	7.4	$2.47\ x10^8$	11.5	36.5
$3.71x10^{-8}$	$1.72x10^8$	6.38	0.07	0.084	7.4	$2.47\ x10^8$	11.8	36.8
$3.71x10^{-8}$	$1.72x10^8$	6.38	0.08	0.09	7.4	$2.47\ x10^8$	12	37
$3.71x10^{-8}$	$1.72x10^8$	6.38	0.09	0.095	7.4	$2.47\ x10^8$	12.3	37.3
$3.71x10^{-8}$	$1.72x10^8$	6.38	0.1	0.1	7.4	$2.47\ x10^8$	12.5	37.5

4.2.1.3. For Lead Screw

Table 4-11 Data and Calculations for Lead Screw

Load (N)	helix angle α (Degree)	Helix angle α(radians)	Tan α	ϕ1 (Degree)	ϕ1(radians)	outer diameter (D) (m)	total radius (D/2) (m)	u2
40	5	0.0872665	0.0874887	16.699	0.29145253	0.008	0.004	0.2
40	10	0.1745329	0.176327	16.699	0.29145253	0.008	0.004	0.2
40	15	0.2617994	0.2679492	16.699	0.29145253	0.008	0.004	0.2
40	18	0.3141593	0.3249197	16.699	0.29145253	0.008	0.004	0.2
40	20	0.3490659	0.3639702	16.699	0.29145253	0.008	0.004	0.2
40	22	0.3839724	0.4040262	16.699	0.29145253	0.008	0.004	0.2

40	25	0.4363323	0.4663077	16.699	0.29145253	0.008	0.004	0.2
40	30	0.5235988	0.5773503	16.699	0.29145253	0.008	0.004	0.2
40	35	0.6108652	0.7002075	16.699	0.29145253	0.008	0.004	0.2
40	40	0.6981317	0.8390996	16.699	0.29145253	0.008	0.004	0.2
40	45	0.7853982	1	16.699	0.29145253	0.008	0.004	0.2

R2 (m)	N	Pitch (p) (m)	µ1	Tangential force P (N)	Torque required to overcome friction between nut and screw T_1 (N-m)	Mean radius of lead screw R (m)	Torque required to overcome friction between screw and collar T_2 N-m
0.003	75	-0.00186	0.299995354	15.91712461	0.063668498	0.004	0.032
0.003	75	0.009691	0.299995354	20.11702941	0.080468118	0.004	0.032
0.003	75	-0.00734	0.299995354	24.70353909	0.098814156	0.004	0.032
0.003	75	-0.00552	0.299995354	27.69628028	0.110785121	0.004	0.032
0.003	75	0.002809	0.299995354	29.81399514	0.119255981	0.004	0.032
0.003	75	0.709832	0.299995354	32.04489662	0.128179586	0.004	0.032
0.003	75	-0.04706	0.299995354	35.63744769	0.142549791	0.004	0.032
0.003	75	-0.00098	0.299995354	42.44548465	0.169781939	0.004	0.032
0.003	75	0.013261	0.299995354	50.64696741	0.20258787	0.004	0.032
0.003	75	-0.00562	0.299995354	60.89186424	0.243567457	0.004	0.032
0.003	75	0.003879	0.299995354	74.28495571	0.297139823	0.004	0.032

Total required torque T N.m	angular velocity ω (rad/sec)	Power of motor P (W)	linear velocity of nut (m/sec)	Efficiency η
0.095668	7.853981634	0.751379	-0.0169	0.1463197
0.112468	7.853981634	0.883323	0.003242	0.25084724
0.130814	7.853981634	1.027412	-0.00428	0.32773113

0.142785	7.853981634	1.121432	-0.00569	0.36409362
0.151256	7.853981634	1.187962	0.011186	0.38501114
0.16018	7.853981634	1.258048	4.43E-05	0.40357325
0.17455	7.853981634	1.370911	-0.00067	0.42743807
0.201782	7.853981634	1.584792	-0.03203	0.45780135
0.234588	7.853981634	1.842449	0.002369	0.47757459
0.275567	7.853981634	2.164302	-0.00559	0.4871981
0.32914	7.853981634	2.585058	0.008099	0.48611559

4.2.2. Graphical Results

4.2.2.1. Cutting Speed Vs. Torque

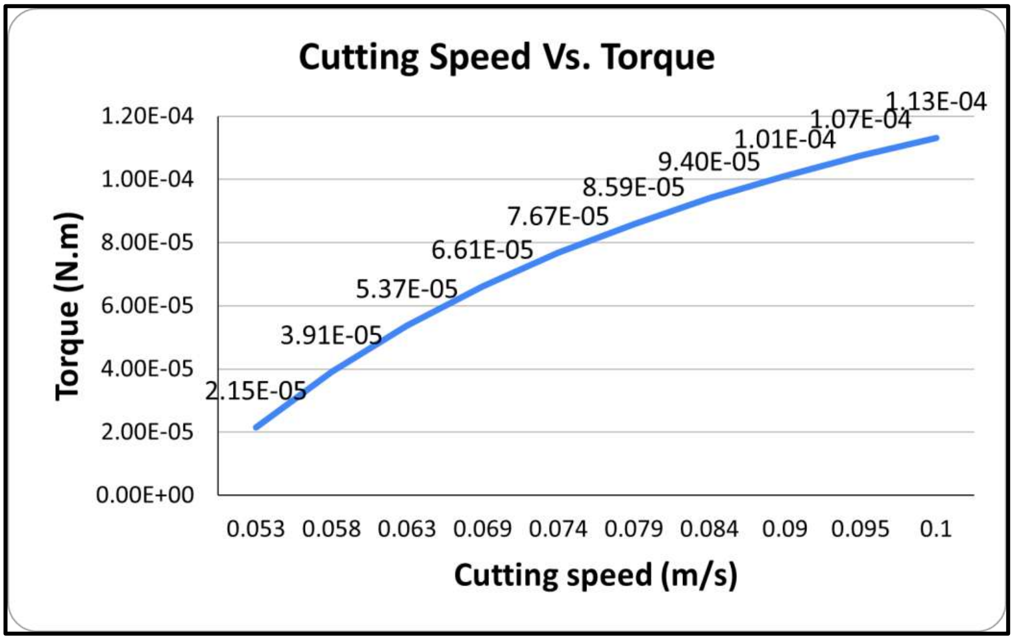

Figure 4-3 Cutting Speed vs. Torque

This graph shows the relationship between Cutting speed and Torque. And it was observed that as Cutting Speed increases, Torque also increases. Because, As cutting speed increases, the tool engages with the workpiece more frequently, resulting in a higher number of cuts per unit of time. This leads to an increase in the volume of material being removed in a given time interval. To remove more material at a faster rate, the tool needs to exert more force, which translates to higher torque.

4.2.2.2. Cutting Speed Vs. Power

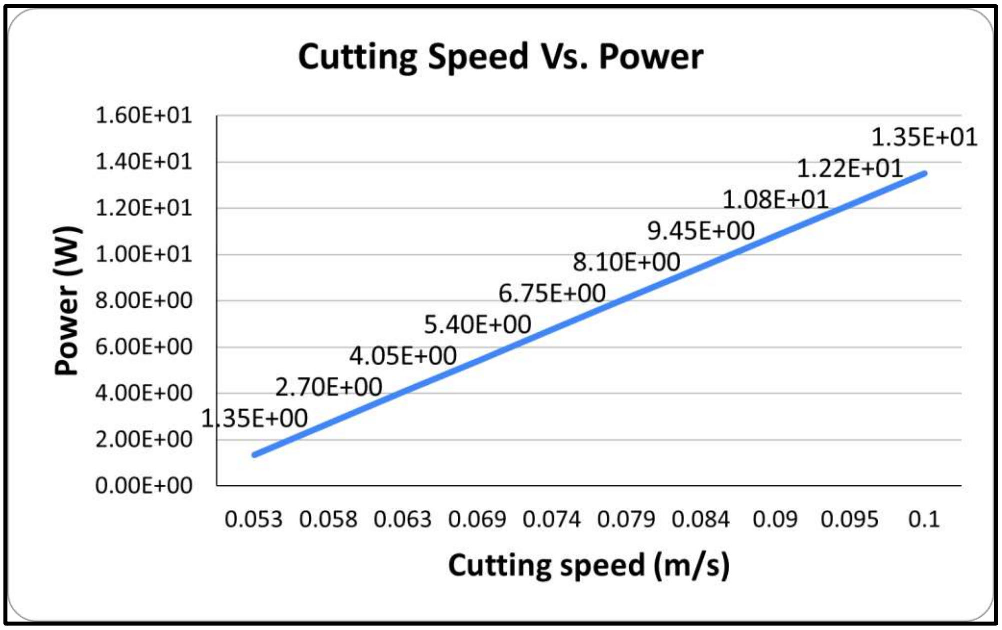

Figure 4-4 Cutting Speed vs. Power

This graph shows the relationship between Cutting speed and Power. And it was observed that as Cutting Speed increases, Power also increases. This is because,

Cutting speed directly affects the material removal rate, which is the volume of material removed per unit of time. As cutting speed increases, the tool engages with the workpiece more frequently, resulting in more material being removed in a given time.

To remove a larger volume of material in a shorter time, the cutting tool needs to expend more energy. This energy is used to overcome the resistance of the material, produce the required chip formation, and perform other cutting-related tasks.

Increase in cutting speed, increases Material removal rate and increases energy, so, the Power also increases.

4.2.2.3. Table Feed Vs. Temperature Rise

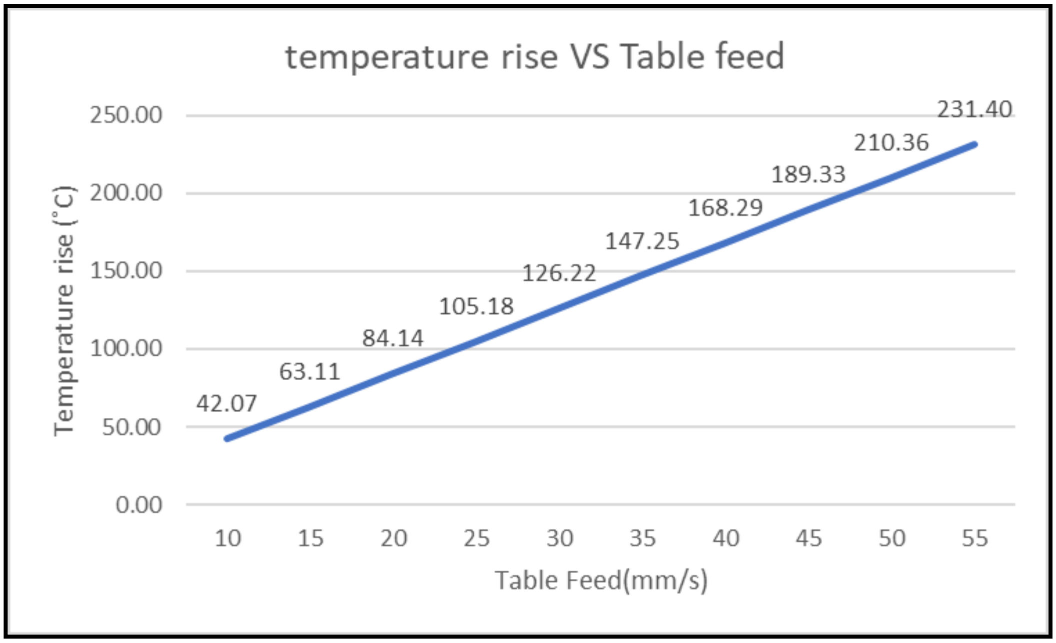

Figure 4-5 Table Feed vs. Temperature Rise

This graph shows the relationship between Temperature Rise and Table feed. And it was observed that as Table Feed increases, Temperature Rise also increases. This is because of the increased friction and heat generation at higher feed rates.

As the table feed rate increases, the tool engages with the workpiece more frequently and for shorter durations. This frequent contact, combined with the relative movement between the tool and the workpiece, generates friction. Friction between the tool's cutting edge and the workpiece generates heat.

At higher feed rates, the chip formation process changes. The chips produced might be smaller and more fragmented. This can lead to increased contact between the tool and the workpiece, contributing to higher friction and heat generation.

So, increase in table feed increases friction and size of chip become small as a result of which heating of contacting surface take place and temperature will rise.

4.2.2.4. Helix Angle Vs. Pitch

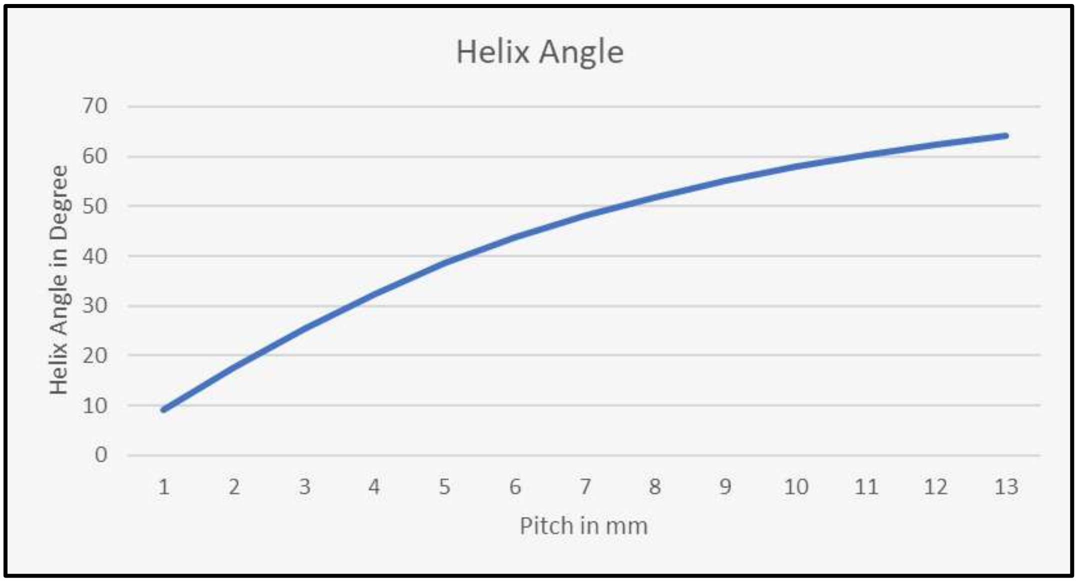

Figure 4-6 Helix Angle Vs. Pitch

This graph shows the relationship between Helix angle and pitch of the lead screw.

The helix angle refers to the angle formed between the helix (spiral) of the threads on the lead screw and the axis of the screw itself. It indicates the steepness of the thread spiral. A smaller helix angle results in a more gradual incline of the threads, while a larger helix angle corresponds to a steeper incline.

On the other hand, the pitch of a lead screw is the distance traveled axially by one complete rotation of the screw. It's the measurement from one thread crest to the next in the axial direction

4.2.2.5. Pitch Vs. Efficiency

Figure 4-7 Efficiency vs. Pitch

This graph shows the relationship between Efficiency and pitch. And as pitch increases, efficiency of the lead screw also increases. This is primarily due to reduced friction and increase in mechanical advantage.

A higher pitch leads to fewer thread turns over the same axial distance compared to a lead screw with a lower pitch. This results in reduced contact between the screw threads and the nut, which in turn reduces frictional losses. With less friction, a greater percentage of the input torque is translated into useful axial movement of the load, improving overall efficiency.

The mechanical advantage of a lead screw-nut system is the ratio of the distance traveled axially (linear movement) to the angular rotation of the lead screw. A larger pitch effectively increases this mechanical advantage, meaning that for the same input torque, the load can be moved a greater distance. This results in better utilization of the input torque and improved efficiency.

4.2.2.6. Required Torque Vs. Pitch

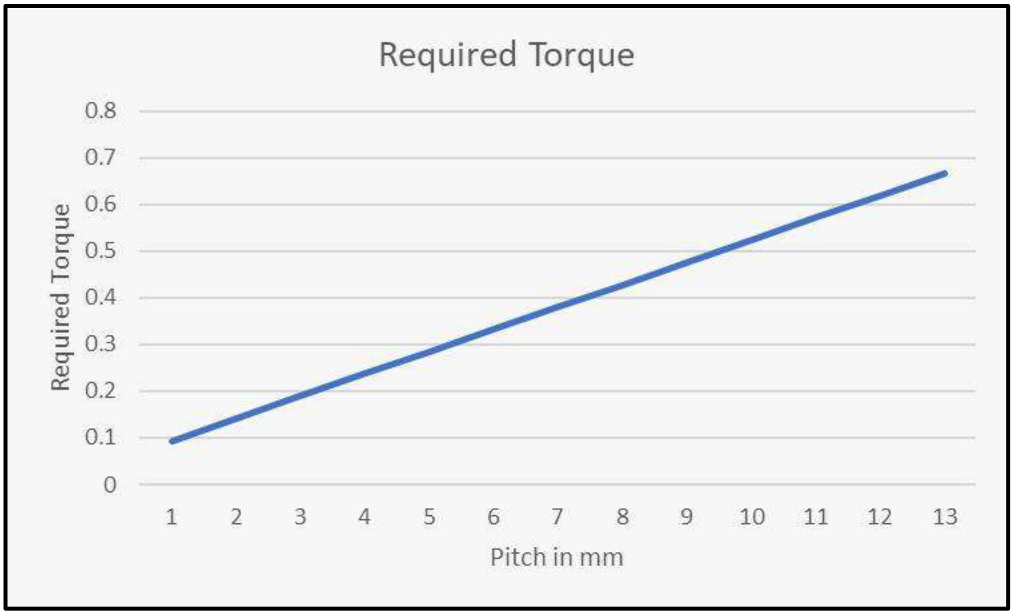

Figure 4-8 Torque Vs. Pitch

This graph shows the relationship between Pitch and the required torque. Torque increases as pitch in a lead screw increases due to the mechanical advantage gained from the larger pitch.

A larger pitch provides a mechanical advantage, allowing the same axial force to generate a higher torque.

4.2.2.7. Number of Start Vs. Efficiency

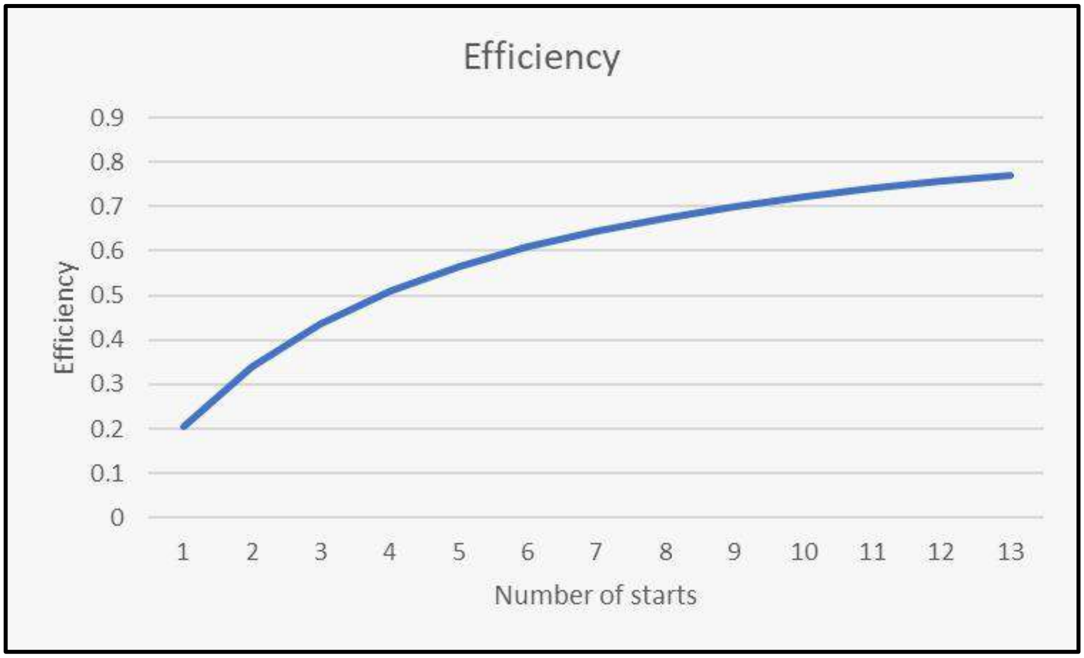

Figure 4-9 Number of Start (multi-start lead screw) vs. Efficiency

This graph shows the relationship between the efficiency and number of starts. The efficiency of a lead screw can increase with an increase in the number of starts due to reduced friction and improved mechanical advantage.

A lead screw with multiple starts has threads that are spaced closer together along its length. This results in more points of contact between the screw and the nut, distributing the load across a greater number of thread surfaces. With reduced pressure on each contact point, frictional losses are typically lower. As a result, more of the input torque is effectively translated into axial movement of the load, leading to improved efficiency.

For a given pitch, increasing the number of starts effectively multiplies the mechanical advantage. This means that the same input torque generates a greater axial movement of the load, improving the efficiency of force transmission.

4.2.3. Motion Analysis Result

For Validation of Results, Motion analysis was conducted in SolidWorks for validation our dynamic analysis so a speed of 10mm/sec and angular acceleration of 450 degree/sec^2 was set as per input in calculation and the results are as follows:

4.2.3.1. Angular Velocity Vs. Time

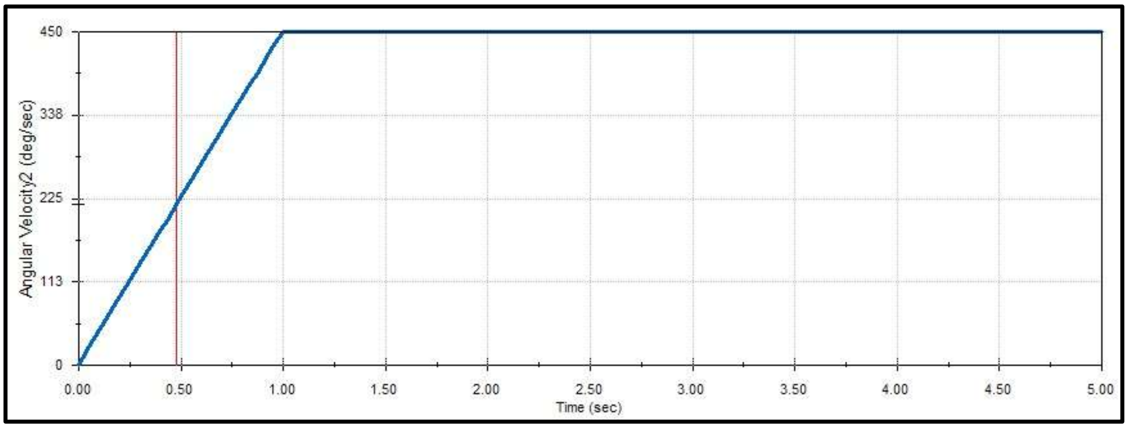

Figure 4-10 Graph of Angular Velocity Vs. Time

This graph shows the relationship between Angular velocity and Time. The velocity increases from 0 to 450 degrees/sec. for the increase in time from 0 to 1 second. And then it goes constant at 450 degrees/sec.

4.2.3.2. Linear Velocity Vs. Time

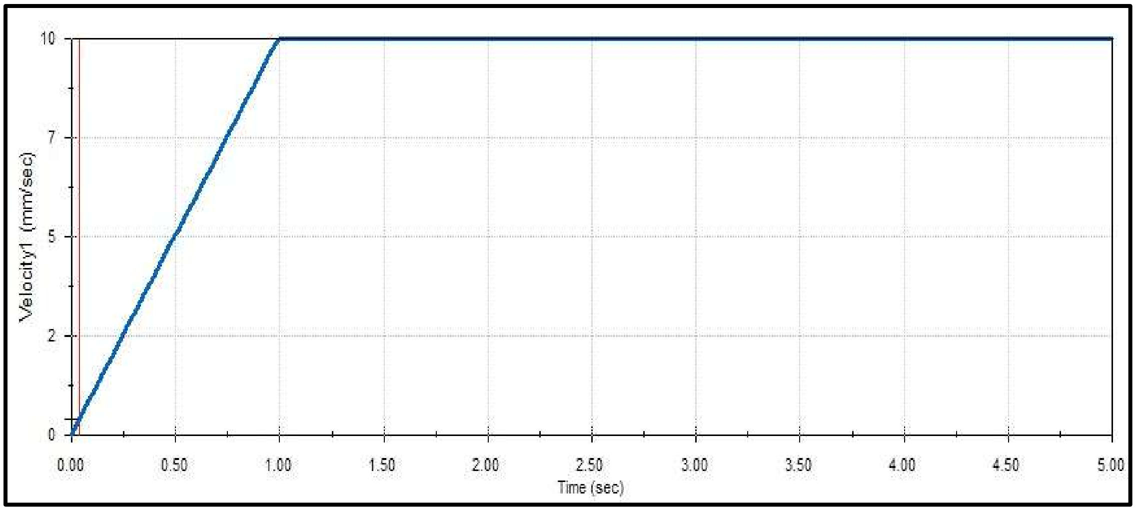

Figure 4-11 Graph of Linear Velocity Vs. Time

This graph shows the relationship between Linear velocity and Time. The velocity increases from 0 to 10 mm/sec. for the increase in time from 0 to 1 second. And then it goes constant at 10mm/sec.

4.2.3.3. Linear Acceleration Vs. Time

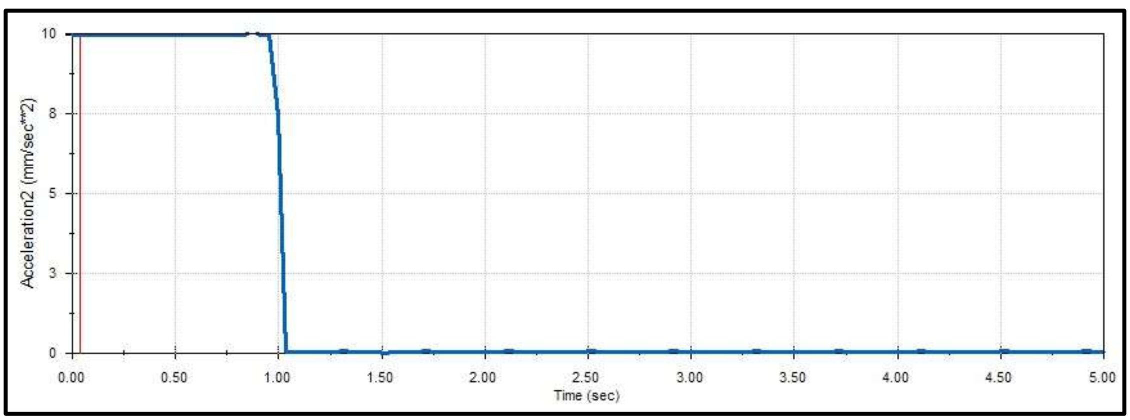

Figure 4-12 Graph of Linear Acceleration Vs. Time

This graph shows the relationship between Linear Acceleration and Time. The acceleration is 10 mm/sec^2. for the increase in time from 0 to 0.9 second. And then it goes decreasing to zero at 1.1 sec. And goes constant at zero mm/sec^2.

4.2.3.4. Motor Torque Vs. Time

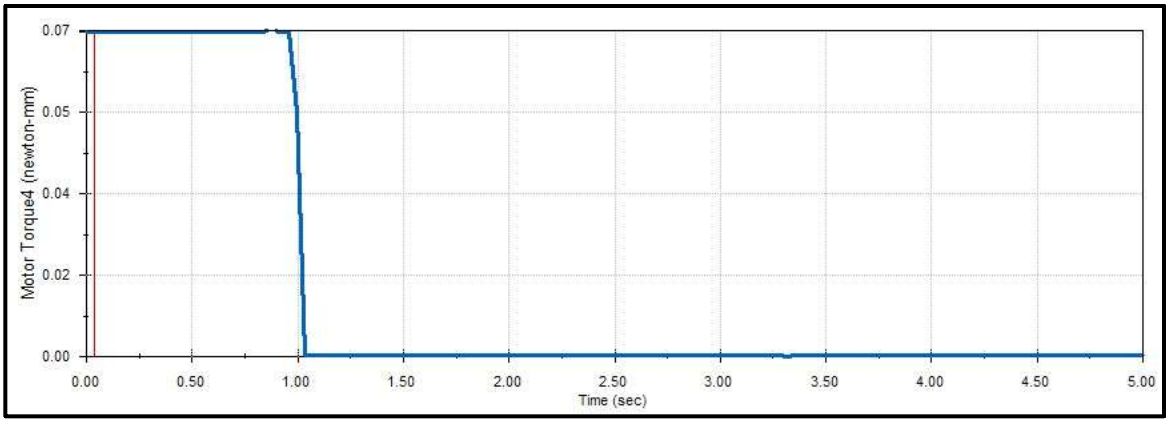

Figure 4-13 Graph of Motor Torque Vs. Time

This graph shows the relationship between Motor Torque and Time. The Torque is 0.07 N.mm. for the increase in time from 0 to 0.9 second. And then it goes decreasing to zero at 1.1 sec. And goes constant at zero N.mm.

Calculated Torque: 0.067 N.mm

Motion Analysis Torque: 0.07 N.mm

$$\%Error = \frac{0.07 - 0.067}{0.07} * 100 = 4.3\%$$

According to the findings of the motion analysis, a marginal discrepancy of 4.3% exists between the computed and simulated outcomes. This disparity, while within tolerable limits for the intended objective, could potentially be attributed to the friction assessment conducted through software. In the calculation, the friction factor was predicated on an ideal scenario involving brass and stainless-steel interactions.

4.2.4. Simulations Related to Project

4.2.4.1. Material and Geometry

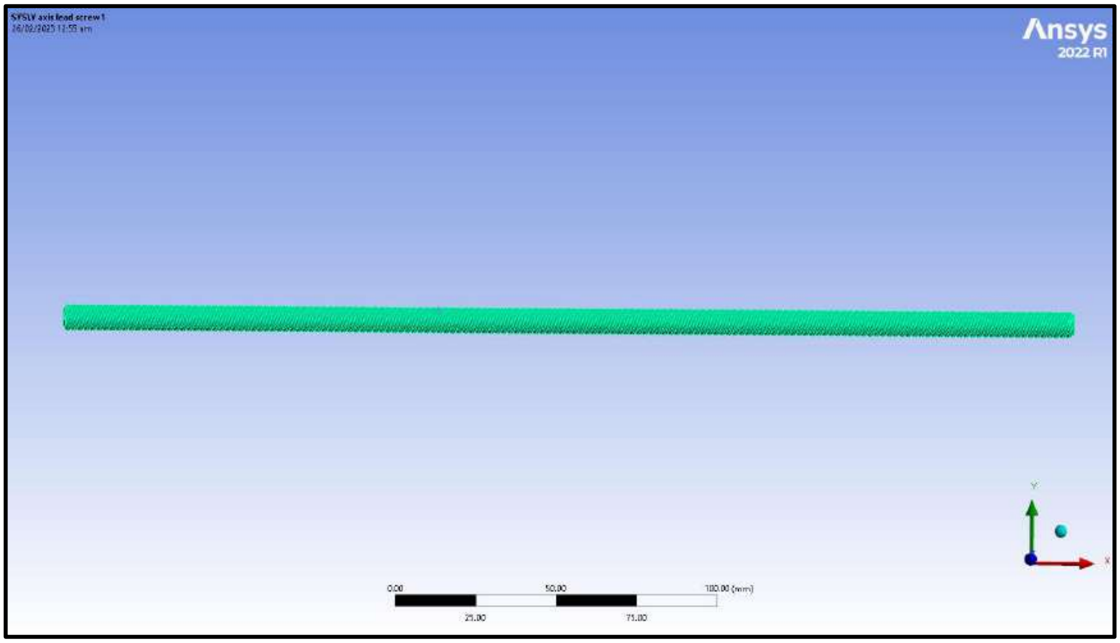

Figure 4-14 Assigning Material (Stainless Steel) to the lead screw Geometry

4.2.4.2. Applying Load on Lead Screw

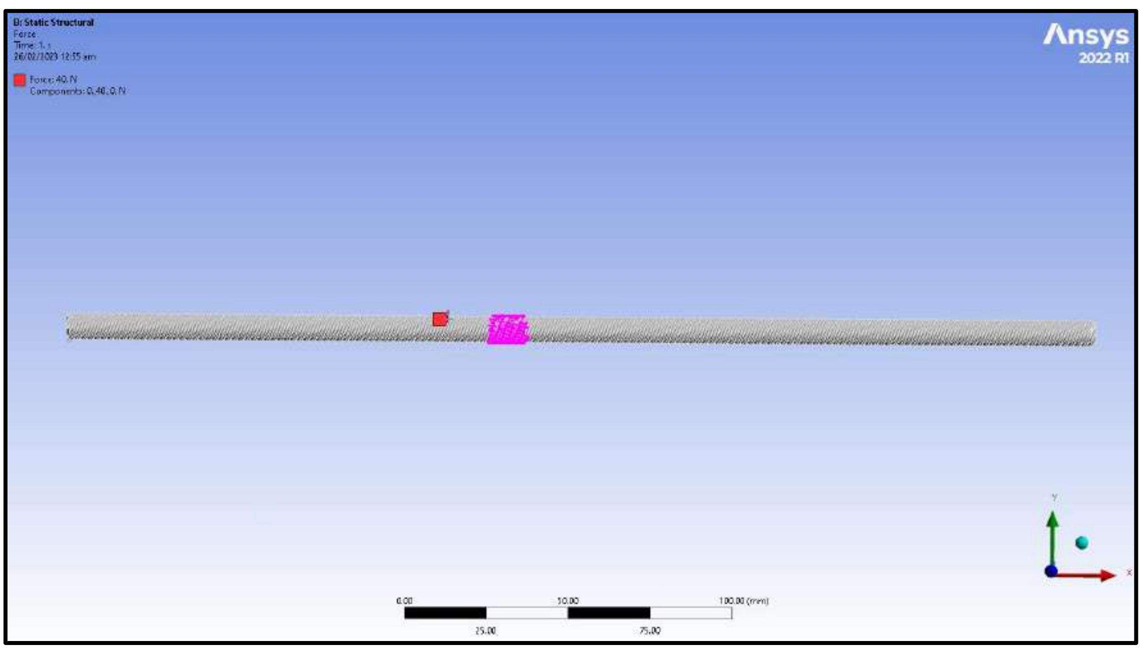

Figure 4-15 Applying load of 40 N on the center of screw

4.2.4.3. Angular Acceleration

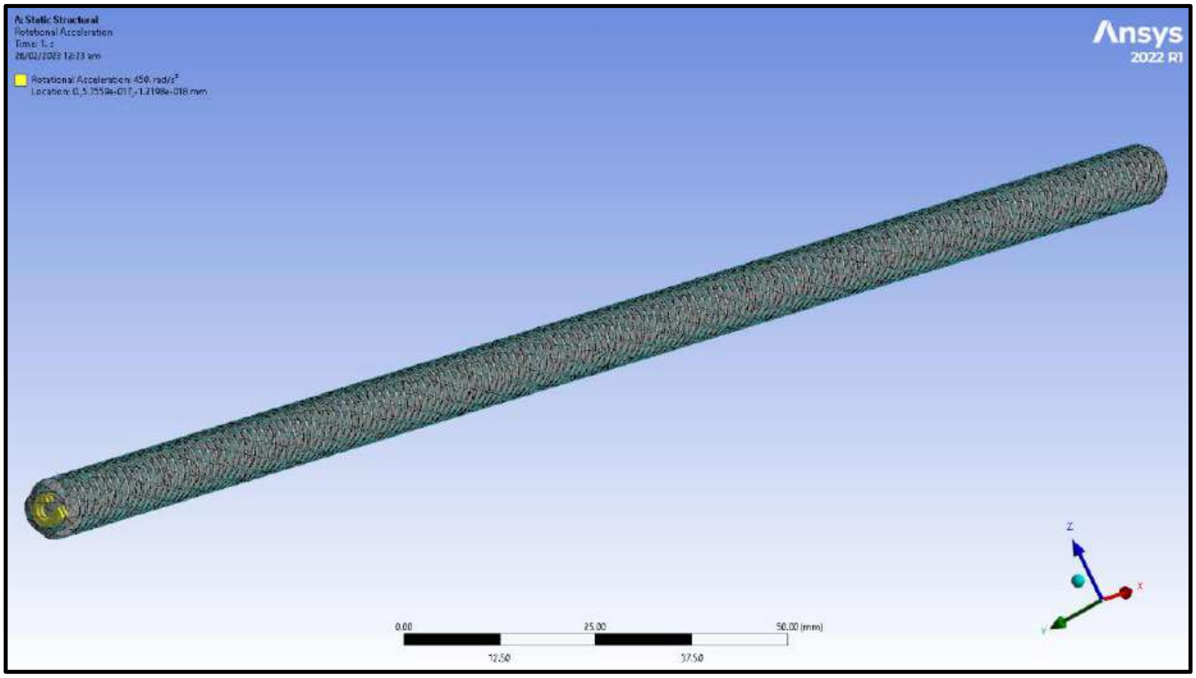

Figure 4-16 Applying Angular Acceleration

Setting Angular Acceleration to 450 degree per second squared.

Meshing

Part name	Total Number of Elements	Total number of Nodes	Length Of Lead Screw
Lead screw Y-axis	35366	65705	360 mm

4.2.4.4. Deformation

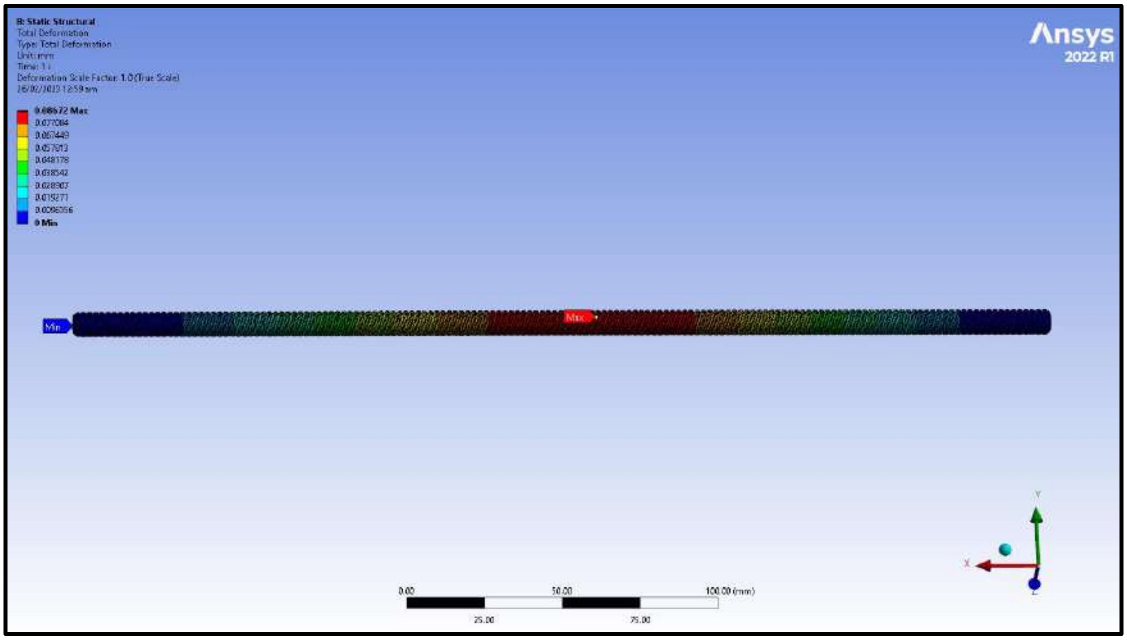

Figure 4-17 Deformation

The simulation involved subjecting the table to an all-encompassing load, neglecting the support elements. The outcome, depicted in Figure 5-1, showcases the maximum deformation transpiring at the central point of the Lead Screw. This deformation is quantified at **0.08672mm** . Importantly, when contextualized within the load-bearing framework, this deformation aligns within the elastic deformation range as delineated by the stress-strain graph of Stainless Steel. Thus, it can be deduced that the structure **remains within a safe operational regime**.

4.2.4.5. Shear Stress

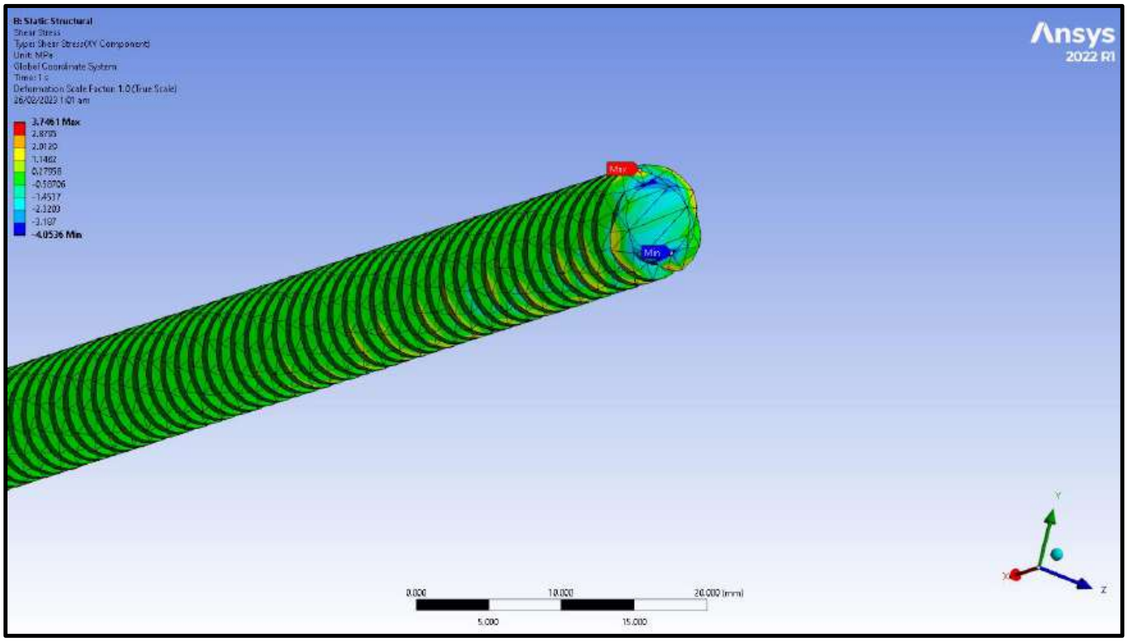

Figure 4-18 Shear Stress

Upon the application of the load and the initiation of Lead Screw rotation, the point of highest shear stress is localized at the outermost section of the screw's teeth. This stress magnitude, as evident in the illustrated findings of Figure 5-2, registers at **3.7461 MPa**. It's noteworthy that this stress value remains well below the shear strength threshold of the stainless steel material, which stands at **515 MPa. The simulation outcomes affirm that the structure is operating within a secure margin.**

4.2.4.6. Equivalent Stress

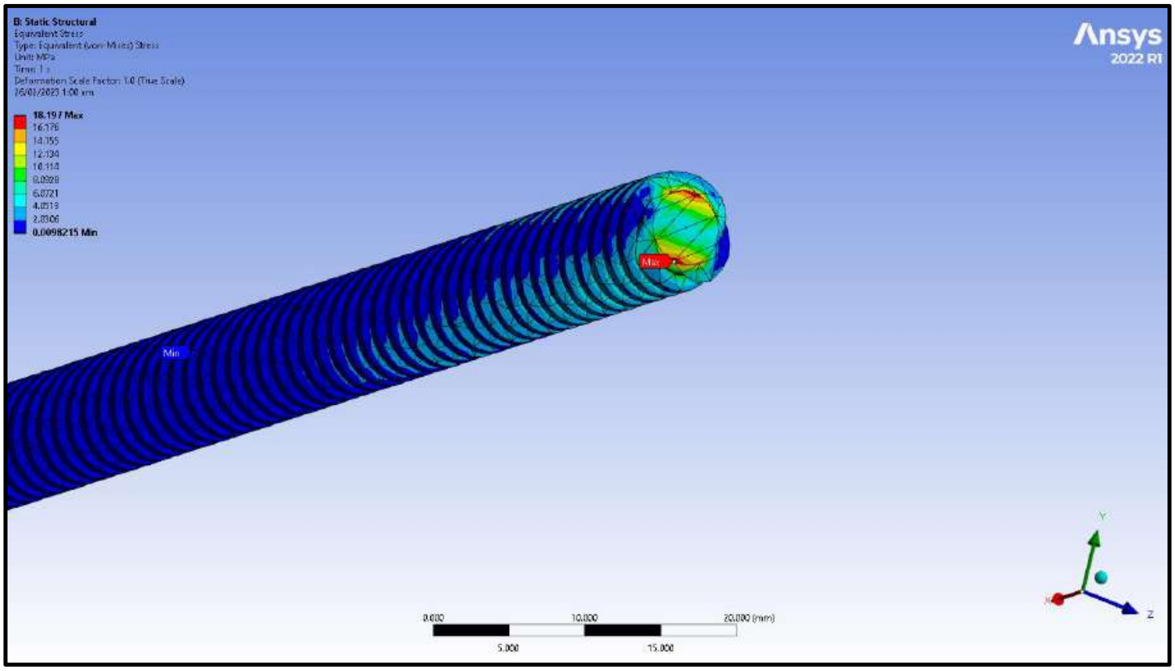

Figure 4-19 Equivalent Stress

In the scenario involving the application of a load and the activation of the motor to rotate the Lead screw, a unique circumstance arises due to the table being adhered to the end of the Lead screw. This leads to a resisting force that opposes the screw's rotation. Under these conditions, an equivalent stress of **18.197 MPa** emerges at the termination point of the Lead screw. It's pertinent to note that this stress magnitude remains significantly lower than the material's Yield Point, which stands at **300 MPa** for Stainless Steel. **As such, the derived result resides comfortably within a range of safety, affirming the stability of the setup.**

4.2.4.7. Shear Stress when load is applied on center of lead screw

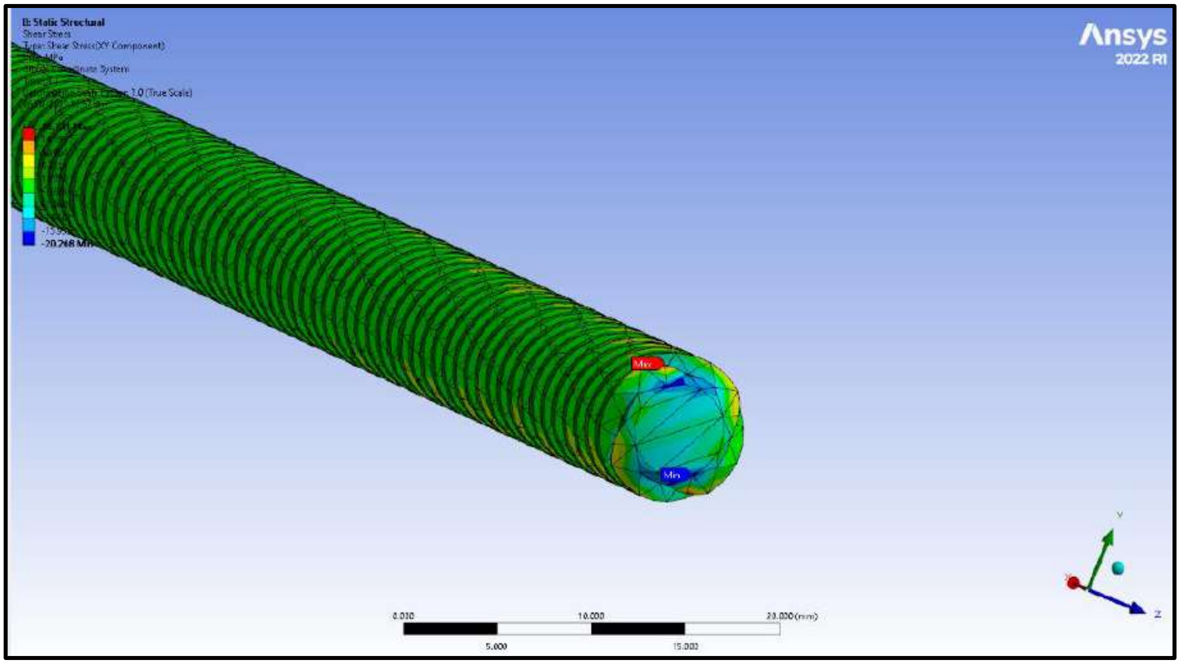

Figure 4-20 Shear Stress when the load (40 N) is applied

Consider a scenario where a load is imposed at the midpoint of the Lead screw, and concurrent with this, the Motor endeavors to induce rotation in the Lead screw, characterized by a consistent angular acceleration of 450 degrees per second squared. However, due to the presence of an obstruction, the Lead screw remains motionless. In this context, the point of highest shear stress manifests at the outermost surface layer of the screw's teeth, yielding a magnitude of **18.731 MPa**. Notably, this stress level stands well beneath the shear strength threshold of the stainless steel material, which is quantified at **515 MPa**. **Hence, the outcomes affirm that the system operates within a secure envelope of safety.**

4.2.4.8. Simulation of Load Distribution of Along Support and nut holder

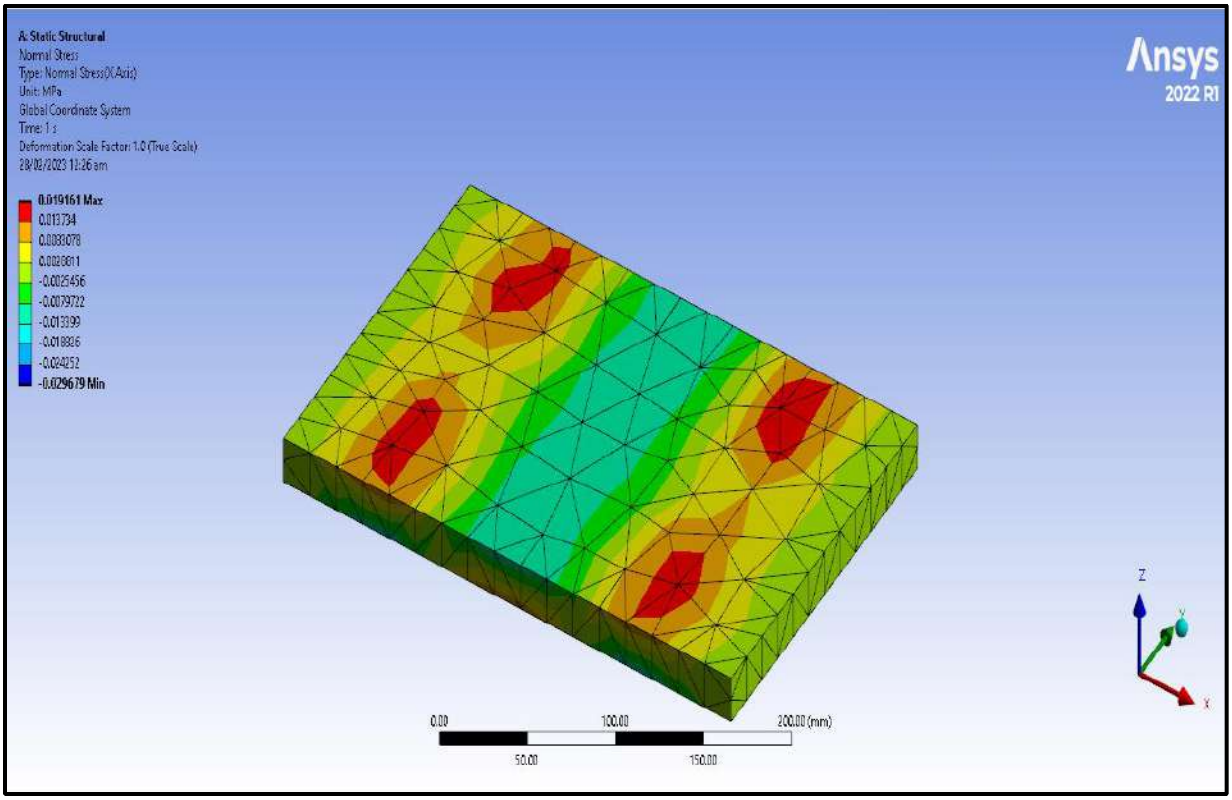

Figure 4-21 Load Distribution On Supports and Lead Screw Nut

In the provided Figure 5-8, the illustration delineates the dispersion of the load across the support structures and the holder of the Lead screw nut. This portrayal offers insight into the manner in which the load is apportioned within the system. Subsequently, Figure 5-9 provides a visual representation of the load specifically applied to the Lead screw nut holder, a load that is designed to be transmitted via the Lead screw. Notably, the highest magnitude of this load is measured at **4.6 Newtons**.

4.2.4.9. Nut Holder for Lead screw

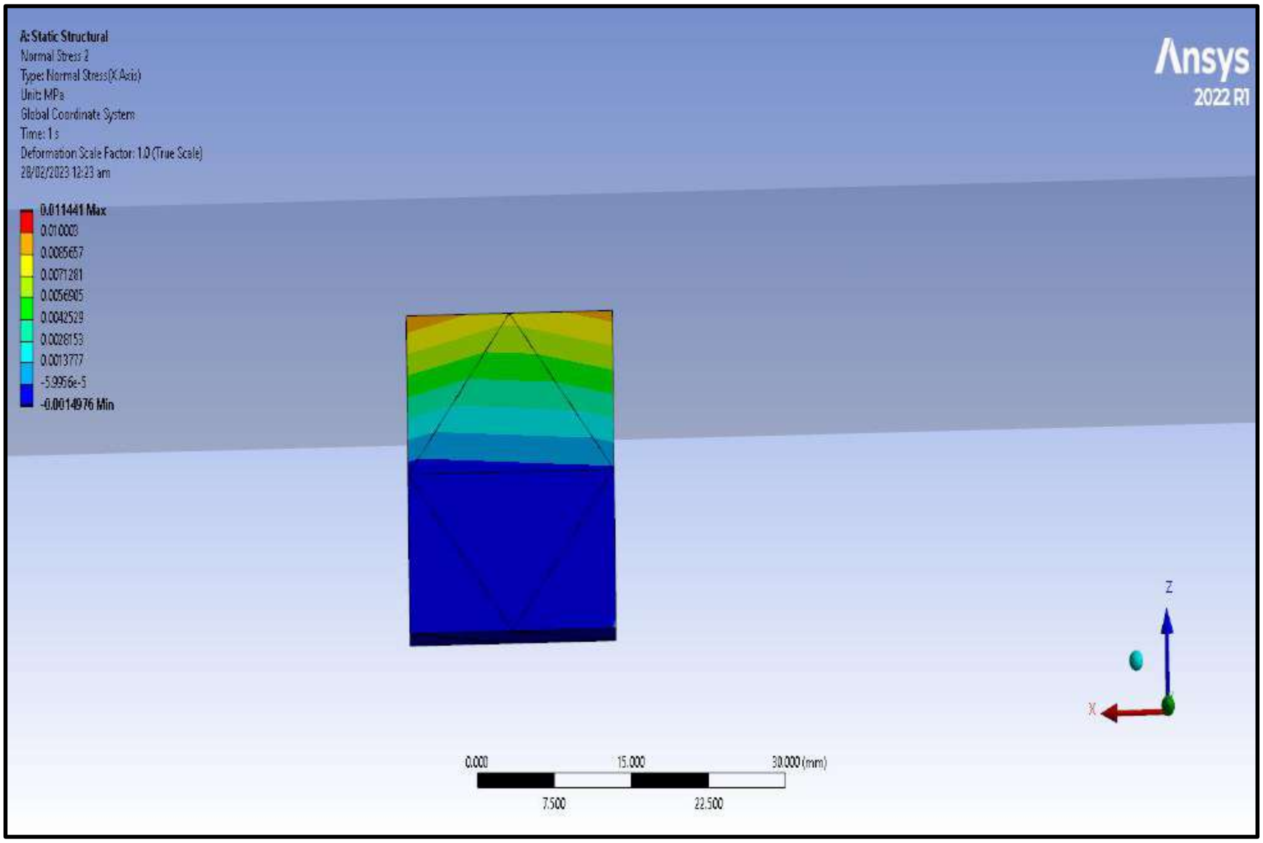

Figure 4-22 Load On Lead Screw Nut Holder

This figure shows the illustration of distributed Force per unit Area along the nut holder for lead screw. The highest magnitude is 0.0085657 MPa.

4.2.5. Fabrication of Machine

4.2.5.1. Steps Involved in Fabrication

5. Gathering all the necessary mechanical components, including raw materials, fasteners (nuts, bolts, screws), brackets, bearings, gears, motors, and any specialized parts.
6. Inspection of the components for defects, ensuring they meet quality standards.
7. Beginning the assembly of the components according to the design plan.
8. Start with the base structure and progressively add components layer by layer.
9. Use of appropriate fasteners, such as screws, nuts, and bolts, to secure components together.
10. Verification of the alignment of moving parts and ensure that they move smoothly without interference.
11. Calibration of moving parts like linear guides, bearings, and gears to ensure proper motion and minimize friction.
12. Testing of the assembled components for functionality, alignment, and overall performance.
13. Checking for any manufacturing defects, misalignments, or improper fits.
14. Use of measuring tools and instruments to verify critical dimensions.
15. Conduct a final inspection to ensure all components are correctly assembled, aligned, and properly fastened.
16. Testing and Validation of Working of Machine.

4.2.5.2. Images of Fabrication of Machine

Figure 4-23 Universal 2020 Aluminum Profile for Frame

Figure 4-24 Aluminum Frame with Nut, Screws and Washers

Figure 4-25 Engraving Tool (30 degree, 3.75mm holding diameter, o.1mm tip diameter)

Figure 4-26 Drilling Tools of 0.2mm to 1.2mm diameter

Figure 4-27 Lead Screw

Figure 4-28 Linear Guide, Bearings and Holders

Figure 4-29 Front View of Assembly of Frame

Figure 4-30 Side View of Frame Assembly

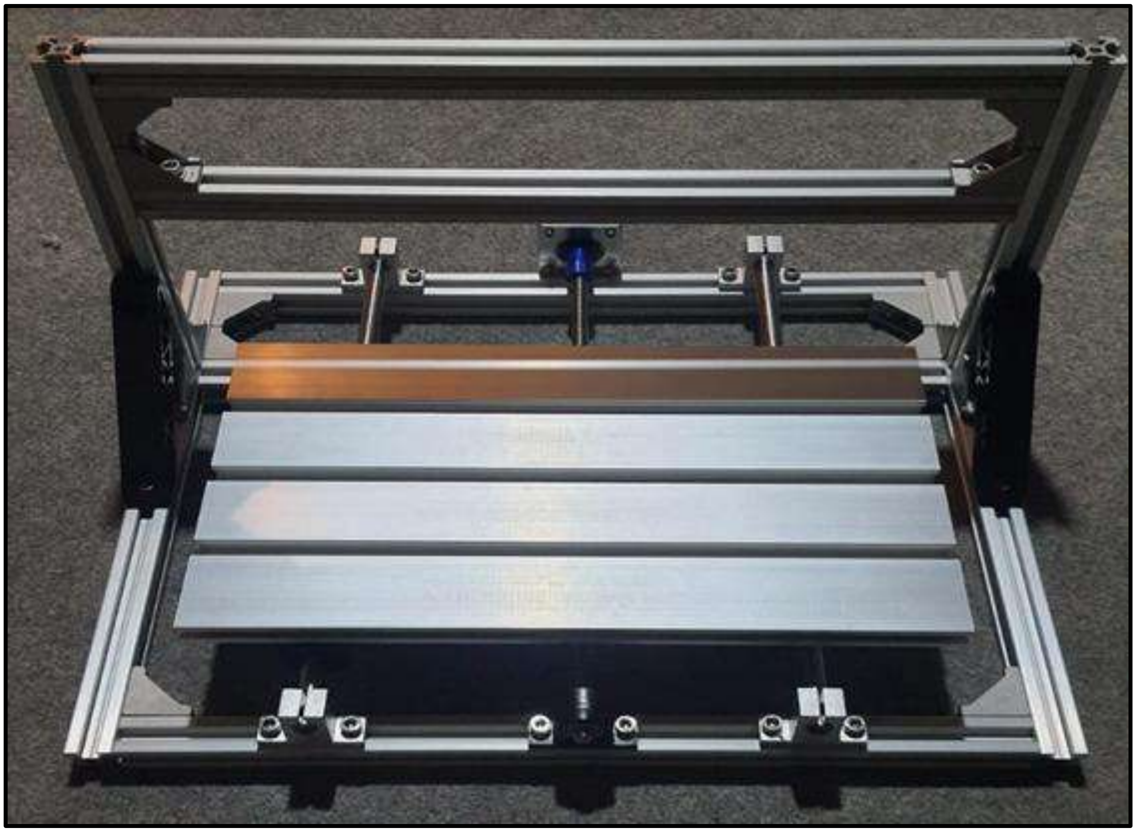

Figure 4-31 Assembly of Machine Frame, motors and bed

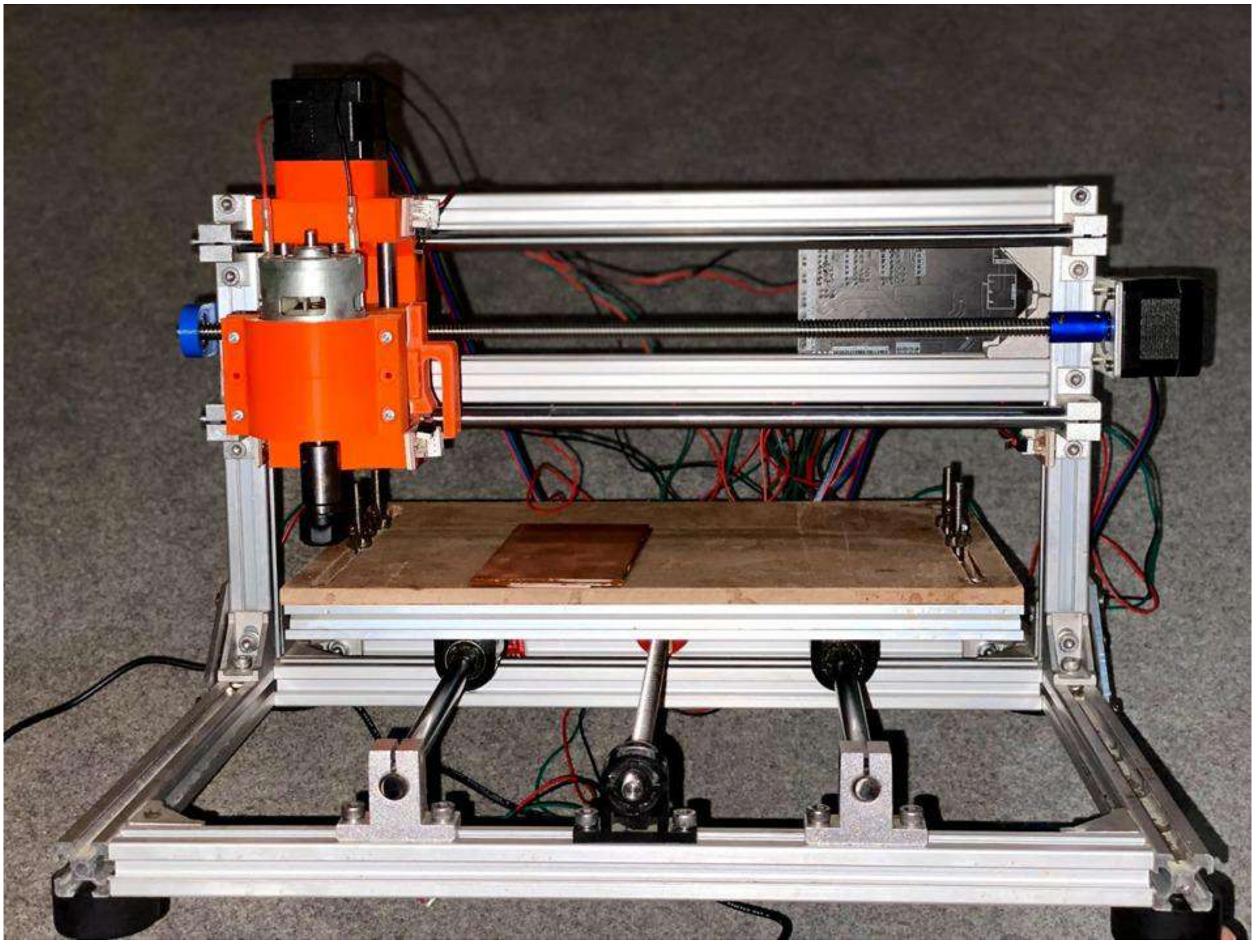

Figure 4-32 Assembly of Machine's frame, bed and spindle

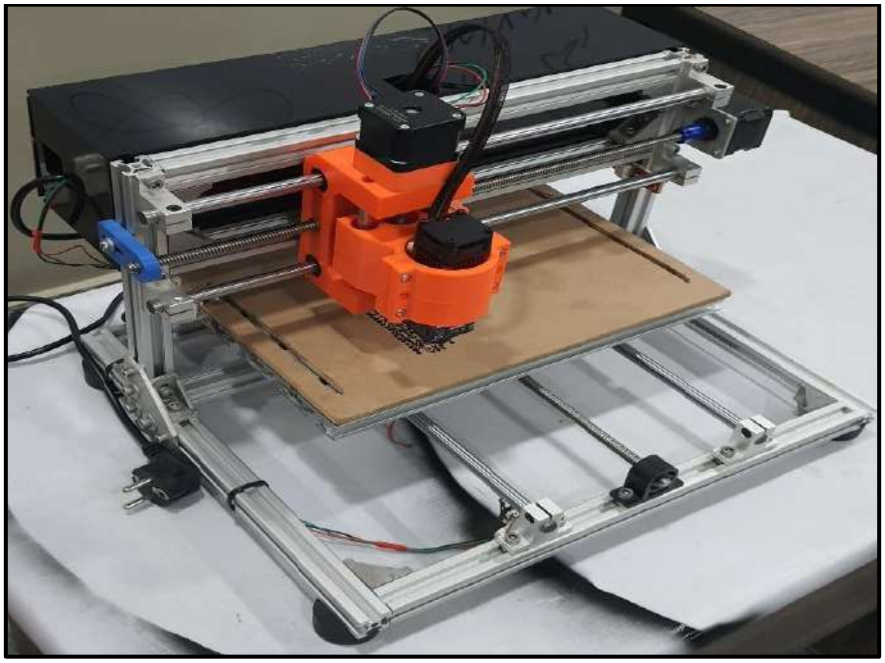

Figure 4-33 Fully fabricated Machine

Figure 4-34 Fully fabricated Covered Machine(due to protection from reflected radiation of laser)

4.2.6. Fabricated Designs of PCBs

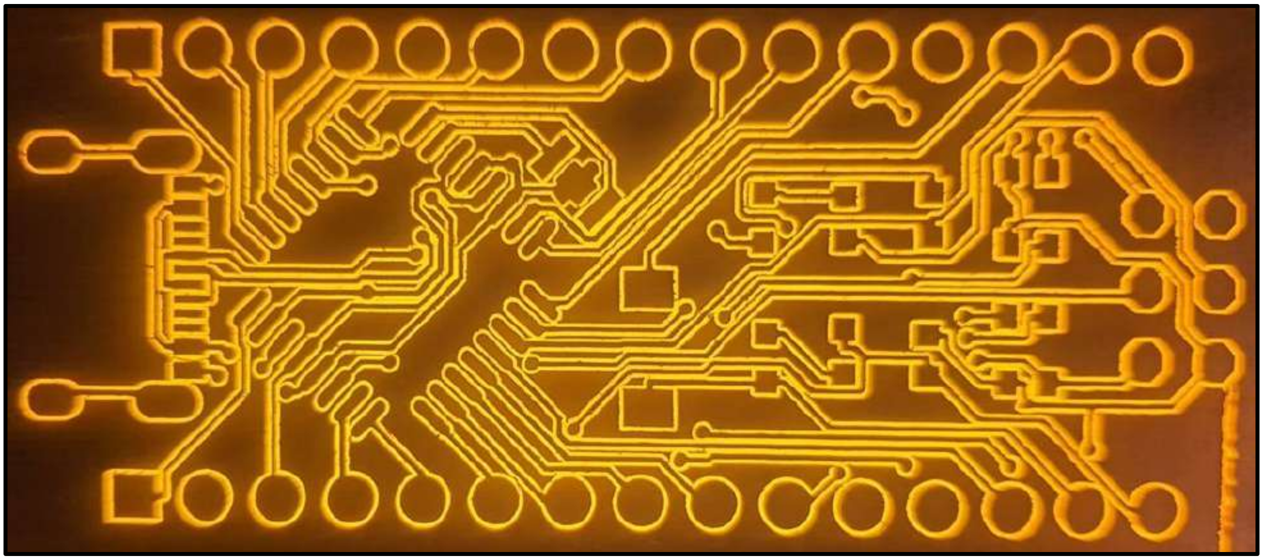

Figure 4-35 Arduino Nano Board is Designed through CNC Milling Machine

Chapter 5

5. IMPROVEMENT IN PROJECT

5.1. Laser Engraving

One outclasses improvement made in the project of CNC milling for PCB fabrication is the introduction of laser engraving as a cutting-edge enhancement. This innovative technique replaces traditional milling methods by utilizing a high-precision laser beam to remove material and create intricate patterns on the PCB surface.

By incorporating laser engraving into the process, several benefits are achieved:

Firstly, the laser engraving technique enables greater accuracy and precision, resulting in finer details and intricate designs on the PCB.

Secondly, it significantly reduces the production time as the laser beam operates at a faster speed compared to traditional milling tools. This improvement enhances overall efficiency and productivity in the PCB fabrication process.

Additionally, laser engraving reduces the risk of mechanical wear and tear, thus prolonging the lifespan of the equipment and reducing maintenance costs.

Furthermore, it allows for a wider range of materials to be processed, including more delicate substrates, thus expanding the possibilities for PCB design. The implementation of laser engraving in CNC milling represents a significant advancement in the project, leading to enhanced quality, efficiency, and versatility in PCB fabrication.

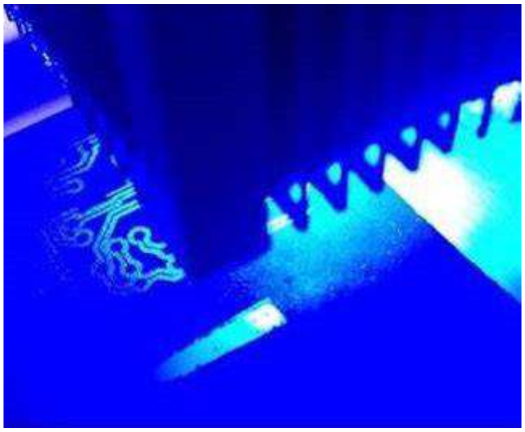

Figure 5-1 Laser Engraving for PCB fabrication

5.2. Calculations for Laser Engraving

5.2.1. Mass of Removed

$$m = Volume\ of\ material\ removed\ \times \rho_{workpiece}$$

Equation 5.5.1

m = Mass of Removed Material (kg)

The total weight of material that is removed from the workpiece during the laser engraving process.

V= Volume of Removed Material (m^3)

The total amount of space occupied by the material that is removed from the workpiece during laser engraving.

$\rho_{workpiece}$ = Density of Workpiece (m^3)

The mass of the workpiece per unit volume.

5.2.2. Energy

$$E = \frac{m\ \times Specific\ Energy\ of\ Evaporation}{Efficiency}$$

Equation 5.5.2

Specific Energy of Evaporation (J/m^3)

The amount of energy required to evaporate a unit volume of material during laser engraving.

Efficiency (%)

The ratio of energy used for material removal to the total energy delivered by the laser system.

5.2.3. Reflectivity

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$$

Equation 5.5.3

R = Reflectivity

The ability of the workpiece material to reflect laser energy.

n = Refractive Index

It represents how much the material bends or refracts light compared to air.

k = Extinction Coefficient

A measure of how strongly a material absorbs laser energy as it passes through.

Absorption Coefficient (m^{-1})

A value representing the fraction of incident laser energy absorbed by the material.

5.2.4. Power

$$P = \frac{Energy}{Time}$$

Equation 5.5.4

Time (sec)

The duration for which the laser is applied to the workpiece during the engraving process.

5.2.5. Time

$$Time = \frac{Volume\ of\ Material\ Removed}{Material\ Removal\ Rate}$$

Equation 5.5.5)

5.2.6. Power of Beam

$$P_{beam} = \frac{Power}{1 - R}$$

Equation 5.5.6

Power of Beam (W)

The rate at which the laser beam delivers energy to the workpiece.

5.2.7. Mass Removal Rate

$$Mass\ Removal\ Rate\ =\ Density\ of\ Copper\ x\ MRR$$

Equation 5.5.7

Mass Removal Rate (kg/sec)

The rate at which material is removed from the workpiece during laser engraving.

Summarization of Results

Input Parameters for Engraving

Table 5-1 Input Parameters for Laser Engraving

w (Width of cut)	w = 0.0003 m
D_e (Depth of cut)	D_e = 0.0001 m
v_f (Table Feed)	v_f = 0.01 m/s
V (Volume of Material Removed)	V = 1.25x10^{-13} m^3
ρ_{copper} (Density of Copper)	8960 kg/m^3
Molar Mass of Copper	63.5 g/mole
Efficiency of Laser	25%
Specific Energy of Evaporation	300.3 kJ/kg
Refractive Index for Copper and Diode Laser of 450 nm wavelength	1.2429

Extinction Coefficient for Copper and Diode Laser of 450 nm wavelength	2.3704
Absorption Coefficient at 450 mm	2.4

Calculations

a) $Q = D_{ap} \times D_e \times v_f$

$$\mathbf{Q = 3 \times 10^{-10} \frac{m^3}{sec}}.$$

b) $m = Volume\ of\ material\ removed \times \rho_{workpiece}$

m = 1.12x10^{-9} kg

c) $E = \frac{m \times Specific\ Energy\ of\ Evaporation}{Efficiency}$

E = 1.32x10^{-6} kJ

d) $R = \frac{(n-1)^2+k^2}{(n+1)^2+k^2}$

R = 0.53

e) $Time = \frac{Volume\ of\ Material\ Removed}{Material\ Removal\ Rate}$

Time = 1.5x10^{-6} sec

f) $P = \frac{Energy}{Time}$

P = 880 W

g) $P_{beam} = \frac{Power}{1-R}$

P_{beam} = 1870 W

h) Mass Removal Rate = Density of Copper x MRR

Mass Removal Rate = 2.7x10^{-6} kg/sec

Output Parameters

Table 5-2 Output Parameters for Laser Engraving

Material Removal Rate	$3x10^{-10}$ m^3/sec
mass of material removed	$1.12x10^{-9}$ kg
Energy	1.32x10-6 kJ
Reflectivity	0.53
Time	1.5x10-6 sec
Power	880 W
Power of Beam	1870 W
Mass Removal Rate	$2.7x10^{-6}$ kg/sec

5.3. PCB Design Fabricated using Laser Engraving

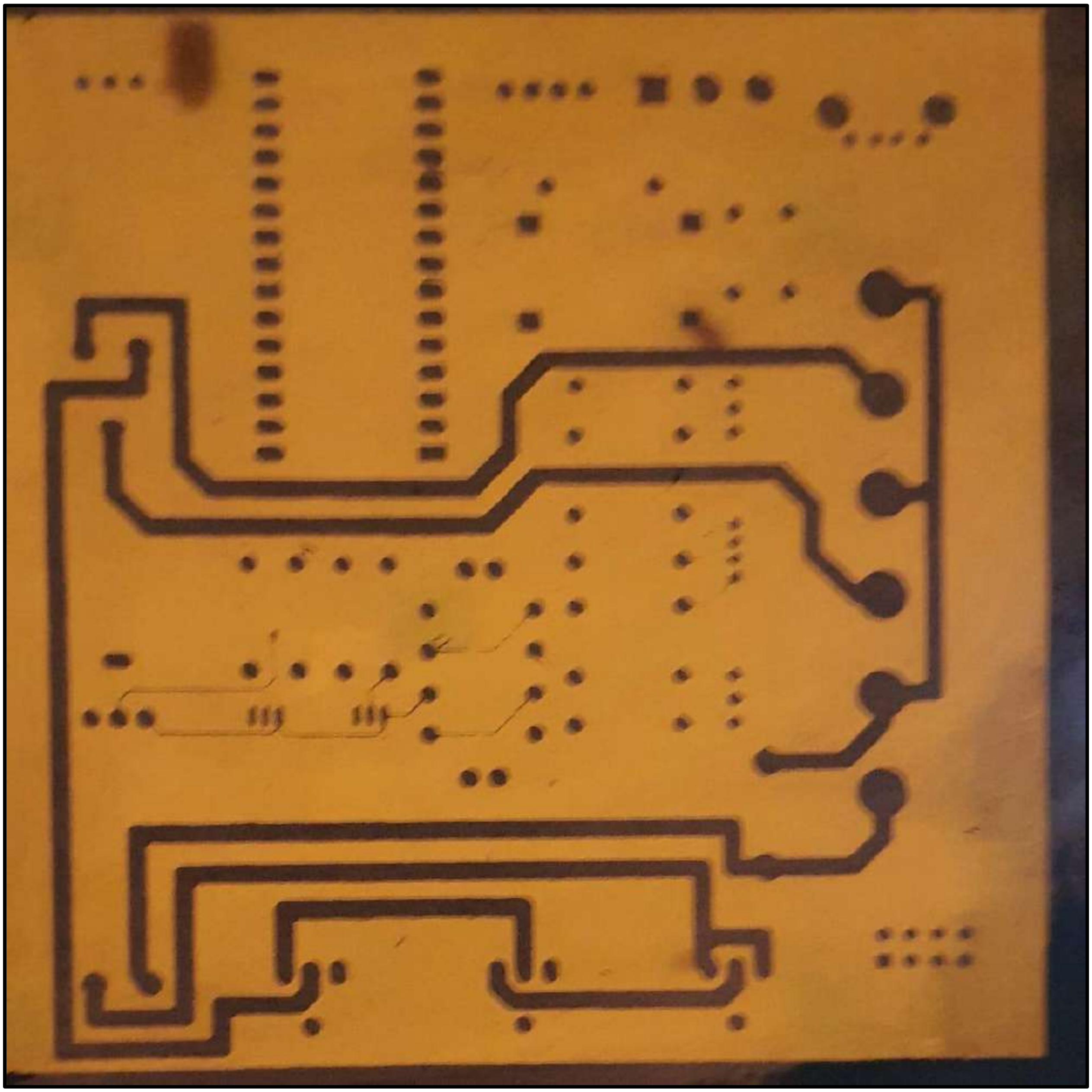

Figure 5-2 Design Fabricated by Laser Engraving

Chapter 6

6. CONCLUSION AND FUTURE RECOMMENDATION

6.1. Project Impact

6.1.1. Enhanced PCB Fabrication Efficiency

The development of a dedicated CNC milling machine for PCB fabrication can significantly improve the efficiency of the fabrication process. By automating the milling process, it reduces the reliance on manual labor and minimizes human errors. This can lead to faster turnaround times, increased production capacity, and improved overall productivity in PCB manufacturing.

6.1.2. Improved Accuracy and Precision

CNC milling machines offer high levels of accuracy and precision in creating PCB circuit patterns. The assigned project can contribute to the development of a highly precise milling machine specifically tailored for PCB fabrication. This can result in improved PCB quality, better alignment of circuit traces, and reduced risk of short circuits or faulty connections.

6.1.3. Cost Reduction

The use of a CNC milling machine for PCB fabrication can potentially reduce manufacturing costs. By automating the process, it eliminates the need for manual labor and streamlines the production workflow. This can lead to cost savings in terms of labor expenses and increased production efficiency, ultimately benefiting PCB manufacturers and end-users.

6.2. Future Recommendation

6.2.1. Scale-up and Commercialization

Explore the potential for scaling up the CNC milling machine design and commercializing it for wider adoption in the electronics industry. Collaborate with industry partners or entrepreneurs to assess the feasibility of production, market demand, and potential business models.

6.2.2. Continuous Improvement

Seek feedback from users and industry experts to identify areas for improvement in the CNC milling machine design. Incorporate user feedback, iterate on the design, and refine the machine's functionality, reliability, and user-friendliness.

6.2.3. Advanced Control and Automation

Investigate advanced control systems and automation technologies to further enhance the efficiency and precision of the CNC milling machine. This may include incorporating advanced sensing and feedback mechanisms, real-time monitoring and diagnostics, and adaptive control algorithms.

6.2.4. Education and Outreach

Promote the knowledge and awareness of sustainable PCB fabrication practices by organizing workshops, seminars, or educational programs. Share the project outcomes, best practices, and lessons learned with the academic and industry community, encouraging further research and adoption of sustainable manufacturing technologies.

6.3. Other Areas of Research

In addition to CNC milling, there are alternative methods for PCB fabrication that can be considered:

Additive manufacturing, also known as 3D printing, has gained attention as a potential technique for PCB fabrication. It involves building the circuit layers layer-by-layer using conductive ink or material deposition. This approach offers the advantage of rapid prototyping and the ability to create complex circuit geometries, including embedded components and flexible circuits. Additive manufacturing for PCBs typically utilizes inkjet printing or aerosol jet printing methods to deposit conductive inks onto the substrate. Research in this area focuses on developing specialized conductive inks with high conductivity, optimizing printing processes for improved resolution and accuracy, and integrating multiple materials and components within the 3D-printed PCB structure. Challenges include achieving high-resolution features, ensuring reliable electrical connections, and optimizing the mechanical and electrical properties of the printed circuits.

Hybrid methods combine multiple fabrication techniques to leverage their respective strengths and overcome limitations. For example, a hybrid approach may involve using traditional PCB manufacturing processes for the majority of the circuit board, while employing additive manufacturing techniques for specific features or components. This allows for a cost-effective and efficient fabrication process while taking advantage of the flexibility and customization offered by additive manufacturing.

Hybrid methods can also involve combining different processes such as laser etching and traditional subtractive methods to achieve desired circuit patterns and features. Research in this area explores the integration of various techniques, process optimization, and identifying the most suitable combination of processes for specific PCB designs and requirements. The aim is to maximize efficiency, reduce costs, and enhance the functionality and performance of the fabricated PCBs.

6.4. Conclusion

The final year design project of the "CNC Milling Machine for PCB Fabrication" has successfully addressed the challenges in traditional PCB manufacturing methods. The machine offers automated and precise milling of circuit patterns, leading to improved accuracy and reduced errors. It enhances fabrication efficiency, reduces costs, and improves overall PCB quality. The project's impact extends to the PCB manufacturing industry, where it streamlines production processes and increases productivity. Future recommendations include integrating advanced features, exploring material compatibility, and collaborating with industry professionals for further advancements in PCB fabrication technology. Overall, the project contributes to the ongoing progress in PCB fabrication, offering a reliable and efficient solution for PCB manufacturers.

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