DESIGN AND ANALYSIS OF MR FINISHING TOOL FOR NANO LEVEL FINISHING ON NON-FERROMAGNETIC WORKPIECE SURFACE

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE AWARD OF THE DEGREE
OF
MASTER OF TECHNOLOGY
IN
PRODUCTION ENGINEERING

Submitted by

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CANDIDATE'S DECLARATION

I, **Bipul Kumar**, 2K21/PRD/14 hereby declare that the major project dissertation titled "**DESIGN AND ANALYSIS OF MR FINISHING TOOL FOR NANO LEVEL FINISHING ON NON-FERROMAGNETIC WORKPIECE SURFACE"** submitted to the Department of MECHANICAL ENGINEERING, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the **Master of Technology**, in Production Engineering was original and not copied from any source without proper citation. This was further to declare that the work embodied in this report has not formed the basis for the award of any degree, diploma, fellowship or other similar title or recognition.

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ABSTRACT

The magnetorheological (MR) finishing process is an innovative technique used for precision polishing of various materials. The present work is aimed to design and analyze the MRF process using ANSYS Maxwell simulation software and STAT-EASE360 software. The MRF process involves the controlled application of magnetorheological fluid (MRF) to a workpiece, which responds to change its properties in an applied magnetic field and produces a polishing effect.

The design phase encompasses the modeling of MR Finishing tool in ANSYS Maxwell software and development of model in STAT-EASE360 software. The simulation are run for different combination of bush height and number of turns obtained by STAT-EASE360 software. The maximum magnetic flux density of 1.941 Tesla was observed at bush height of 5 mm and number of turns 2000.

Then a crucial analysis has been performed for magnetic flux density using three different MR fluids at bush height 5mm and number of turns 2000. The simulation results provide valuable insights into the behavior of the MR fluid in the finishing process. The maximum flux density has been found to be 1.740 Tesla for MRF-122EG for bush height 5mm and number of turns 2000. Furthermore, the analysis phase involves employing analysis of variance (ANOVA) techniques to evaluate the influence of various process parameters on the output response. ANOVA allows for a statistical assessment of the significance of bush height and number of turns and its interaction with magnetic flux density, thereby aiding in process optimization and improvement. The predicted value of magnetic flux density was found to be 2.00994 Tesla, whereas the optimized value of magnetic flux density was found to be 2.010 Tesla at bush height 6.63 mm and number of turns 2133.

The findings from the ANSYS Maxwell simulation and ANOVA analysis provide valuable information for enhancing the efficiency and effectiveness of the MRF process. The optimized design parameters can lead to improved surface quality, reduced processing time, and increased material removal rates, making the MRF process an attractive option for precision polishing in various industries.

Keywords: MRF, ANSYS Maxwell, Aluminium, Magnetic Flux Density, ANOVA

ACKNOWLEDGMENT

I would like to express my special thanks of gratitude to **Dr. M. S. Niranjan** for his guidance, unwavering support, and encouragement. This project work could not have attained its present form, both in content and presentation, without his active interest, direction, and guidance. His personal care has been the source of great inspiration. He has devoted his invaluable time and took personal care in motivating me whenever I was disheartened.

I would also like to thank Prof. S.K. Garg, HOD (Department of Mechanical Engineering),for his support and guidance, although he had a very busy schedule in managing the corporate and academic affairs.

I am thankful to the technical staff of Delhi Technological University.

My deep and sincere gratitude to my family for their continuous and unparalleled love, help and support. I am grateful to my brothers for always being there for me as a friend and always with me in every situation. I am forever indebted to my parents for giving me the opportunities and experiences that have made me who I am. They encouraged me to explore new directions in life and seek my own destiny. This journey would not have been possible if not for them, and I dedicate this milestone to them.

I also want to thank all those who are directly or indirectly support me for my project.

Bipul Kumar
(2K21/PRD/14)

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ABBREVIATIONS

MRF	Magneto Rheological Finishing
ANOVA	Analysis of Variance
CIPs	Carbonyl Iron Particles
MRR	Material Removal Rate
AFM	Abrasive Flow Machining
MAF	Magnetic Abrasive Finishing
MRAFF	Magnetorheological Abrasive Flow Finishing
RMS	Root Mean Square
MFAF	Magnetic Field Assisted Finishing
CMPs	Composite Magnetic Particle
BEMRF	Ball End Magnetorheological Finishing
FMAB	Flexible Magnetic Abrasive Brush
VRR	Volumetric Removal Rate
BCC	Body Centered Cubic

CHAPTER 1

INTRODUCTION

The finishing process plays a crucial role in various industries, including manufacturing, construction, and textiles. It involves a series of operations that are performed on a product or material to enhance its appearance, functionality, and durability. The goal of the finishing process is to provide a final surface treatment that meets the desired requirements and specifications. This process typically occurs after the primary manufacturing or construction process is complete.

Metal finishing processes are vital for improving the properties and aesthetics of metal components across various industries. These processes involve a range of techniques and methods aimed at enhancing the surface characteristics of metals, such as corrosion resistance, wear resistance, and visual appeal. Metal finishing processes have significant implications for industries such as manufacturing, automotive, aerospace, electronics, and construction. They enable the production of high-quality metal components with improved performance, extended lifespan, and enhanced functionality. The understanding and classification of metal finishing processes allow engineers and manufacturers to select the most appropriate techniques for specific applications, optimize production efficiency, and meet stringent quality standards.

The finishing processes, such as honing, lapping, and, grinding are characterized by labor-intensive procedures and a relatively lower level of control when compared to other finishing operations in precision part manufacturing. Typically, these processes utilize a rigid tool that applies significant normal stresses to the workpiece, potentially leading to the formation of micro-cracks and other flaws. As a consequence, the strength and reliability of the machined parts may be compromised. Among these methods, achieving high-quality surface finishes at the nanometer level on advanced materials and intricate geometrical shapes remains a challenging endeavor. In the manual grinding and polishing processes, excessive local pressure can result in subsurface damage. To mitigate this issue and minimize damage done to the subsurface parts of the metal, it is imperative to employ gentle finishing conditions by applying extremely low forces. Over the past ten years, numerous sophisticated fine finishing techniques have emerged, aiming to meticulously regulate the abrading forces. Examples of these methods include magnetic float polishing (MFP) [1], magnetic abrasive finishing (MAF) [2], magnetorheological abrasive flow finishing (MRAFF) [3], magnetorheological jet finishing (MRJF) [4], and magnetorheological finishing (MRF) [5]. These techniques employ magnetic fields to exert control over the abrading forces. However, the utilization of these processes is constrained to particular geometries, such as concave, convex, flat, and aspherical shapes. This limitation arises from the constraints imposed on the relative movement of the finishing medium and the workpiece. Consequently, these methods are incapable of achieving surface finishing on intricate 3D-shaped surfaces. Nano-level finishing processes have gained significant attention in recent years due to their potential to enhance the surface properties of materials at the nanoscale. With advancements in nanotechnology, researchers and industries have focused on developing innovative techniques for achieving precise surface modifications and improvements in various materials. The nano-level finishing process involves manipulating and controlling the material at the atomic or molecular level to achieve desired surface characteristics.

1.1 MAGNETORHEOLOGICAL FINISHING PROCESS

The magnetorheological (MR) process is an advanced and innovative technique used for precision surface finishing of various materials. It utilizes the unique properties of magnetorheological fluids, which are smart fluids composed of micron-sized magnetic particles suspended in a carrier fluid [6]. These fluids exhibit a remarkable change in their rheological behavior in the presence of a magnetic field, transforming from a free-flowing liquid to a semi-solid state. The MR process takes advantage of this property to precisely control the material removal and achieve high-quality surface finishes.

In the MR process, a workpiece is immersed in a magnetorheological fluid, and a magnetic field is applied to control the behavior of the fluid. The magnetic particles within the fluid align themselves along the field lines, creating chains or structures that increase the fluid's viscosity and stiffness. This transformation allows for a controlled and localized removal of material from the workpiece's surface.

One of the significant advantages of the MR process is its ability to adapt to various surface geometries, including flat, curved, and complex 3D shapes. Unlike traditional finishing techniques that are limited by the relative movement between the finishing medium and the workpiece, the MR process can adapt to intricate surface contours. This makes it particularly suitable for finishing parts with complex geometries, such as turbine blades, biomedical implants, optical components, and automotive parts.

Furthermore, the MR process offers several benefits over conventional finishing methods. It provides greater precision and control over the material removal rate, allowing for the attainment of nanometer-level surface finishes. The process is highly controllable, enabling operators to adjust the magnetic field strength, fluid composition, and process parameters to achieve the desired surface quality and roughness.

The MR process also offers enhanced surface integrity, as it minimizes the risk of subsurface damage and heat-affected zones typically associated with high-pressure grinding or polishing methods. This makes it particularly suitable for finishing delicate or heat-sensitive materials.

Additionally, the MR process is versatile and can be applied to a wide range of materials, including metals, ceramics, composites, and polymers. It is a flexible and environmentally friendly technique, as the magnetorheological fluid can be easily removed, recycled, and reused, reducing waste and minimizing environmental impact.

1.2 MR FLUID

Magnetorheological (MR) fluid is a type of smart fluid that exhibits unique rheological properties when subjected to an external magnetic field. It is composed of micron-sized magnetic particles suspended in a carrier fluid, typically oil or water. These particles are typically coated to prevent agglomeration and improve stability.

One of the most remarkable characteristics of MR fluid is its ability to undergo rapid and reversible changes in its viscosity and flow behavior when exposed to a magnetic field. In the absence of a magnetic field, the fluid flows freely like a conventional liquid, allowing for easy movement and manipulation. However, when a magnetic field is applied, the suspended particles align themselves along the field lines, causing the fluid to exhibit a substantial increase in its viscosity. This phenomenon, known as the magnetorheological effect, enables precise and on-demand control over the fluid's flow properties.

The magnetorheological effect arises from the interaction between the magnetic particles and the applied magnetic field. The particles have a response time on the order of milliseconds, making the fluid's viscosity adjust almost instantaneously when the magnetic field strength or direction changes. This rapid response time makes MR fluid an excellent choice for various applications where quick and precise adjustments of flow properties are required.

1.2.1 Phases Present in MR-Fluid

The primary components of the mixture include a base fluid, stabilizing additives, and small magnetic particles. To create MRF, these ingredients are blended together in appropriate proportions. The role of the base oil is to serve as a medium for suspending magnetizable particles, along with stabilizing agents. These additives help decrease the sedimentation rate of the MR (magnetorheological) fluid, which occurs due to the difference in density between the magnetic particles and the carrier fluid. The magnetization effect heavily relies on the significance of magnetic particles. To achieve this, it is necessary to combine these magnetic particles in a manner that prevents them from clumping together and maintains a uniform mixture. A straightforward and effective method for creating a magnetic-responsive fluid (MRF) involves mixing magnetic particles with silicone oil (SO) and employing a small amount of surfactants to prevent clumping. The most effective approach to creating stable MR fluids is to disperse additives prior to introducing magnetic particles into the carrier oil. The fluids can be divided into two phases: the dispersed phase and the continuous phase, as depicted in the illustration.

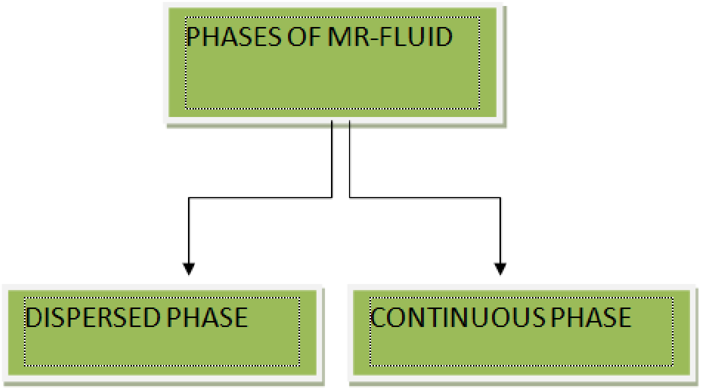

Figure1.1: Different phases of MR-fluid

- DISPERSED PHASE:

The dispersed phase of magnetorheological (MR) fluid plays a crucial role in its unique properties and applications. The dispersed phase consists of small, magnetizable particles suspended within the carrier fluid. The particles are typically micrometer-sized and are often made of materials such as iron, cobalt, or their alloys. The choice of particle material depends on the desired response and application requirements. The dispersed phase particles exhibit ferromagnetic or superparamagnetic behavior, meaning they become magnetized in the presence of a magnetic field but lose their magnetization once the field is removed. This behavior enables MR fluids to undergo rapid and reversible changes in their viscosity or flow characteristics. Ferromagnetic materials like ferrite-polymer, iron-cobalt alloy, nickel-zinc ferrites, and alloy [7], along with ceramic composites, function as a dispersed component within the MR suspension [8,9].

- CONTINUOUS PHASE:

The continuous phase of magnetorheological (MR) fluid plays a crucial role in its unique rheological properties and versatile applications. The continuous phase, also known as the carrier fluid, provides the medium through which the dispersed magnetic particles move and interact. The choice of continuous phase in MR fluids depends on several factors, including the desired application, temperature range, and compatibility with other components in the system. Various fluids have been explored as continuous phases in MR fluids, with the most commonly used being oils, such as silicone, mineral oil, and hydrocarbon-based fluids[9].

The characteristics of MRF primarily rely on two factors: the viscosity of the underlying fluid and the concentration of particles in terms of volume [10]. Reduced fluid thickness results in fluid instability, while increased fluid thickness can elevate the viscosity of MRF when it is not in use. In order to achieve the highest MR impact, it is important for the base oil's viscosity to be minimized [8].

1.2.2 Technique For MR-Fluid Stabilization

Stabilization techniques play a crucial role in maintaining the stability and longevity of magnetorheological (MR) fluids, ensuring their consistent performance and reliable operation. These techniques are employed to prevent particle settling, agglomeration, and sedimentation, which can negatively impact the fluid's rheological properties and compromise its functionality. The presence of a difference in density between the particles suspended in a fluid and the fluid itself results in the occurrence of particle settling in MR fluids.

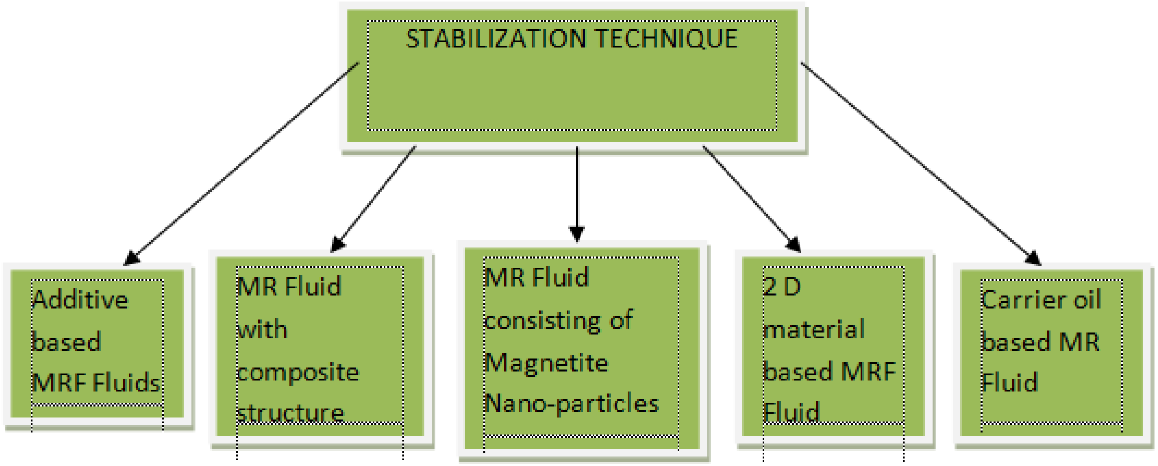

Figure 1.2: schematic diagram illustrating stabilization techniques

Furthermore, the significant ratio between surface area and volume tends to decrease the amount of surface energy, resulting in the formation of clusters between particles. This phenomenon contributes to significant challenges in terms of the ability to disperse the particles again and maintain their stability [11].

1.2.3 Properties of MR-Fluid

Understanding the flow behavior and magnetic field response of magnetorheological (MR) fluids relies on comprehending their rheological properties. These properties encompass viscosity, shear thinning behavior, yield stress, and other flow-related characteristics, and are crucial for characterizing MR fluid behavior. MR fluids possess distinctive rheological properties that render them valuable for a wide range of applications.

- Viscosity pertains to the resistance of MR fluids to flow. In the absence of a magnetic field, MR fluids typically exhibit low viscosity, allowing for easy flow. However, when subjected to a magnetic field, the viscosity can significantly increase due to the formation of particle chains or clusters. This change in viscosity is reversible and can be controlled by adjusting the strength of the magnetic field.
- Shear thinning behavior is commonly observed in MR fluids, where their viscosity decreases as the shear rate increases. This behavior is attributed to the reorientation and alignment of the suspended magnetic particles in response to shearing forces. As the particles align and slide past each other, the resistance to flow decreases, resulting in a decrease in apparent viscosity.
- Yield stress represents the minimum stress required for an MR fluid to initiate flow. MR fluids typically exhibit a yield stress behavior, remaining in a solid-like state until a critical stress threshold is surpassed. Once this threshold is exceeded, the fluid transitions into a flowing state, and its viscosity decreases. The yield stress can be adjusted by factors such as particle concentration and magnetic field strength.
- Thixotropy refers to the property of MR fluids to display a time-dependent decrease in viscosity under constant shear stress. When subjected to shear stress for a specific duration, the viscosity gradually decreases, facilitating easier flow. However, upon removal of the stress, the fluid's viscosity gradually recovers. Thixotropic behavior in

MR fluids is associated with the rearrangement and realignment of the magnetic particles.

- Stability is crucial for the long-term performance of MR fluids, ensuring consistent rheological response over time and resisting issues like particle settling, agglomeration, and sedimentation. Stable MR fluids maintain a uniform dispersion of magnetic particles in the continuous phase, guaranteeing predictable and reliable rheological properties.

It's important to note that the rheological properties of MR fluids can be influenced by various factors, including the type and concentration of magnetic particles, characteristics of the continuous phase, temperature, and applied magnetic field strength. By adjusting these parameters, these properties can be customized and optimized for specific applications.

1.2.4 Process Parameters of MR-Fluid.

The process parameters of magnetorheological fluid can be controlled to produce a fluid with the desired properties for a specific application. For example, a fluid with a high viscosity can be used for damping applications, while a fluid with a low viscosity can be used for lubrication applications. The behavior of MR fluids can be manipulated by controlling various process parameters. Here are the key process parameters involved in the preparation and utilization of magnetorheological fluids:

- *Base Fluid:* MR fluids are typically composed of a carrier fluid, which acts as the base material. Common carrier fluids include mineral oil, silicone oil, water, and synthetic hydrocarbon oils. The choice of base fluid depends on the desired application and operating conditions.
- *Magnetic Particles:* Magnetic particles suspended within the base fluid are responsible for the responsiveness of MR fluids to magnetic fields. These particles are usually micron-sized, with materials such as iron, cobalt, nickel, or their alloys exhibiting magnetic properties. The size, shape, concentration, and surface coating of the magnetic particles play a crucial role in determining the rheological properties of the MR fluid.
- *Particle Concentration:* The concentration of magnetic particles in the MR fluid significantly affects its rheological behavior. Increasing the particle concentration

typically results in an increase in the fluid's yield stress and viscosity. However, excessively high concentrations can lead to particle aggregation and settling, which may adversely affect the fluid's performance.

- *Applied Magnetic Field Strength:* The strength of the magnetic field applied to the MR fluid influences its response. By varying the magnetic field strength, the rheological properties of the fluid can be manipulated, enabling control over its flow behavior, viscosity, and yield stress. Typically, stronger magnetic fields yield a more pronounced change in the rheological properties.
- *Temperature:* Temperature plays a vital role in the behavior of MR fluids. Changes in temperature can affect the viscosity, yield stress, and stability of the fluid. Generally, MR fluids exhibit a decrease in viscosity and yield stress with increasing temperature. However, the choice of carrier fluid and the specific magnetic particles used can influence the temperature sensitivity of the fluid.
- *Shear Rate:* The shear rate, which represents the rate at which the MR fluid is subjected to deformation, also influences its rheological behavior. Different applications may require specific shear rates to achieve the desired flow characteristics and response to the magnetic field.
- *Particle Size Distribution:* The size distribution of magnetic particles within the MR fluid affects its stability and rheological properties. A narrow particle size distribution is generally preferred to ensure uniform and predictable fluid behavior.

It is important to note that the specific process parameters involved in magnetorheological fluids may vary depending on the intended application, formulation, and experimental setup. Therefore, it is crucial to consider these parameters and tailor them accordingly to achieve the desired performance characteristics of the MR fluid.

1.3 MR FINISHING SETUP

The MR finishing tool is mounted in a vertical orientation on a Z-slide, allowing the tip of the tool to approach the workpiece surface. It is driven by a servo motor, and a motion controller is employed to accurately regulate the rotational speed of the MR finishing tool. The upper part of the MR finishing tool houses components such as a ball bearing, slip ring, timing pulley, and rotary valve. The device consists of a vertically oriented magnetorheological (MR) finishing tool, which is composed of an inner core, an electromagnet coil, and an outer core arranged concentrically.

The MR finishing tool is mounted in a vertical orientation on a Z-slide, allowing the tip of the tool to approach the workpiece surface. It is driven by a servo motor, and a motion controller is employed to accurately regulate the rotational speed of the MR finishing tool. The upper part of the MR finishing tool houses components such as a ball bearing, slip ring, timing pulley, and rotary valve. The workpiece holding mechanism consists of a platform positioned on X-Y linear movement slides. To control the linear motion in the X-Y-Z directions, three stepper motors are employed. Motion controllers for X-Y direction motion are utilized to regulate the horizontal linear motion of the workpiece, while the Z motion controller is responsible for controlling the vertical linear motion of the MR finishing tool.

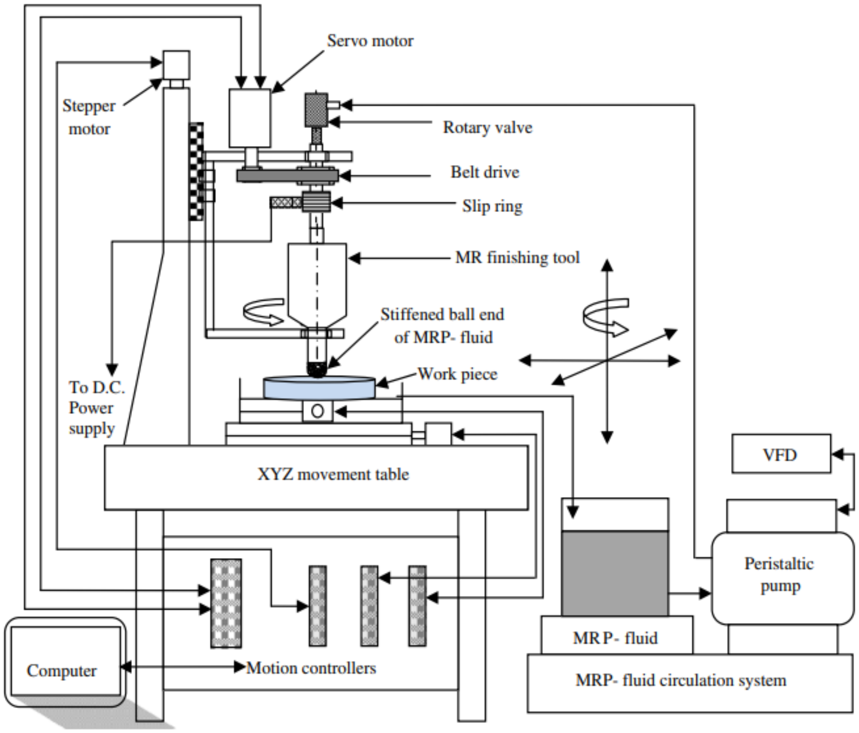

Figure 1.3: Diagram illustrating the setup of the recently developed MR finishing machine[12]

1.3.1 Working Principle of MRF

The basic principle of MRF revolves around the manipulation of the MR fluid using a magnetic field. The MR fluid exhibits unique properties that allow it to change its viscosity and flow behavior when subjected to a magnetic field. This property forms the basis of the finishing process.

The MRF process starts by placing the workpiece, which needs to be polished, in close proximity to a ball-shaped tool coated with a polishing abrasive material. The MR fluid is then applied to the interface between the workpiece and the tool. When a magnetic field is applied to the MR fluid, the magnetic particles align themselves along the field lines, causing the fluid to thicken and behave like a solid. This transformation is known as the magneto-rheological effect.

As the tool rotates and moves over the workpiece surface, the MR fluid in the vicinity of the magnetic field experiences changes in viscosity, allowing it to transfer the abrasive particles to the workpiece. The movement of the tool and the application of the magnetic field create a controlled polishing action. The ball-shaped tool helps ensure uniform contact and pressure distribution across the workpiece surface, resulting in a consistent finish.

The MRF process offers several advantages. First, it enables precise control over the polishing action, allowing for accurate removal of material and achieving the desired surface quality. The magnetic field strength and duration can be adjusted to control the viscosity and polishing forces of the MR fluid. This flexibility allows for customization based on the specific requirements of the workpiece.

Moreover, MRF is a non-contact process, meaning that the tool does not physically touch the workpiece. This characteristic reduces the risk of damage to delicate or complex geometries. Additionally, the use of MR fluid allows for a high material removal rate while maintaining surface integrity.

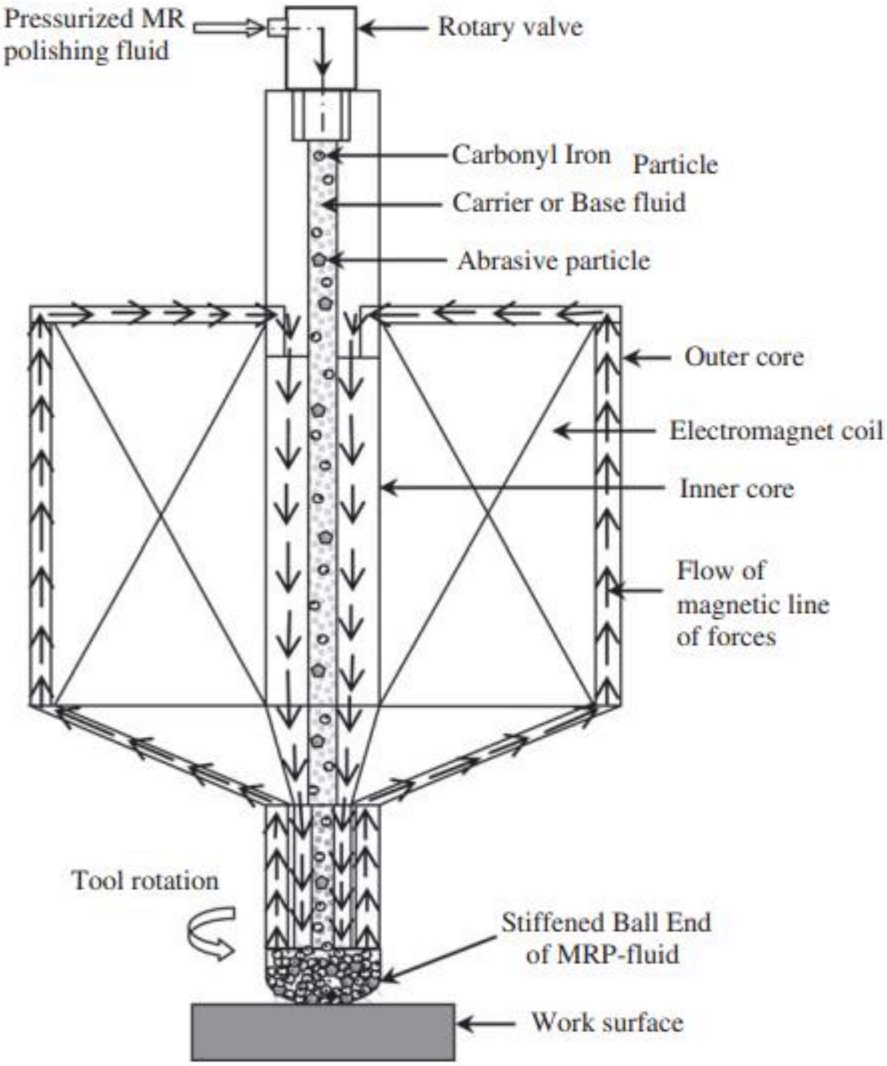

Figure 1.4: MR polishing fluid forms a stiffened ball end at the tool's tip[12]

1.3.2 Process Parameters

The process parameters involved in MRF are crucial for controlling the material removal rate, surface quality, and overall efficiency of the finishing process. Here are the key process parameters in magnetorheological finishing:

- *Magnetorheological Fluid Composition:* The composition of the magnetorheological fluid used in MRF plays a significant role in the finishing process. The fluid consists of a carrier fluid, magnetic particles, and abrasive particles. The choice of carrier fluid, magnetic particle concentration, and abrasive type and concentration depends on the material being finished, desired surface quality, and the specific MRF setup.
- *Magnetic Field Strength and Orientation:* The strength and orientation of the magnetic field applied during MRF impact the material removal rate and finishing quality. By adjusting the magnetic field strength and direction, the forces acting on the abrasive particles within the fluid can be controlled, influencing the material removal behavior.
- *Gap Width:* The gap width refers to the distance between the workpiece and the finishing tool. It affects the depth of material removal and the surface finish quality. Adjusting the gap width allows for control over the aggressiveness of material removal and the level of surface smoothness achieved.
- *Feed Rate:* The feed rate determines the speed at which the workpiece moves relative to the finishing tool. It affects the material removal rate and surface quality. The feed rate should be optimized to achieve the desired surface finish while avoiding excessive material removal or insufficient polishing.
- *Pressure:* The pressure applied during MRF affects the contact between the finishing tool and the workpiece, influencing the material removal rate and surface finish quality. Proper control of the pressure ensures uniform and consistent polishing across the workpiece surface.
- *Abrasive Particle Size and Concentration:* The size and concentration of abrasive particles within the magnetorheological fluid impact the material removal rate and surface roughness. The selection of abrasive particles should consider the hardness of the workpiece material and the desired finishing requirements.

- *Slurry Flow Rate:* The flow rate of the magnetorheological fluid during the MRF process affects the distribution and replenishment of the abrasive particles. Controlling the slurry flow rate ensures an adequate supply of abrasive particles to the workpiece surface, contributing to efficient and consistent material removal.
- *Process Time:* The duration of the MRF process influences the total material removal and the final surface finish achieved. Optimizing the process time is essential to achieve the desired finishing results without compromising the dimensional accuracy or inducing surface damage.

1.4 ADVANTAGES

Magnetorheological (MR) fluids offer a range of advantages that make them highly valuable and versatile materials in various applications. These advantages stem from their unique rheological properties and their ability to rapidly respond to changes in magnetic fields. Here are some key advantages of MR fluids:

- *Adjustable Viscosity:* One of the primary advantages of MR fluids is their ability to undergo rapid and reversible changes in viscosity. When exposed to a magnetic field, the viscosity of an MR fluid can increase significantly, allowing for precise control over the fluid's flow behavior. This adjustability makes MR fluids ideal for applications where variable damping, shock absorption, and controllable lubrication are required.
- *Real-Time Responsiveness:* MR fluids exhibit a near-instantaneous response to changes in magnetic fields. This real-time responsiveness enables quick and precise adjustments in the fluid's rheological properties. As a result, MR fluid-based systems can adapt and respond rapidly to varying operating conditions, enhancing performance and functionality.
- *Wide Range of Applications*: MR fluids find applications across diverse industries. They are used in various fields such as automotive, aerospace, robotics, civil engineering, medical devices, and haptic interfaces. MR fluid-based devices and systems include dampers, shock absorbers, clutches, brakes, vibration isolators, prosthetic devices, and tactile feedback systems. The ability to tailor the rheological properties of MR fluids to specific application requirements allows for their widespread use.

- *Energy Efficiency:* MR fluids offer energy-efficient solutions in many applications. In devices such as dampers and shock absorbers, MR fluids can rapidly adjust their viscosity, allowing for precise control of damping forces. This adaptability minimizes energy loss and enhances energy absorption capabilities, resulting in improved energy efficiency compared to traditional damping systems.
- *Safety and Reliability:* MR fluids are generally considered safe and reliable materials. They are non-toxic and non-flammable, making them suitable for use in various environments and industries. Moreover, MR fluid-based systems often have a simpler and more compact design compared to conventional mechanical systems, resulting in reduced maintenance and improved reliability.
- *Controllability:* MR fluids offer excellent controllability, enabling precise regulation of their rheological properties. The viscosity, yield stress, and damping characteristics of MR fluids can be adjusted by varying the magnetic field strength, providing a high degree of control over the system's behavior. This controllability allows for fine-tuning of damping forces, response times, and overall system performance.
- *Adaptability to Various Conditions:* MR fluids can operate effectively over a wide range of temperatures and operating conditions. They exhibit stable performance across different temperatures, allowing for reliable operation in both extreme hot and cold environments. Additionally, MR fluids are adaptable to varying shear rates, making them suitable for applications with changing flow conditions.

1.5 LIMITATIONS

Magnetorheological (MR) fluids are versatile and innovative materials with numerous applications. However, like any technology, they do have certain limitations that should be considered. Here are some common limitations of MR fluids:

- *Sedimentation and Particle Settling:* Over time, magnetic particles in MR fluids may experience sedimentation or settling, causing a loss of homogeneity and stability. Sedimentation can occur due to gravitational forces or inadequate stabilization techniques. This limitation can impact the long-term performance and consistency of MR fluid-based systems.

- *Limited Temperature Range:* MR fluids typically exhibit temperature-dependent rheological properties. Extreme temperatures can affect the fluid's viscosity and stability, potentially leading to a loss of performance or changes in the desired rheological behavior. High temperatures can cause particle agglomeration, while low temperatures can increase the fluid's viscosity and reduce its responsiveness to magnetic fields.
- *Shear Thinning and Abrupt Yielding:* While the shear thinning behavior of MR fluids can be advantageous in certain applications, it can also present challenges. The abrupt transition from a solid-like state to a flowing state (yield stress) can introduce sudden changes in the fluid's behavior, leading to unpredictable responses under varying shear conditions. This limitation may require careful consideration and adjustment to achieve desired performance.
- *Dependency on Magnetic Field Strength:* MR fluids are highly responsive to magnetic fields, but their rheological properties are strongly dependent on the magnetic field strength. This means that achieving consistent and precise control of the fluid's behavior may require accurate and controlled magnetic field generation. Fluctuations or inconsistencies in the field strength can affect the fluid's response, limiting its reliability and controllability.
- *Limited Stability under Shear:* MR fluids may experience reduced stability under continuous shear conditions. Prolonged shearing can lead to particle alignment and chain formation, resulting in changes in viscosity and performance. The ability to maintain stability and uniformity under extended shear conditions is a challenge that should be considered in certain applications.
- *Wear and Contamination:* The presence of abrasive particles or contaminants in MR fluids can accelerate wear and degradation of mechanical components, such as seals, valves, and actuators. Additionally, the presence of foreign substances can alter the fluid's rheological properties and compromise its performance. Proper filtration and maintenance practices are necessary to minimize the impact of wear and contamination.
- *Sensitivity to External Factors:* MR fluids can be sensitive to external factors such as humidity, pressure, and vibration. High humidity can lead to moisture absorption, potentially affecting the fluid's stability and performance. Changes in pressure and vibration levels can also influence the fluid's behavior, necessitating careful design and

consideration of environmental conditions.

1.6 APPLICATIONS

Magnetorheological Finishing (MRF) is a precision polishing process that finds applications in various industries where achieving high-quality surface finishes and precise dimensional control is crucial. Here are some common applications of MRF:

- *Optics and Photonics:* MRF is extensively used in the optics and photonics industry for polishing optical components such as lenses, mirrors, prisms, and filters. The process enables precise control over surface quality, shape accuracy, and surface roughness, resulting in improved optical performance and reduced scattering and wavefront errors.
- *Semiconductor Industry:* MRF plays a vital role in the semiconductor industry for polishing wafers and other components. It helps achieve precise planarity, flatness, and surface roughness, critical for the fabrication of microelectronic devices, integrated circuits, and other semiconductor components.
- *Aerospace and Defense:* MRF is employed in the aerospace and defense sectors for finishing critical components, including turbine blades, jet engine parts, optical systems, and radar components. The process ensures the desired surface finish, dimensional accuracy, and performance of these high-value components.
- *Automotive Industry:* MRF is utilized in the automotive industry for finishing various components such as crankshafts, camshafts, gears, and pistons. It improves the surface finish, reduces friction, enhances wear resistance, and optimizes the performance and efficiency of these automotive parts.
- *Medical Devices:* MRF is employed in the manufacturing of medical devices, particularly implants and surgical instruments, where precise surface finishes, dimensional accuracy, and smoothness are essential. It helps achieve optimal biocompatibility, reduces friction, and enhances the performance and longevity of medical implants.
- *Precision Machining:* MRF is used in precision machining applications, where achieving ultra-smooth surfaces and precise form accuracy is critical. It is employed for finishing components used in industries such as aerospace, automotive, optics, and electronics,

ensuring superior surface quality and dimensional control.

- *Research and Development:* MRF is utilized in research and development settings to explore new materials, study surface phenomena, and develop advanced manufacturing processes. Its versatility and ability to produce controlled surface finishes make it a valuable tool for investigating material properties, tribology, and surface interactions.

CHAPTER 2

LITERATURE REVIEW

Rabinow [13] is credited with the creation of magnetorheological (MR) fluid, a magnetic fluid composed of small iron particles suspended in oil. The magnetic fluid clutch represented the initial utilization of an iron-oil mixture, demonstrating the magnetic influence on the fluid's iron particles. The inclusion of liquid in the mixture was intended to ensure the seamless operation of the clutch. This concept effectively eliminated the disparity between static and kinetic friction. Subsequently, researchers embraced this concept and integrated it into the field of manufacturing engineering. The current technology employs a unique fluid that exhibits alterations in its rheological characteristics when subjected to a magnetic field. This fluid is referred to as magnetorheological (MR) polishing fluid.

Wang and Meng [14] conducted an analysis of the operational modes of MR fluid devices. The crucial aspect in the successful advancement of MR fluid technology lies in the designs of MR fluid devices and formulation of high-performance MR fluids. In this study, the initial challenge arose when applying electrical current to MR fluid devices, leading to an issue of settling instability within the MR fluids. Another challenge that emerged was the higher initial expense associated with controllable MR fluid devices in comparison to conventional passive devices. Hence, taking into account these two factors, a novel approach was devised wherein the fluid was encapsulated within an absorbent matrix.

According to Rosenfeld et al. [15], they introduced a magnetorheological (MR) fluid utilizing a combination of nanometer-scale, micrometer-scale, and hybrid-scale powders. The Bingham plastic model defined the yield stress and plastic viscosity, and it was evident that MR fluids containing nano and hybrid powders exhibited a greater zero field yield stress compared to fluids at the micron scale. The plastic viscosity observed was consistent among the three MR fluids, leading to the conclusion that all of them exhibited indications of shear thinning.

Jha and Jain [16] suggested utilizing a blend of abrasive flow machining (AFM) and magnetic abrasive finishing (MRF) for the polishing of irregular inner surfaces. The fundamental concepts of MRAFF closely resemble those of traditional AFM, where a polishing substance is repeatedly pushed and pulled at high pressure through a channel created by the workpiece and fixture. They employed an electromagnet coil in the final stage of MRAFF to produce a magnetic field. This magnetic field enhanced the rigidity of the finishing media, which consisted of 6 μm magnetic carbonyl iron particles and 17 μm non-magnetic SiC abrasives. These particles were suspended in a viscoplastic base medium. They showcased that employing MRAFF can lower the surface roughness of a stainless steel workpiece, initially measuring 0.47 μm Ra, to 0.34 μm Ra after subjecting it to 200 extrusion cycles under an extrusion pressure of 3.75 MPa and a magnetic field strength of 0.575 T.

Singh et al. [17] conducted research on magnetic abrasive finishing (MAF) technique. They investigated various factors affecting the process, including the electromagnet's DC voltage, the working gap, the rotational speed of the magnet, and the size of the abrasive particles (indicated by mesh number). According to reports, the experimental results regarding the forces involved in the MAF process have established a connection between the surface finish and these forces. An resistance-based force transducer, known as a ring dynamometer, was created and manufactured. This was employed for quantifying the standard magnetic force element accountable for microscopic penetration into the object being worked on, as well as the tangential cutting force element generating small fragments. The study found that factors such as voltage and abrasive size had a greater impact on the alteration of surface roughness (ΔRa).

Kordonski et al. [18] presented a technique to enhance the stability of jets by utilizing an axial magnetic field to magnetize the circular stream of magnetorheological polishing fluid as it emerges from the nozzle. Experimental evidence demonstrates that the utilization of a magnetically stabilized circular stream of MR polishing fluid leads to the creation of a consistent material removal effect (polishing spot) at a significant distance from the nozzle, typically measured in centimeters. MR Jet finishing is capable of generating incredibly accurate surfaces at the nanometer scale, achieving roughness levels below 1 nm root mean square (rms). Because this method does not consider the offset distance, it can be useful for completing intricate forms, particularly those with deep concaves and various cavities.

In their study, Yamaguchi et al. [19] employed magnetic rheological (MR) fluid in a magnetic field-assisted finishing (MFAF) technique to polish wafers. Essentially, this method resembles traditional lapping, but with the distinction that the applied normal force is generated through magnetic forces. In just 5 minutes, the surface roughness of the wafer was significantly reduced from 1.14 nm to 0.58 nm by using a polishing medium composed of a mixture of 7 μm magnetic carbonyl iron particles, non-magnetic diamond abrasives smaller than 0.25 μm, and silicone oil. The surface texture of the wafer worsened from 1.27 nm Ra to 2.04 nm Ra when larger diamond abrasives (< 0.5 μm) were employed.

Cheng et al. [20] developed a magnetorheological (MR) fluid by combining composite magnetic particles (CMPs) through a chelation reaction involving CIPs and ethylenediamine triacetic acid. Additionally, they investigated the rheological properties associated with this fluid. In the presence of a magnetic field, researchers noticed that the MR fluid, which was prepared, displayed elevated shear/yield stress as well as enhanced resistance to oxidation and improved stability of dispersion.

Singh et al. [21] introduced an innovative method for addressing the challenge of finishing complex 3D surfaces. They developed a ball-end magnetorheological (MR) finishing tool capable of handling both flat and three-dimensional surfaces. The tool demonstrated the ability to complete the finishing process for both ferromagnetic and non-ferromagnetic materials. It was observed that the shape and size of the finishing spot varied as the working gap distribution changed, even when the magnetizing current remained constant. The application of a recently developed MR finishing technique was utilized on the three-dimensional surfaces of a ferromagnetic material. The effectiveness of the ball-end MR finishing tool was proven by achieving a surface finish of 70.0 nm on a ferromagnetic EN31 workpiece, reducing it from 414.1 nm, within a finishing time of 100 minutes. In a span of 60 minutes, the surface roughness of a copper sample that is not made of iron or its alloys was decreased from an initial measurement of 336.8 nm to a final measurement of 102 nm.

In their research, Sidpara and Jain [22] employed magnetorheological finishing as a method to polish crystal silicon blanks. This technique involves the utilization of magnetorheological fluid, which is a mixture containing magnetic particles, non-magnetic abrasives, and various additives suspended in water or a carrier solution. A study was performed to forecast the impact of various process factors, including the concentration of magnetic particles combined with abrasive particles, the speed of the carrier wheel, and the initial roughness of the surface. The experiments yielded impressive results in terms of the average roughness (Ra), with values ranging from 8 nm to 1300 nm. These outcomes were achieved within a finishing time of 210 minutes, as reported by Sidpara and Jain in 2012.

Singh et al. [23] conducted research on the enhancement of 3D workpiece surfaces through the utilization of a ball-end magnetorheological finishing technique. The milling process was employed to create the workpiece, which involved working on different surface angles such as flat, 30 degrees, 45 degrees, and curved surfaces. After the milling process, the obtained average roughness (Ra) values on the center line were 1334.1 nm, 1452.3 nm, 2739.3 nm, and 1754.7 nm respectively. Additionally, a Ra value of 142.9 nm was obtained after the grinding procedure. The tests were conducted with a tool rotating at a speed of 500 rpm, a magnetizing current of 4 amperes, and a working gap of 0.66 millimeters. After 120 minutes of finishing time, the ground flat surface's Ra value decreased from an initial value of 142.9 nm to a final value of 19.7 nm.

The same year, Singh et al. [24] conducted a study focusing on fused silica glass. They utilized the BEMRF process to minimize surface roughness and achieve a flawless finish in fused silica glass. The research employed a specific experimental arrangement comprising an electromagnet, a cylindrical hollow tool, servo motors controlling three axes, and enabling rotational motion of the tool. The utilization of Figure 2.3 elucidated the working principle of the MR polishing fluid. Following a 90-minute MR finishing process, the surface roughness value decreased from an initial measurement of 0.74 nm to a final value of 0.146 nm.

Baranwal and Deshmukh [25] outlined the key characteristics of magnetorheological finishing (MRF) technology. The analysis reveals that the key characteristics of this technology were its rapid and immediate reactions, a simple and direct connection between electrical input and mechanical output, and ultimately, an intelligent and adjustable system. From a business perspective, it is necessary to enhance the sensitivity of the MRF system.

This can be achieved by incorporating sensors and implementing a closed loop system to gather feedback.

J. P. Segovia-Gutiérrez et al. [26] conducted research on Magnetorheological fluids to explore the gelation regime. They found that higher concentrations of magnetic particles by volume percentage resulted in enhanced magnetic rheological properties. Furthermore, they observed a sudden increase in values once the critical concentration was reached. The gel was created when Carbonyl iron particles were present at a concentration of 10% and subjected to a magnetic field with a strength of 10 kA/m. Once the volume percentage of Carbonyl Iron Particles reaches around 20% for all Magnetic field strengths, there will be no significant rise in the Storage modulus.

Jiao et al. [27] employed a magnetic compound fluid (MCF) wheel to refine optical glass, employing a technique known as "semi-fixed-abrasive" and "ultra-fine" finishing. This approach enables the attainment of a precise surface finish for optical glass. Some adjustments were implemented to the existing arrangement in order to assess how well the altered wheel performed in spot-polishing fused silica glass. Tests were conducted to assess the elimination of material and the smoothness of the surface of the glass sample using the altered wheel. The outcomes of these tests indicated an improvement in material removal. The enhanced MCF wheel outperformed the original wheel significantly. The quantities of material removed and the surface roughness were measured for both the enhanced and original MCF wheels, resulting in values of 0.04 mm3 and 0.0088 mm3 for material removal and Ra values of 5.624 nm and 14.67 nm respectively. Hence, this research demonstrated that smaller working clearances or gaps and increased wheel rotational speeds resulted in improved work surface quality and enhanced material removal.

Song Li et al. [28] utilized a computer model called Simulink to determine the theoretical shear stress values of Magnetorheological grease under various Magnetic field strengths. They then conducted a comparison between these theoretical values and the corresponding experimental data. The simulation took into account the electrostatic properties. An analysis was conducted to examine the effect of particle size on shear stress under a zero magnetic field strength, as well as the relationship between shear stress and field strength. The coincidence between the shear strength values and experimental data was noticed in relation to the lower density of ferromagnetic particles in the MR grease. The experimental results show that as the density of Ferromagnetic particles increases, the Shear strength values decrease.

Guo et al. [29] conducted a study to examine how micro-structures impact both surface roughness and subsurface damage. The main emphasis of this paper is on a range of micro-structured coarse-grained diamond wheels employed in the surface grinding of optical glass. The objective was to enhance the grinding effectiveness, particularly concerning subsurface damage. The subsurface damage depth was significantly decreased from 5 to 1.5 μm when comparing it to the conventional coarse-grained diamond wheel. Maybe the improved roughness of the surface wasn't achieved using the recently introduced diamond wheel with a coarse-grained micro-structure.

In another paper, Guo et al. [30] conducted a study to examine how the material removal rate is distributed during spot polishing of borosilicate glass. ANOVA was conducted by taking into account three process parameters, namely magnet revolution speed, MCF carrier rotational speed, and working gap pressure. The measurement of shear stress and material removal rate (MRR) was used to evaluate the response. The findings indicated that the pressure was greater in the vicinity of the central region of the polishing spot, which represented the interacting area. The concluding observation indicated that there is minimal removal of material at the central point, while the highest amount of material is removed at a distance of around 8.2 to 10.2 mm from the central point.

Pattanaik and Agarwal [31] introduced a novel technique known as the flexible magnetic abrasive brush (FMAB), which combines the magnetic rheological fluid (MRF) with the pillar drill machine. The purpose of its development was to complete freeform surface objects. Additionally, the experiments were conducted by altering the composition of the slurry. The type of container used to store MR fluid has been determined to have an impact on the surface finish achieved through this method. The findings indicate that there is a 77% enhancement in the finishing of copper workpieces with flat surfaces, while a 67% improvement is observed for workpieces with cylindrical surfaces.

Miao Yu et al. [32] developed a Magnetorheological gel that consisted of Carbonyl Iron particles evenly distributed within a Polyurethane gel. They investigated the resistance values of the gel when subjected to varying magnetic field strengths, focusing on different concentrations of Carbonyl Iron particles by weight. The outcomes of the experiment indicated that the resistance was influenced primarily by the level of CIP concentration, and manipulating the strength of the magnetic field could modify the resistance values. The CIP composition, comprising 70% by weight, exhibited a resistance of 7.56 MΩ when exposed to a magnetic field strength of 0.1T. However, as the magnetic field strength rose to 1 T, the resistance decreased to 2.4 MΩ.

In their experimental study on the finishing of Silicon wafers, K. Saraswathamma et al. [33] implemented a new method called Ball End Magnetorheological finishing process. A combination of deionized water, cerium oxide, and carbonyl particles was employed to polish silicon wafers. The utilization of ANOVA has been employed to examine the process variables. Increasing the current results in stronger magnetic field strength, leading to an increase in magnetic force. As a consequence, the surface roughness would diminish. Reducing the distance between the workpiece and the tool would result in a decrease in the roughness of the final product. The working gap is considered the most crucial factor in the BEMR process.

In their study, Pashmforoush and Rahimi [34] employed the magnetic abrasive finishing (MAF) technique to finish the BK7 optical glass, which is known for being challenging to machine and store securely. They implemented effective measures to minimize the occurrence of surface defects and ensure the safe handling of the material. The researchers employed statistical methods to determine the best process conditions and examine how different process parameters influenced surface roughness. This was done using response surface methodology. This study took into account different factors related to the final touches, including the size of the abrasive, the speed of rotation, and the proportion of binding agent by weight. The graph in Figure 2.4 demonstrates how the Ra value is linked to the time required for finishing, and it shows that the lowest achieved surface roughness value was 23 nm.

Yuyue Wang et al. [35] introduced a fresh approach to magnetic abrasive finishing called Dual Rotation Magnetorheological finishing. They examined the surface texture of both Magnetorheological finishing and Dual Rotation Magnetorheological finishing. Magnetorheological finishing encompassed two distinct textures: Raster path and Spiral path. These textures were characterized by their directionality and uniform groove angle. In contrast, Dual Rotation Magnetorheological finishing lacked any directional texture and featured a uniform distribution of groove angle.

Shih-Hsien Chou et al. [36] introduced an innovative gel designed for the magnetic abrasive finishing method to enhance the surface of mild steel rods. Bean Gel formulated specifically for this objective has the ability to retain the Ferrous particles, preventing them from being carried away by centrifugal forces during the Magnetic Abrasive Finishing (MAF) procedure. The experiment involved testing three different gels. The Bean gel had a viscosity of 1.2 Pa-S, Silicone Gel I had a viscosity of 120 Pa-S, and Silicone Gel II had a viscosity of 500 Pa-S. The Bean gel produced a superior surface finish compared to the other gels. When the Bean gel was used as a medium for a 5-minute finishing time, the surface roughness values improved from 0.65 μm to 0.09 μm.

Wang et al. [37] developed a new method for nano-finishing K9 glass using a magnetic resonance force (MRF) strategy with permanent magnetic yoke excitation. The new method was shown to be effective in producing high-quality, smooth surfaces on K9 glass. It was discovered that using both translational and rotational motions of the trough significantly increased the surface planarity. A volumetric removal rate (VRR) model was created by coupling the effects of normal and tangential forces. It was discovered that the tangential force was the key factor. The brick magnet case was discovered to have the highest VRR.

Zafar Alam et al. [38] conducted a study where they employed the Ball End Magnetorheological finishing process to model the surface roughness of a ferromagnetic workpiece. The flux density exhibited a sinusoidal pattern, peaking at the midpoint of the tool. The magnetic abrasive chain, which is believed to have a body-centered cubic (BCC) structure, consists of abrasive particles located at the center. The increase in flux density led to a rise in the yield stress of the Magnetorheological polishing fluid. The difference between the predicted surface roughness value and the actual experimental surface roughness ranged from 7.23% to 31.19%.

Chen et al. [39] developed a specialized tool with a ball-shaped permanent magnet for performing magnetic field-assisted finishing (MRF) on optical glasses. An additional proposition was made for a material removal function, taking into account both the hydrodynamic effect and Preston's equation. An association was found between the increase in shear stress and the rise in MRR.

Xiu et al. [40] developed and evaluated a reciprocating MR finishing technique for the purpose of polishing K9 borosilicate glass. They conducted a study to assess the effectiveness of MR polishing fluid in achieving better surface quality during the polishing process. The results showed a significant improvement of more than 95% in the percentage change of surface roughness (ΔRa), indicating the successful application of the developed approach.

Kashif Ali Abroa et al. [41] conducted a mathematical analysis that examined how the magnetic field affects viscoelastic fluid. They employed the Mathematical Transformation Technique for their study. Mathematical solutions have been derived to describe the behavior under the influence of both magnetic and non-magnetic fields. The findings indicate that the velocity field becomes denser and the shear stress becomes more dispersed as the viscosity increases. The speed at which the medium flows and the amount of shear stress it experiences are inversely related to the strength of the magnetic field.

Ranjan et al. [42,43] proposed a chemical-assisted magnetic abrasive finishing (MRF) technique for achieving nano-finishing of Aluminium alloy. With the help of a chemical reagent, a gentle and protective layer was created on the surface of the workpiece. This layer can be readily eliminated when the MRF (mechanical abrasion) process is applied.

Arora et al. [44] introduced a novel MRF approach for achieving the final touches in the production of straight bevel gears. Furthermore, an approach was devised to create a model that takes into account the interplay between abrasives and surface peaks, aiming to diminish the roughness of the surface. The findings indicate that the magnetic flux density is evenly spread across the tooth profile, resulting in consistent polishing of the gear tooth.

2.1 RESEARCH GAP

Based on the review of existing literature, following gap in research has been identified:

1. The current situation acknowledges the established concept of MR finishing. There is a need to explore the design and development of an optimal MR finishing tool using the latest software.
2. Exploring the modelling of MR finishing tool design can be beneficial in predicting and improving its accuracy, thereby aiding in the development of effective models and simulations.

2.2 RESEARCH OBJECTIVES

Based on the examination of existing literature, following research goals has been identified:

1. To design and develop the robust model using ANSYS Maxwell simulation software for MR finishing.
2. To simulate the designed model for different combination of bush height and number of turns in order to get the maximum magnetic flux density at the tip of MR finishing tool.
3. To study three different MR fluids in order to get the maximum flux density at the tip of the MR finishing tool.
4. To conduct parametric study and its optimization using ANOVA approach to identify the optimal combination of design parameters to achieve maximum magnetic flux density.

CHAPTER 3

DESIGN AND MODELING OF MR FINISHING TOOL

The ANSYS Maxwell simulation software was used to create a three-dimensional representation of an MR finishing tool, incorporating a MRP-fluid, workpiece and, a magnet. The material assigned for both the inner and outer core is iron with a relative permeability of 4000. The assigned value for the material properties of MR fluid indicates a relative permeability of 4. A slender brass bush with a 1.5 mm thickness and a relative permeability of 2 is employed as a separator between the inner and electromagnet coil on the tool's tip side, to concentrate the magnetic field at tip of the tool.

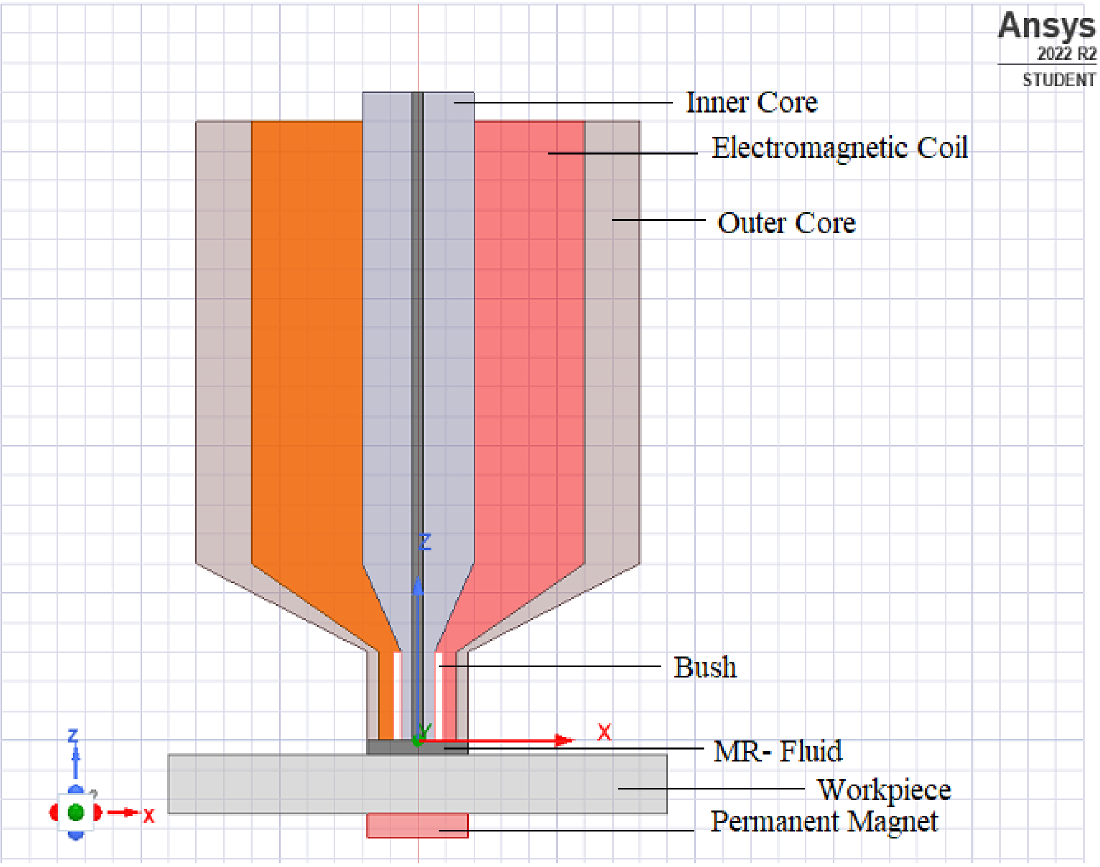

Figure 3.1: Schematic Diagram of MR-Finishing tool

The present values for the current and the number of turns given to the electromagnet are 2 A and 2000 turns, respectively. The copper used in the electromagnet coil has a relative permeability of 1.

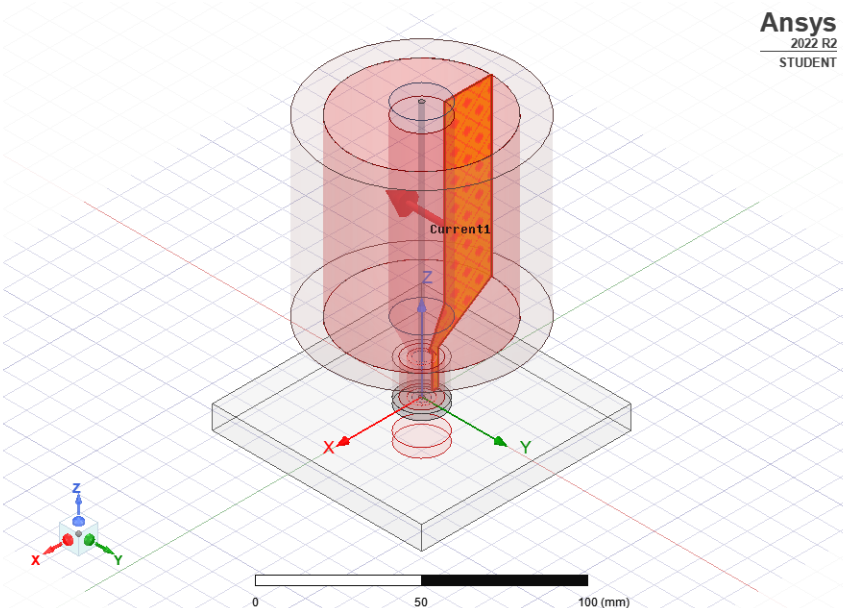

Figure 3.2: MR-Finishing tool with excited current set as 2A

The Boundary condition are applied to make the electromagnetic coil as insulated because it assists in confining and guiding the electromagnetic fields produced by the coil, enabling enhanced accuracy and predictable manipulation of its magnetic characteristics.

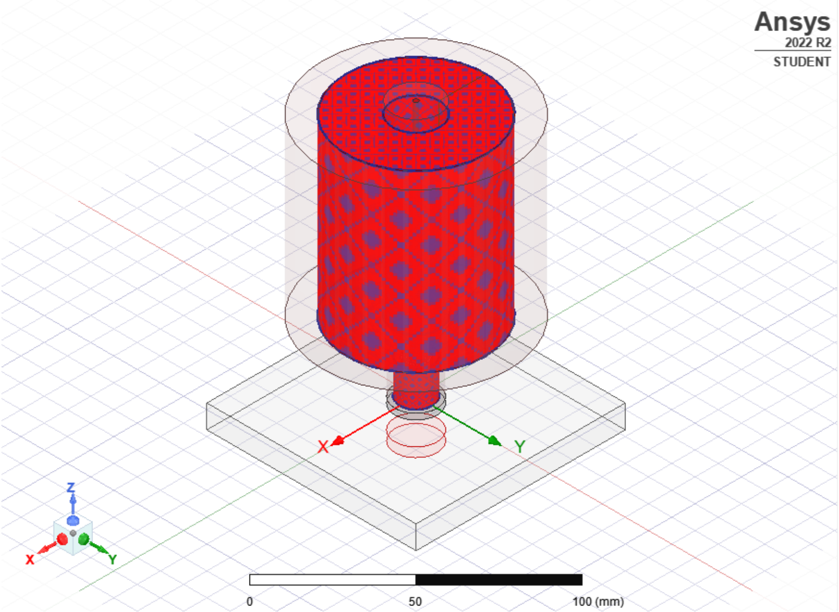

Figure 3.3: MR-Finishing tool with insulated electromagnetic coil

The need for an electromagnetic model arises from the desire to optimize the interaction between the magnetic field and MR fluids, leading to enhanced material removal rates and surface quality.

A magnet made of NdFe30 material, measuring 9 mm in radius and 4 mm in thickness, is created and positioned beneath the object to draw the magnetic field lines when dealing with non-ferromagnetic materials.

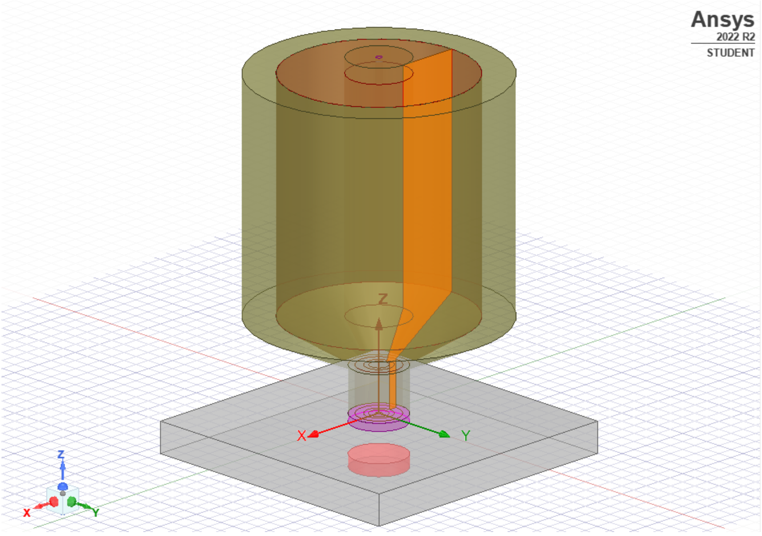

Figure 3.4: 3D MR-finishing tool with permanent magnet placed beneath the workpiece

Table 3.1: Assigned parameters to electromagnet model

Parameter	**Material**	**Relative Permeability**	**Current**	**No. of turns**
MRP-Fluid	MR Fluid	4		
Inner Core	Iron	4000		
EM-Coil	Copper	1	2 Amp	2000
Outer Core	Iron	4000		
Workpiece	Aluminium	1		
Permanent Magnet	NdFe30	1.04457		

Table 3.2: Dimension of electromagnet model

Parameter	**Diameter (mm)**
MRF	2
Inner Core	20
EM-Coil	60
Outer Core	80
Permanent Magnet	18

Table 3.3 Dimension of workpiece

Parameter	**Dimension**
Workpiece	100mm*100mm*10mm

CHAPTER 4

MAGNETOSTATIC SIMULATION

4.1 DESIGN OF EXPERIMENT (DOE)

Extensive research has clearly shown that the process parameters related to magnetic flux density, such as the working gap, current, number of turns, and bush height, significantly influence the physical properties of the specimen under investigation. The conventional approach to design is utilized in situations where a specific factor is altered, and its effects are observed. This indicates the need to conduct multiple experiments to analyze its importance but the whole procedure is quite tiresome and consumes a significant amount of time. Essentially, the procedures for designing experiments can be broken down into three key principles:

Randomization: In order to minimize the influence of external variables, it is recommended to organize experimental trials in a random sequence..

Replication: It is expected that each combination of factors will result in comparable experimental runs, facilitating the calculation of generated experimental errors. The measurement of errors plays a crucial role in determining if the differences in the data exhibit mathematical variability.

Blocking: This particular factor is beneficial in reducing the influence of elements that affect the outcome but holds little significance for our objective. These factors are commonly known as noise elements.. The term commonly used to describe comparable experimental scenarios is Block, where the researcher divides the study based on the mathematical model into groups that correspond to each block [45].

The complete procedure involves examining the input parameters and constructing statistical models to comprehend the relationship between these parameters. The process undertaken to accomplish the aforementioned state involves:

1. Identification of essential process control factors.

2. Deciding the working scope of the procedure control factors, viz. Bush Height, and Number of turns.
3. Developing the design matrix.
4. Conducting the simulation according to the design matrix.
5. Recording the response.
6. Developing the numerical models.
7. Checking the adequacy of the models.
8. Finding the significance of the coefficient.
9. Developing the final proposed models.
10. Plotting of diagrams and drawing conclusion.
11. Discussion of the outcomes.

4.1.1 Identification of multiple factors influencing process control.

When considering the magnetorheological tool geometry, two specific parameters that require attention are the height of the bush and the number of turns.

4.1.2 Deciding the extent of the variables involved in the process

The working gap and current is kept constant. The coding scheme has been established with +2 and -2 designated as the upper and lower boundaries. To determine coded values for intermediate values, a formula is used, where Xi represents the desired coded value of a variable X within the range of Xmin to Xmax. Xmax and Xmin represent the highest and lowest levels of the factors. Table 3.1 presents the selected process parameters, their respective upper and lower limits, as well as relevant documentation and units.

Table 4.1: Process control parameters and their range

S. No.	**Process Parameter**	**Unit**	**Levels**				
			-2	**-1**	**0**	**1**	**2**
1	Bush Height	mm	5	10	15	20	25
2	Number of turns		1800	1900	2000	2100	2200

4.1.3 Constructing the design framework

The composite design with non-center points: 8 and center points: 5 under response surface methodology is selected for design framework in STAT-EASE360 software. Each Numeric factor is set to 5 levels, ranging from -2 to +2. The height of the bush and the number of turns are regarded as variables, and a design of experiments (DOE) table is created to study them. The following table illustrates the encoded values assigned to each numerical factor.

Table 4.2: Design matrix

Std	Run	Coded value of Bush Height	Coded value of Number of Turns	Actual value of Bush Height (mm)	Actual value of Number ofTurns
1	10	0	0	15	2000
2	5	0	0	15	2000
3	3	-1	1	10	2100
4	6	1	-1	20	1900
5	12	0	2	15	2200
6	2	1	1	20	2100
7	1	-2	0	5	2000
8	7	0	0	15	2000
9	13	-1	-1	10	1900
10	9	0	0	15	2000
11	11	0	0	15	2000
12	4	0	-2	15	1800
13	8	2	0	25	2000

4.2 VARIATION OF MAGNETIC FLUX DENSITY AT MR-FINISHING TOOL TIP

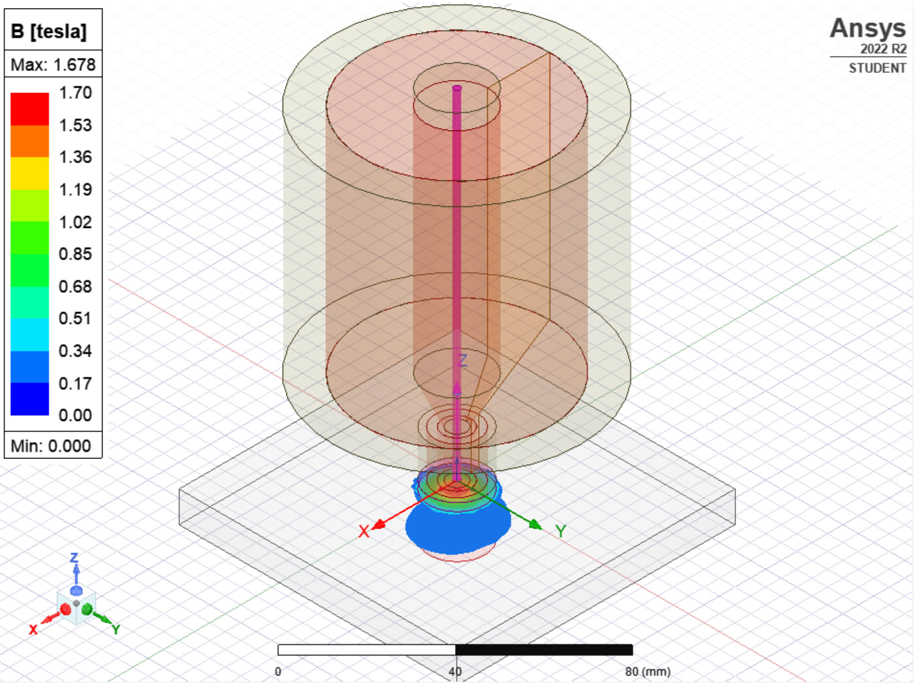

Figure 4.1: Magnetic flux density at bush height 15 mm and number of turns 2000

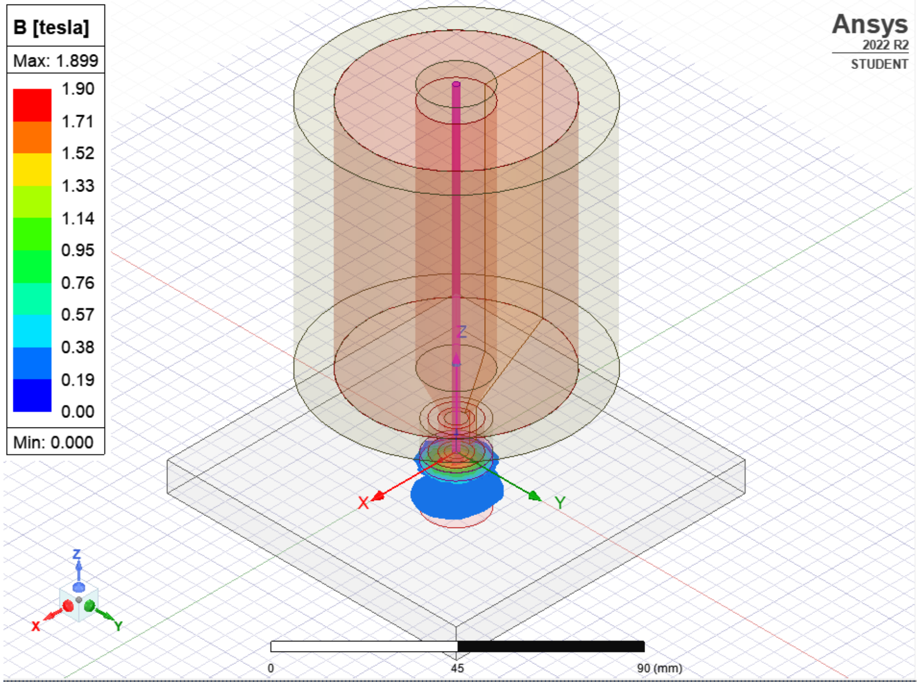

Figure 4.2: Magnetic flux density at bush height 10 mm and number of turns 2100

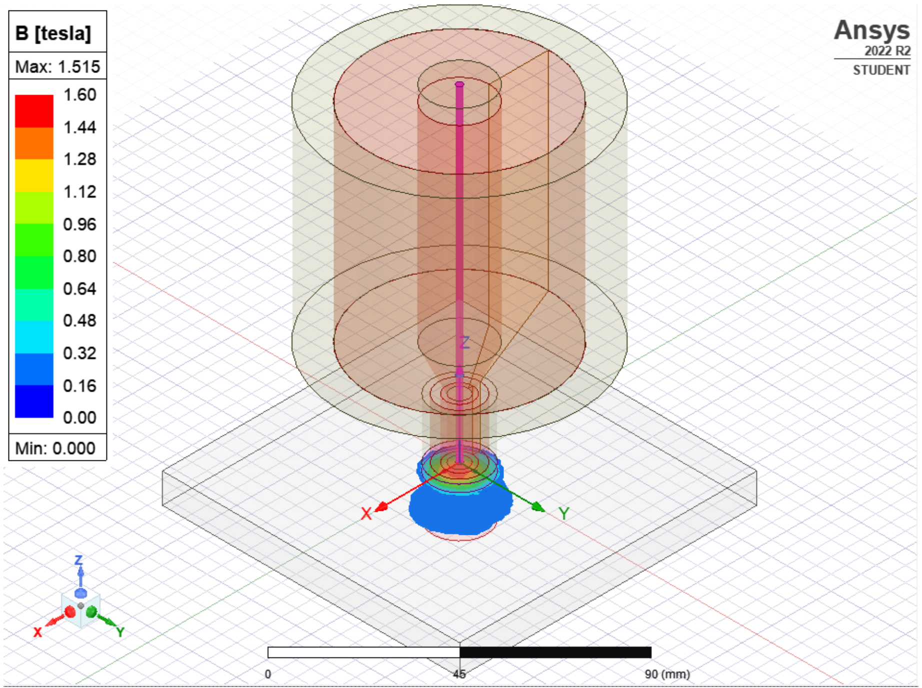

Figure 4.3: Magnetic flux density at bush height 20 mm and number of turns 1900

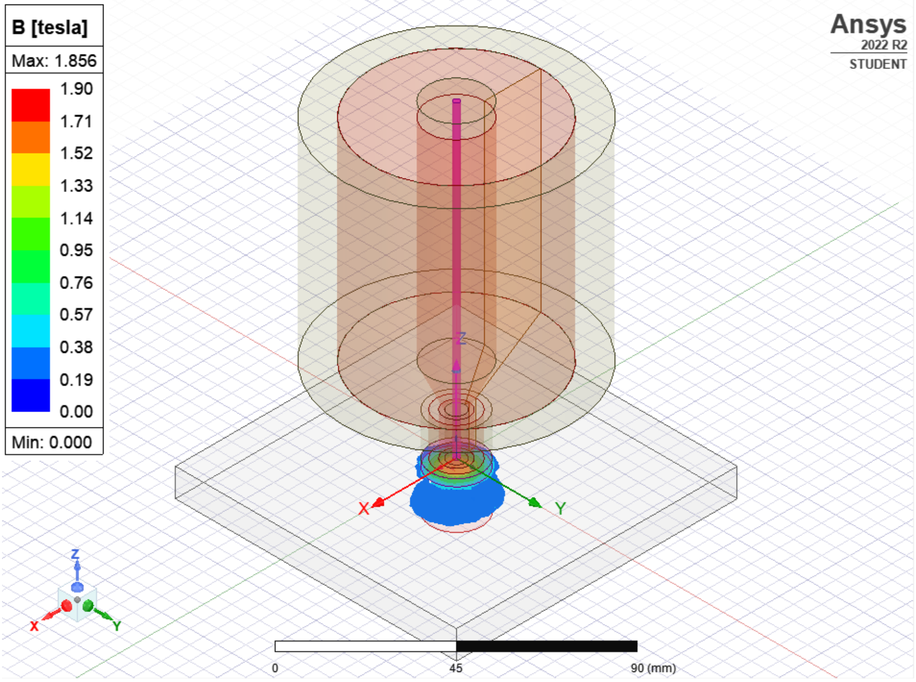

Figure 4.4: Magnetic flux density at bush height 15mm and number of turns 2200

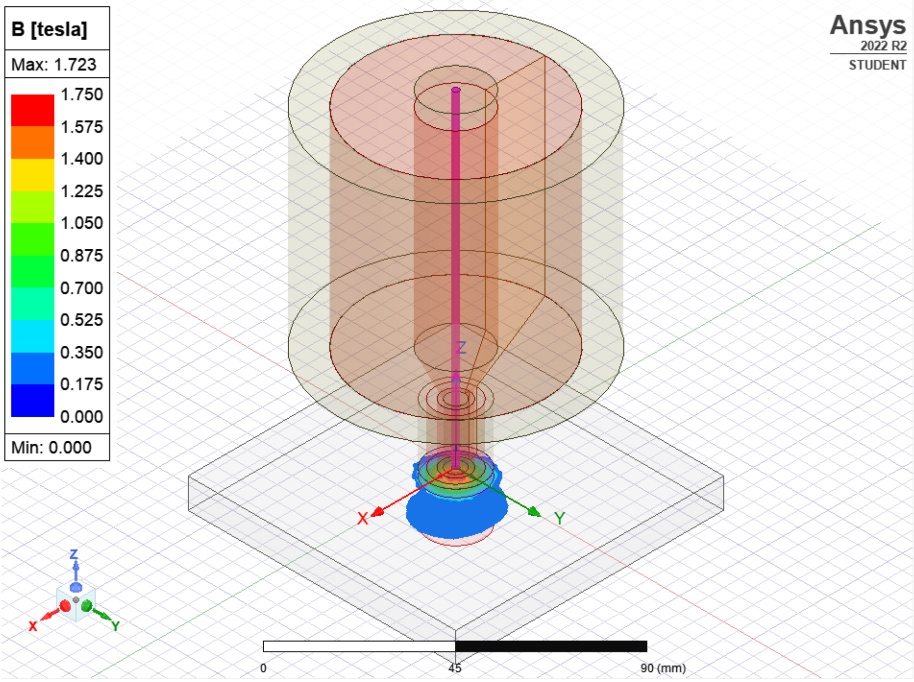

Figure 4.5: Magnetic flux density at bush height 20 and number of turns 2100

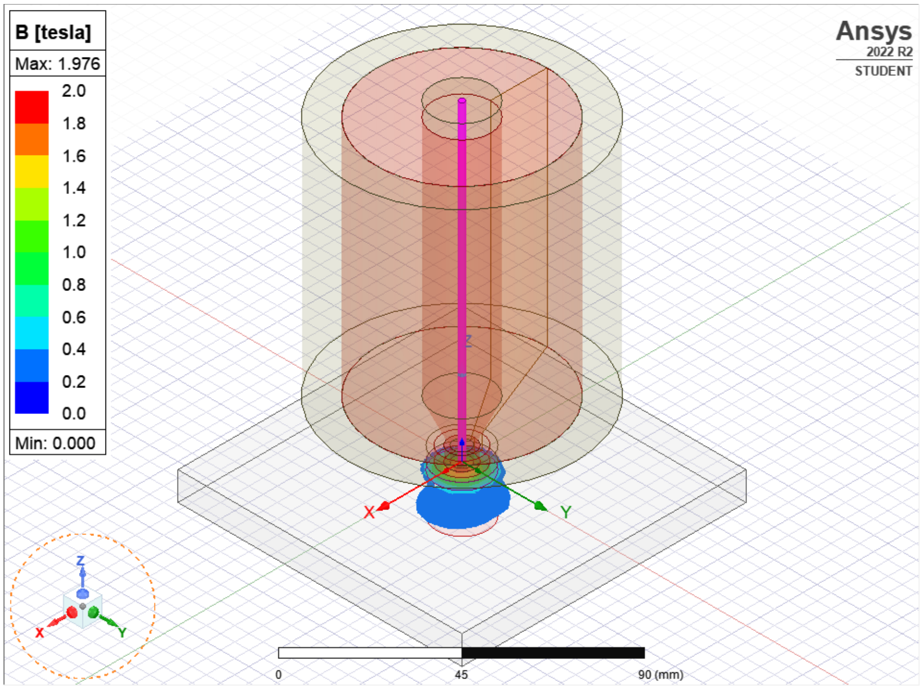

Figure 4.6: Magnetic flux density at bush height 5 mm and number of turns 2000

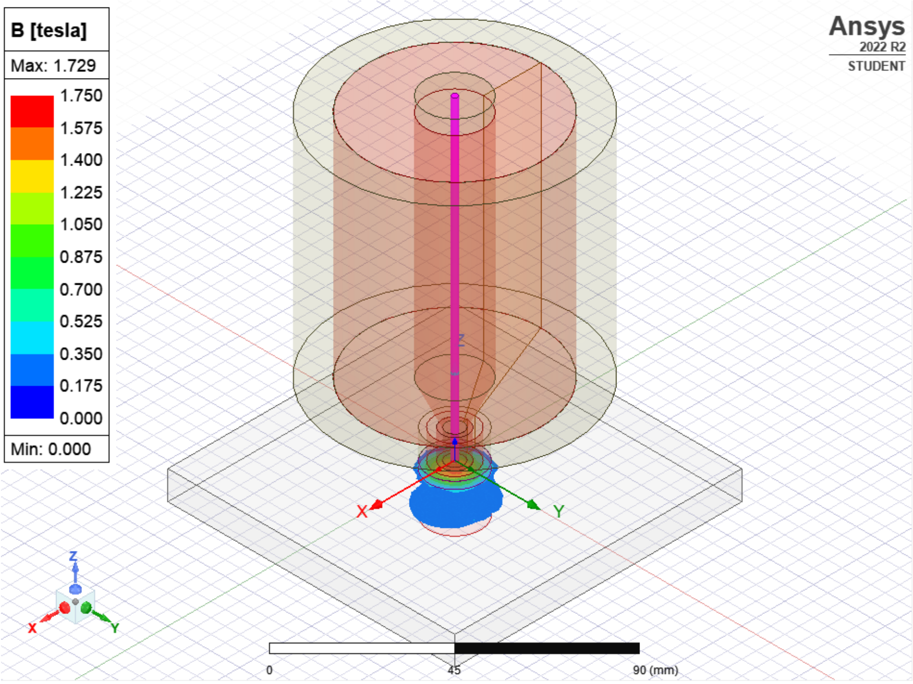

Figure 4.7: Magnetic flux density at bush height 10 mm and number of turns 1900

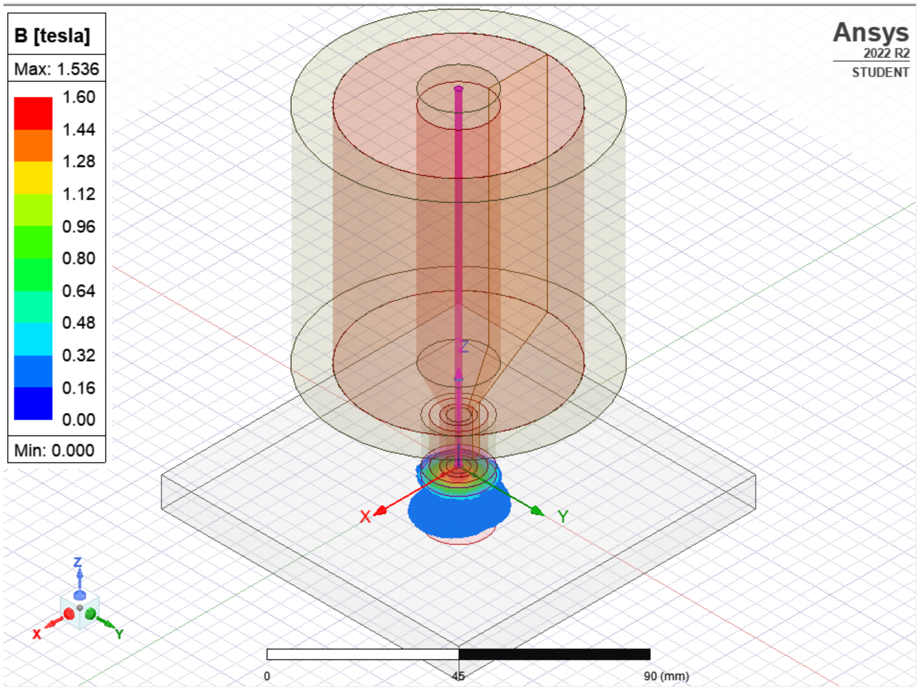

Figure 4.8: Magnetic flux density at bush height 15 mm and number of turns 1800

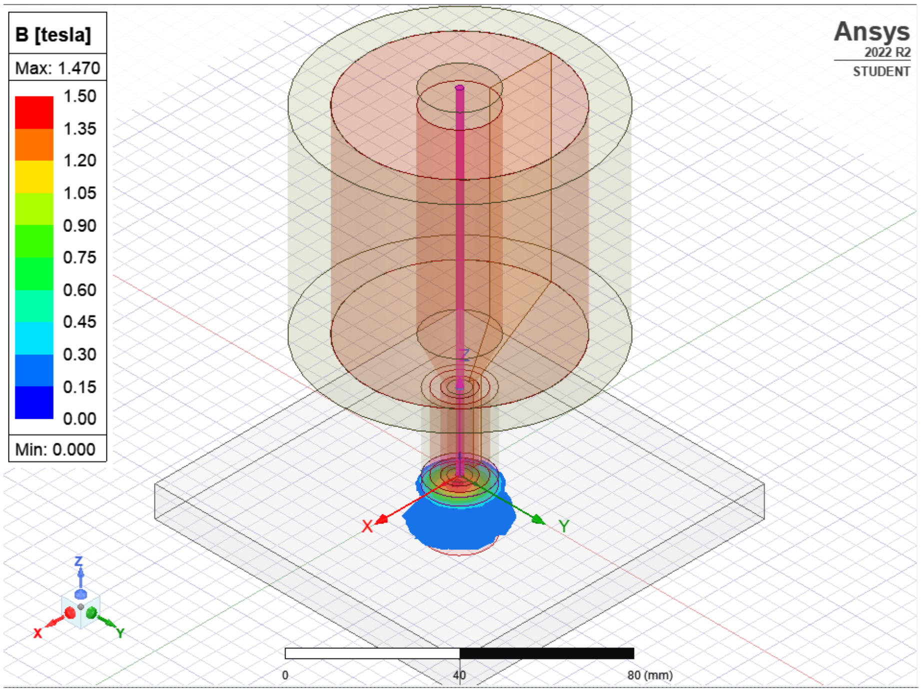

Figure 4.9: Magnetic flux density at bush height 25 mm and number of turns 2000

4.3 MAGNETOSTATIC SIMULATION OF DIFFERENT MR-FLUID

The MRF-122EG, MRF-126LF and, MRF-140CG fluid consists of tiny magnetizable particles dispersed in a fluid medium. The rheology of the these fluids undergoes a reversible and immediate transformation, shifting from a liquid that flows freely to a semi-solid state with an adjustable yield strength when subjected to a magnetic field [46]. Modifying the intensity of the magnetic field applied accurately and proportionately regulates the uniformity or resilience of the fluid. These fluids has the versatility to be employed either in valve mode, where it flows through an orifice, or in shear mode, where it shears between two surfaces [47]. When there is no magnetic field present, these fluids can move without any restrictions or obstacles. When a magnetic field is applied, the particles of the fluid align in a linear manner with the direction of the field. As a result, the fluid's movement within the gap is limited in proportion to the intensity of the magnetic field.

These fluid is an MR fluid that relies on hydrocarbons and is designed to be used in various applications that require controlled and energy-dissipating functions, such as shocks, dampers, and brakes [48].

Table 4.3: Properties of MRF Fluids [46-48]

MR-Fluid	**Density**	**Viscosity**	**Solid Content by Weight, %**	**Operating Temperature**	**Flash Point**	**Appearance**
MRF-122EG	2.28-2.48	0.042 ± 0.020	72	-40 to +130	>150	Dark Gray Liquid
MRF-126LF	2.64-2.84	0.070 ± 0.020	78	-40 to +130	>150	Dark Gray Liquid
MRF-140CG	3.54-3.74	0.280 ± 0.070	85.44	-40 to +130	>150	Dark Gray Liquid

The tool with maximum flux density as obtained in fig. 4.6 is further used to analyze the effect of magnetic flux density on three different MR Fluid. The magnetic behavior of these MR fluids is characterized by non-linearity, and this characteristic has been simulated using ANSYS Maxwell software. The data points of B-H curve is imported to analyze the effect of magnetic flux density at the tool's tip.

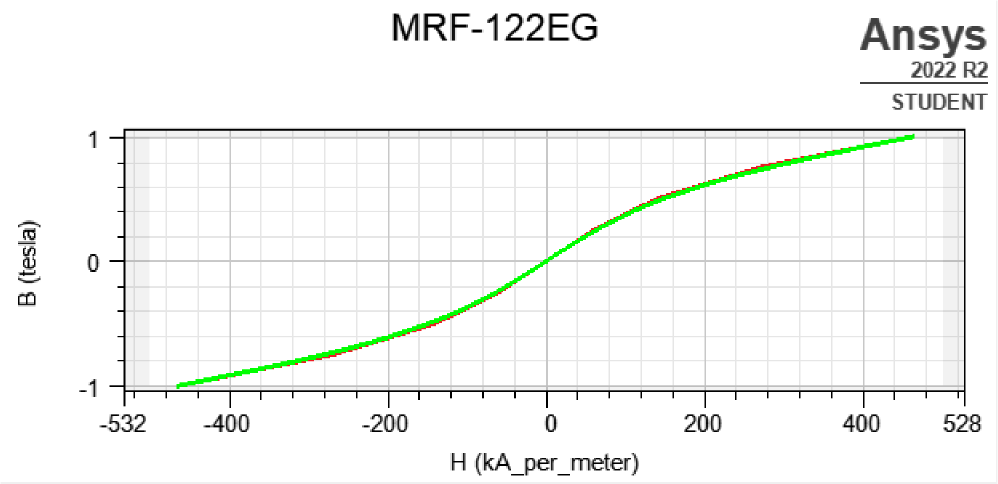

Figure 4.10: B vs H for MRF-122G

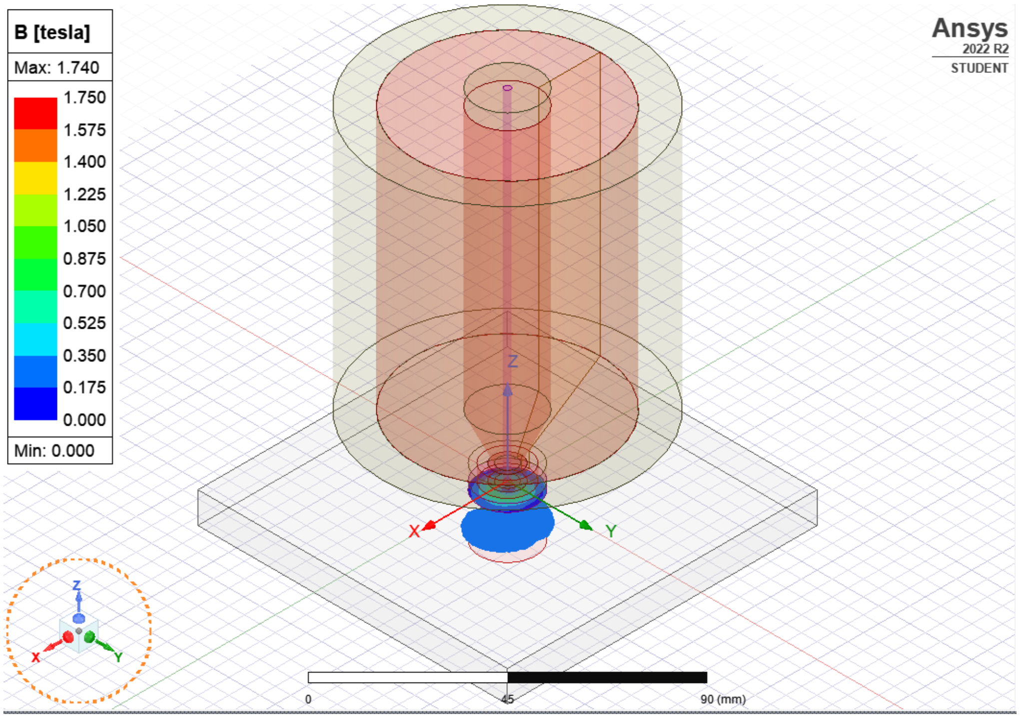

Figure 4.11: Magnetic flux density of MRF-122EG at bush height 5 mm and number of turns 2000

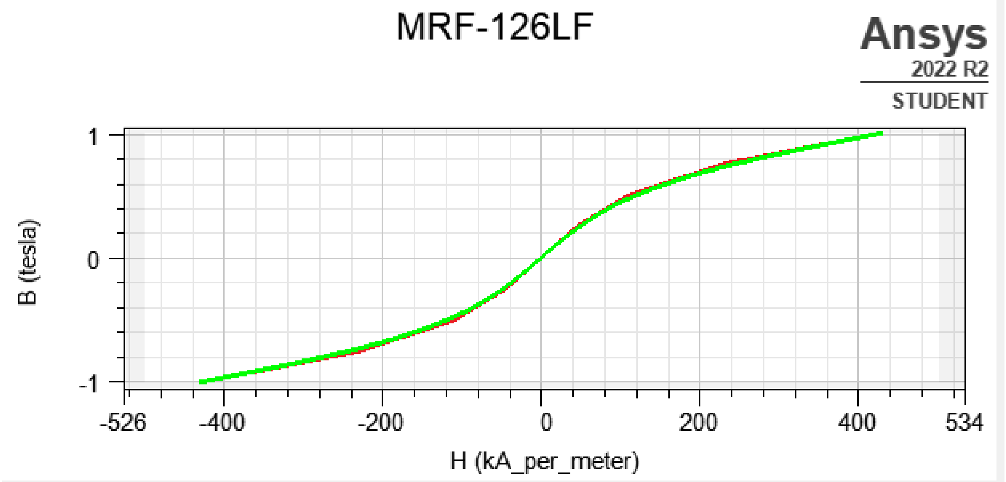

Figure 4.12: B vs H for MRF-126LF

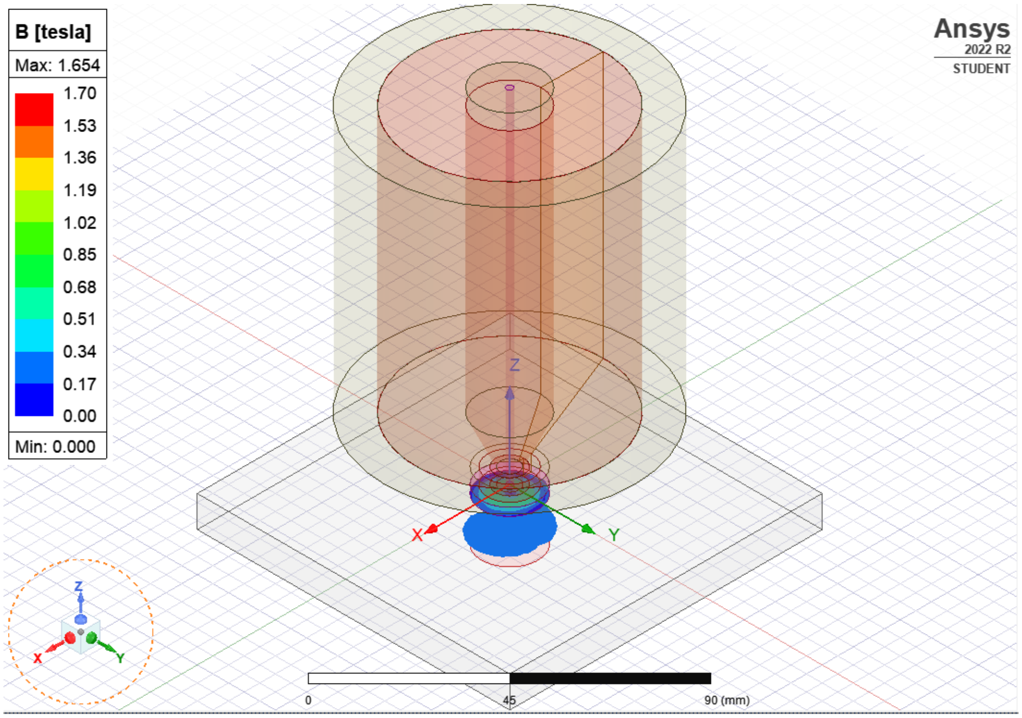

Figure 4.13: Magnetic flux density of MRF-126LF at bush height 5 mm and number of turns 2000

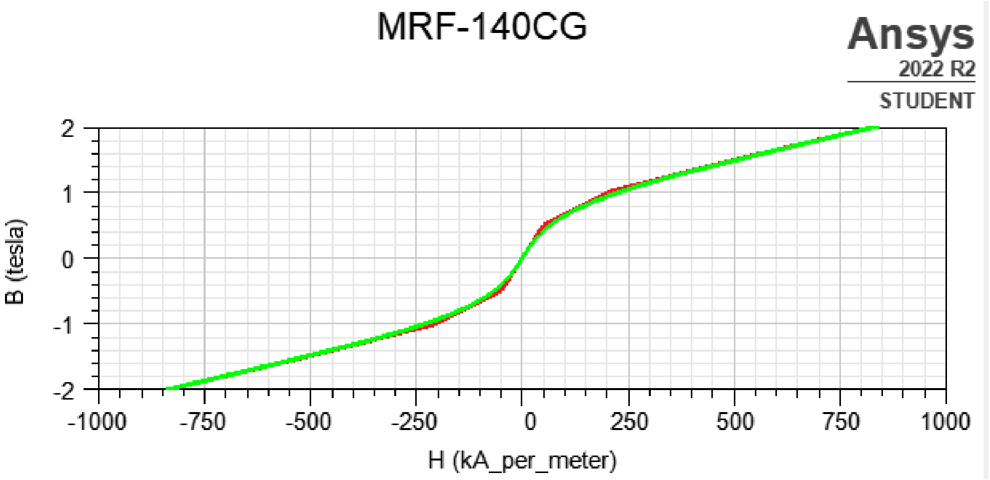

Figure 4.14: B vs H for MRF-140CG

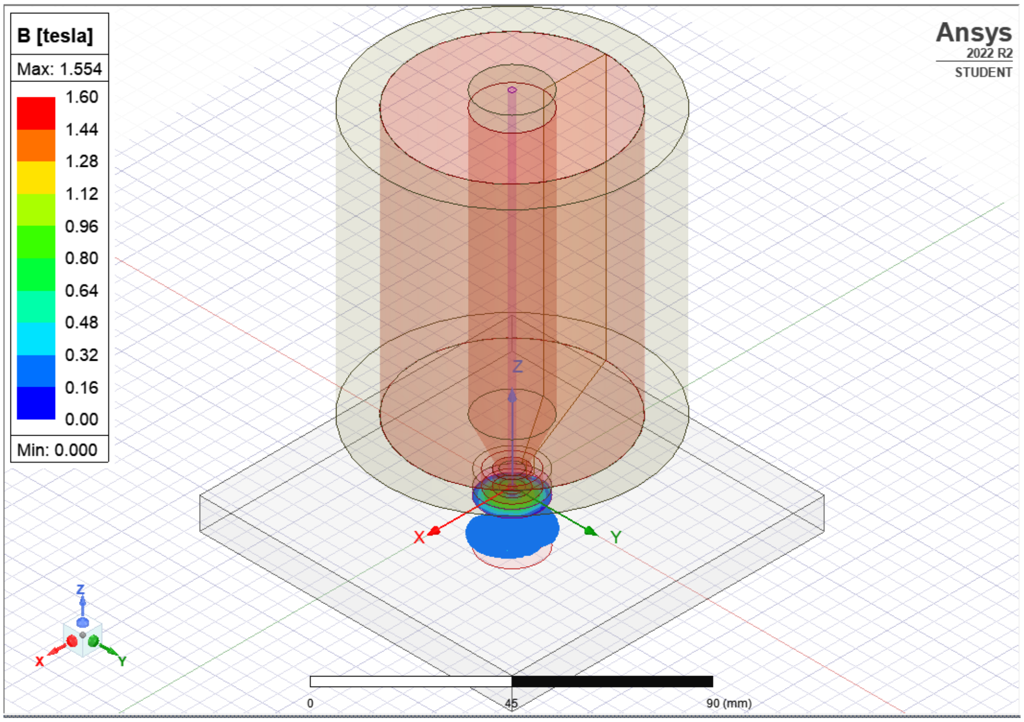

Figure 4.15: Magnetic flux density of MRF-140CG at bush height 5 mm and number of turns 2000

4.4 Recording of responses

After simulating various models of MRF tools, the responses were recorded. The magnetic flux density served as the output response in this experiment. The recorded responses were entered into Design Expert Software and are presented in Table 4.4

Table 4.4: Recording of responses

Std	Run	Coded value of Bush Height	Coded value of Number of Turns	Actual value of Bush Height (mm)	Actual value of Numberof Turns	Magnetic Flux Density (Tesla)
1	10	0	0	15	2000	1.678
2	5	0	0	15	2000	1.678
3	3	-1	+1	10	2100	1.899
4	6	1	-1	20	1900	1.515
5	12	0	+2	15	2200	1.856
6	2	1	1	20	2100	1.723
7	1	-2	0	5	2000	1.976
8	7	0	0	15	2000	1.678
9	13	-1	-1	10	1900	1.729
10	9	0	0	15	2000	1.678
11	11	0	0	15	2000	1.710
12	4	0	-2	15	1800	1.536
13	8	+2	0	25	2000	1.470

Table 4.5: Magnetic Flux Density of different MR-Fluid

S.No.	MR-Fluid	Maximum Flux Density (Tesla)	Minimum Flux Density (Tesla)
1	MRF-122EG	1.740	0
2	MRF-126LF	1.654	0
3	MRF-140CG	1.554	0

CHAPTER 5

STATISTICAL ANALYSIS

5.1 INTRODUCTION

Models are built to establish a connection between input factors such as the height of a bush and the number of turns, and the resulting output response, specifically the magnetic flux density. These computer models are utilized to evaluate the reaction for a specific set of process parameters when they are integrated into the system. The ultimate information was collected to assess the linear and non-linear characteristics of the models, and thereafter the viability of the model is evaluated through ANOVA and visual representations.

The task was accomplished using the trial version of STAT-EASE 360 22.0.6 software.

5.1.1 Developments of statistical models.

The output response in relation with input process parameter can be expressed as:-

Y = f (Bush Height, Number of Turns)

Y = Magnetic Flux Density

5.1.2 STAT-EASE 360 Trial Version 22.0.6 software.

The utilization of STAT-EASE 360 software proves to be highly valuable when it comes to implementing significant advancements to a product or a process. STAT-EASE 360 provides advanced statistical analysis functionalities alongside its experiment design features. It offers a wide range of tools for examining experimental data extensively, such as analysis of variance (ANOVA), multiple regression, optimization, and visual representation in graphs. These instruments empower individuals to recognize important elements, measure their impacts, and establish the best configurations for attaining desired results.

In STAT-EASE 360, the ANOVA method entails dividing the overall observed variation in the response variable into distinct categories of variation, including the primary effects of factors and their interactions. The act of partitioning enables the evaluation of the individual contributions of each factor and helps determine their importance in impacting the response.

5.2 INVESTIGATING THE FEASIBILITY OF THE MODEL

The ANOVA technique is beneficial for assessing the practicality of the suggested model. This approach allows for the examination of the proposed model's viability:

1. The F ratio serves as a means to assess the confidence test by comparing the calculated tabulation with the reference tabulation, thereby examining their similarity.
2. A crucial requirement for determining feasibility is that the Calculated F ratio should always be lower than the reference value, indicating that the model is sufficiently suitable. In our analysis, we have set the confidence level at 95%.

5.2.1 Response 1: Magnetic Flux Density

Table 5.1: ANOVA for Reduced linear model of R1

Source	**Sum of Squares**	**Df**	**Mean Square**	**F-value**	**p-value**	**Status**
Model	0.2502	2	0.1251	170.70	< 0.0001	significant
a-Number of turns	0.0864	1	0.0864	117.86	< 0.0001	
B-Bush Height	0.1638	1	0.1638	223.55	< 0.0001	
Residual	0.0073	10	0.0007			
Lack of Fit	0.0065	6	0.0011	5.30	0.0643	not significant
Pure Error	0.0008	4	0.0002			
Cor Total	0.2575	12				

Factor coding is **coded**.

The **Type III - Partial** designates that the sum of squares is calculated as the sum of squared values.

The model's F-value of 170.70 indicates its significance. The probability of obtaining such a large F-value by chance alone is extremely low, at only 0.01%.

Model terms are considered significant when their p-values are below 0.0500**.** The importance of terms a and B has been noted/observed. In this scenario, the terms A and B hold importance in the model. Values exceeding 0.1000 suggest that these terms lack significance.. Model reduction can enhance your model if it contains numerous inconsequential terms, excluding those needed for hierarchy support.

Ultimately, the lack of significance in the Lack of fit F value should be maintained when comparing a model to the pure error. The Lack of Fit F-value, which is 5.30, suggests that there is a 6.43% probability for such a significant Lack of Fit F-value to happen purely by chance or random variation.

Table 5.2: Fit Statistics

Std. Dev.	0.0271	**R^2**	0.9715
Mean	1.70	**Adjusted R^2**	0.9659
C.V. %	1.59	**Predicted R^2**	0.9473
		Adeq Precision	35.9389

The **Predicted R^2** value of 0.9473 closely aligns with the Adjusted R^2 value of 0.9659, indicating a negligible difference of less than 0.2.

Adeq Precision evaluates the ratio between the signal and background noise. An ideal situation involves a ratio that exceeds 4. In our situation, the proportion stands at 35.939, suggesting a satisfactory signal. This particular model has the potential to guide us through the various possibilities in the design realm.

Final Equation in Terms of Coded Factors

$$R1 = +1.64 + 0.0848 * a - 0.1753 * B \qquad (5.1)$$

The equation that involves coded factors enables the prediction of the response for specific levels of each factor. The coding for the high levels of the factors is +1, while the coding for the low levels is -1, as a default setting. The encoded formula is beneficial in determining the relative influence of the factors by examining the coefficients assigned to each factor.

Final Equation in Terms of Actual Factors of R1

$$R1 = +0.355833 + 0.000848 * \text{Number of Turns} - 0.023367 * \text{Bush Height} \qquad (5.2)$$

The equation, when considering real factors, enables us to forecast the outcome based on specific levels of each factor. In the original units for each factor, it is important to provide specific levels. Using this equation to assess the comparative influence of each factor is not recommended due to the coefficients being adjusted to match the units of the factors and the intercept not being positioned at the center of the design space.

CHAPTER 6

RESULT ANALYSIS AND DISCUSSION

6.1 ANALYSIS OF ANSYS Maxwell SIMULATION RESULT

The maximum value of magnetic flux density at tool's tip is found to be 1.976 Tesla and it is achieved at bush height 5 mm and number of turns 2000.

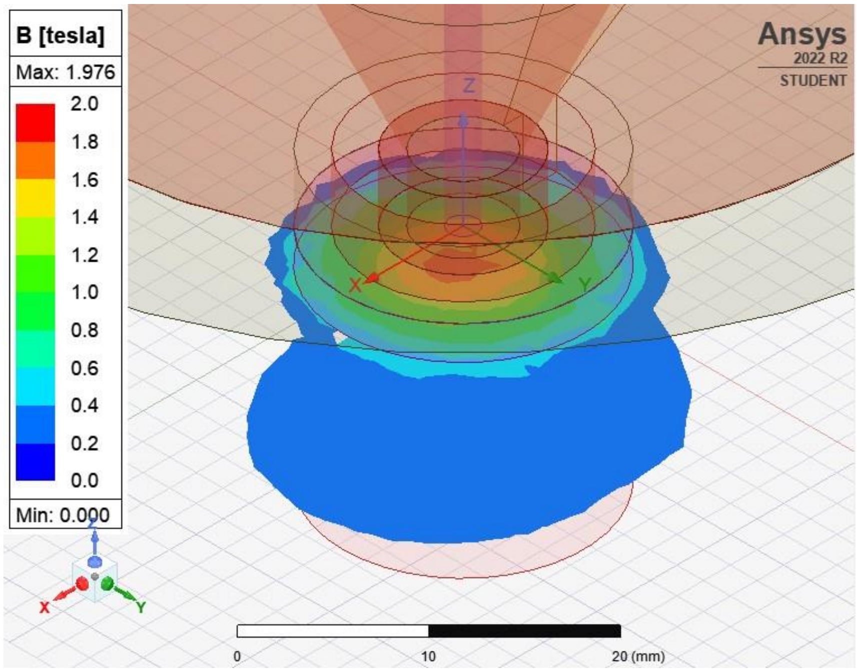

Figure 6.1: Maximum value of Magnetic Flux Density at bush height 5 mm and number of turns 2000

6.2 STATISTICAL ANALYSIS RESULT

6.2.1 Predicted and Actual point of Magnetic Flux Density

The graph presented illustrates the Magnetic Flux Density with actual data shown on the x-axis and predicted data on the y-axis. The red dots represent the highest values of Magnetic Flux Density, while the blue dot represents the lowest values. The graph clearly indicates a resemblance between the actual and predicted data, indicating a correlation between the two sets of data points.

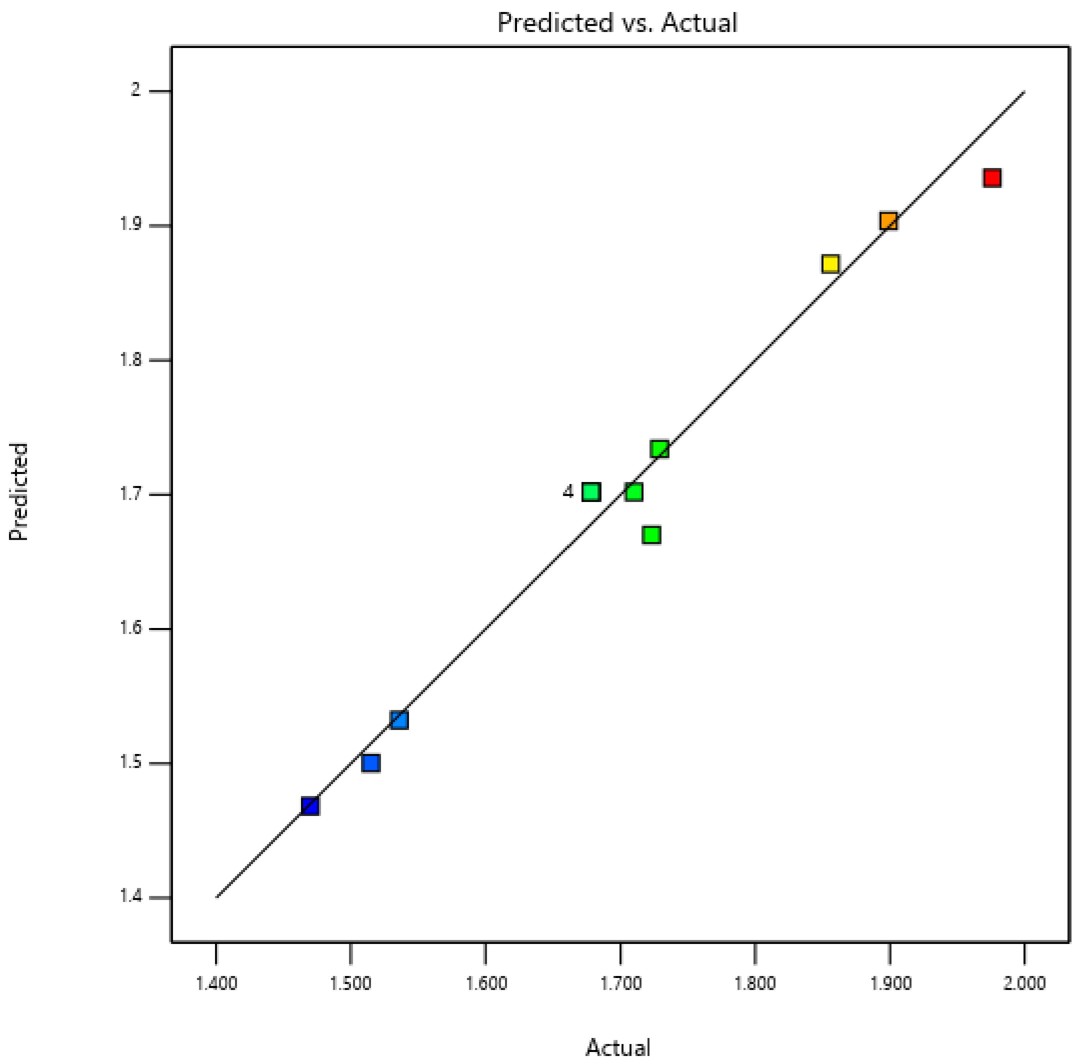

Figure 6.2: Predicted vs. Actual points of Magnetic Flux Density

6.2.2 Variation of Magnetic Flux Density with Bush Height and Number of turns

As the number of turns in the electromagnet coil increases, the magnetic flux density also increase. This enhanced magnetic flux leads to a stronger interaction between the suspended magnetic particles in the MRF and the workpiece surface. The greater the magnetic flux, the more pronounced the forces acting on the particles, resulting in higher material removal rates during the finishing process.

However, it is important to note that there is an optimal range for the number of turns in the electromagnet coil. Increasing the number of turns beyond this range may lead to diminishing returns or even detrimental effects. Excessive magnetic field strength can cause agglomeration of the magnetic particles, resulting in non-uniform material removal and surface defects.

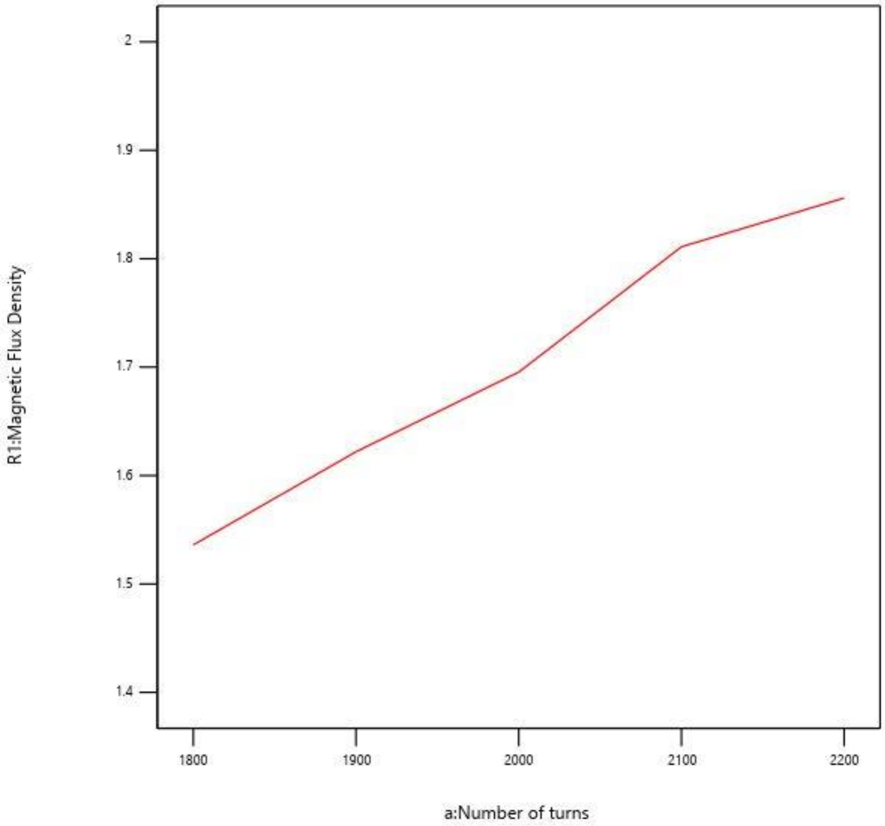

Figure 6.3: Number of turns vs. Magnetic Flux Density

As the bush height increases in a magnetorheological finishing tool, the magnetic flux density typically decreases. This decrease in magnetic flux density occurs due to the spreading out of the magnetic field as it propagates from the electromagnet to the workpiece surface.

At smaller bush heights, the distance between the electromagnet and the workpiece surface is reduced, leading to a higher concentration of magnetic field lines in the vicinity of the workpiece. This concentrated magnetic field results in higher magnetic flux density in the MRF, leading to stronger forces acting on the suspended magnetic particles.

Conversely, as the bush height increases, the magnetic field lines become more spread out, causing a decrease in the magnetic flux density. This decrease in magnetic flux density weakens the interaction between the MRF particles and the workpiece surface. Consequently, the material removal rates during the finishing process may be reduced.

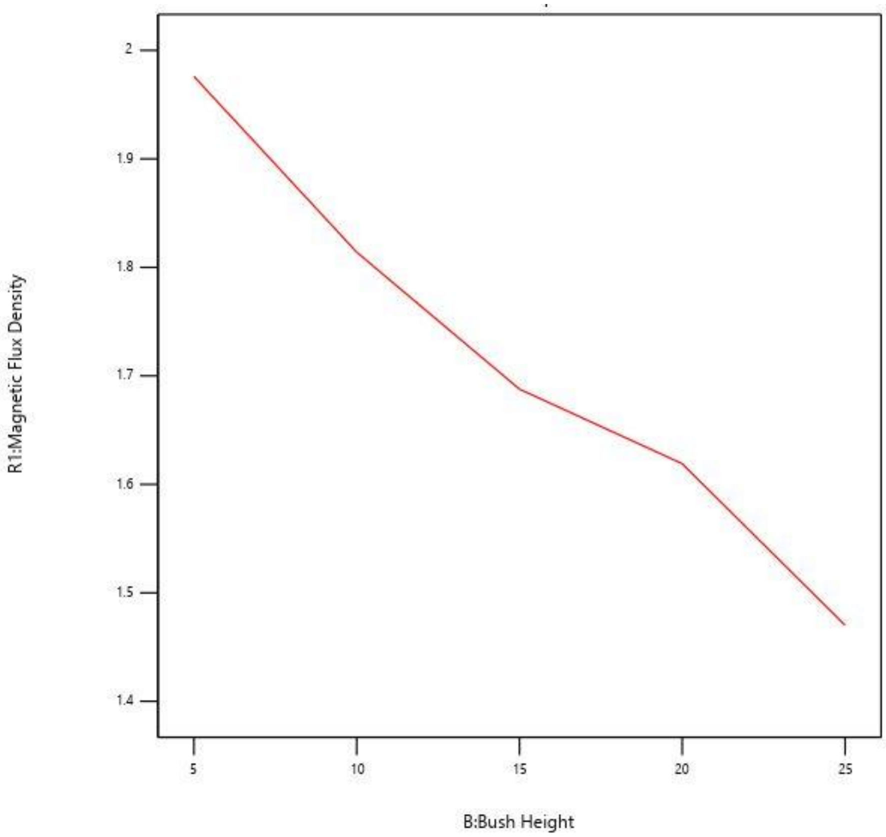

Figure 6.4: Bush Height vs. Magnetic Flux Density

6.2.3 Contour plot of Magnetic Flux Density with Bush Height and Number of turns

The contour plot displays the connection between the response, numeric factors, and/or mixture components by representing them in a two-dimensional format. It visually demonstrates how these variables are related to each other.

The graph illustrates the relationship between number of turns and bush height (mm). The magnetic flux density point is achieved on this curve. The red regions indicate the highest magnetic flux density (2.010 Tesla), while the blue regions indicate the lowest magnetic flux density (1.4 Tesla).

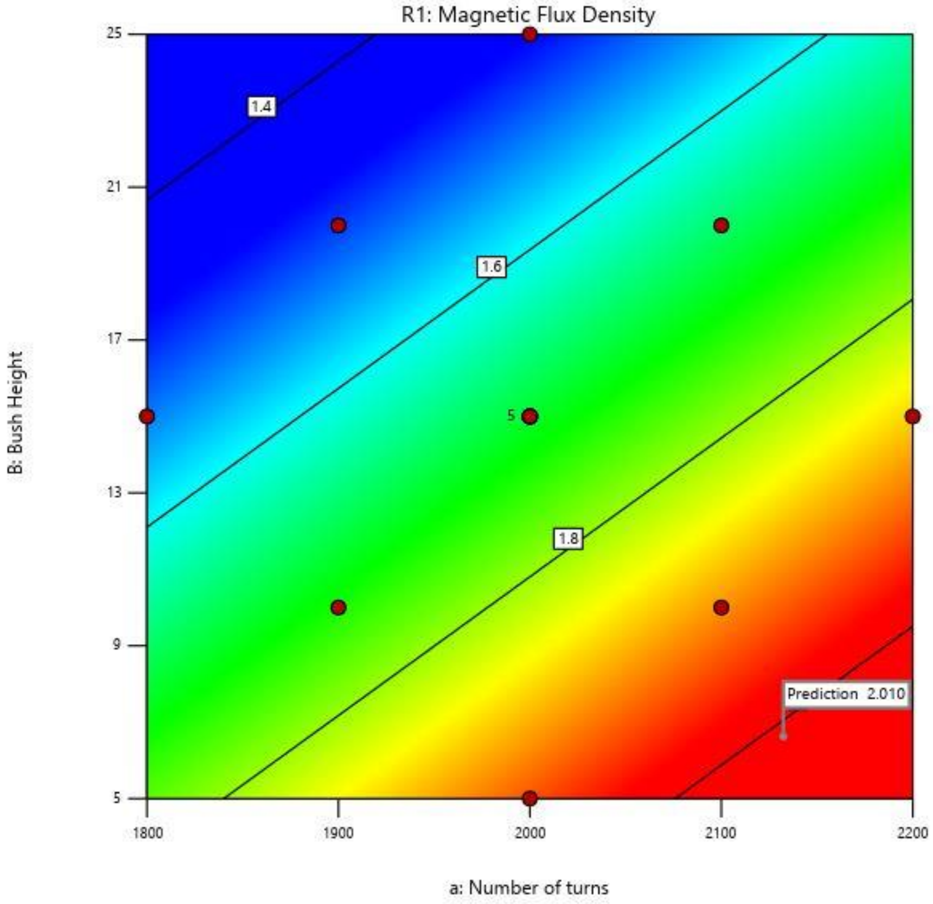

Figure 6.5: Contour plot of Magnetic Flux Density between bush height and number of turns

The 3D Surface plot adds visual depth to the contour plot by displaying the shape along with the color and contour.

The graph illustrates the relationship between number of turns and bush height on the x1 and x2 axes, respectively, while magnetic flux density is represented on the y-axis. The response surface is three-dimensional in its geometry.

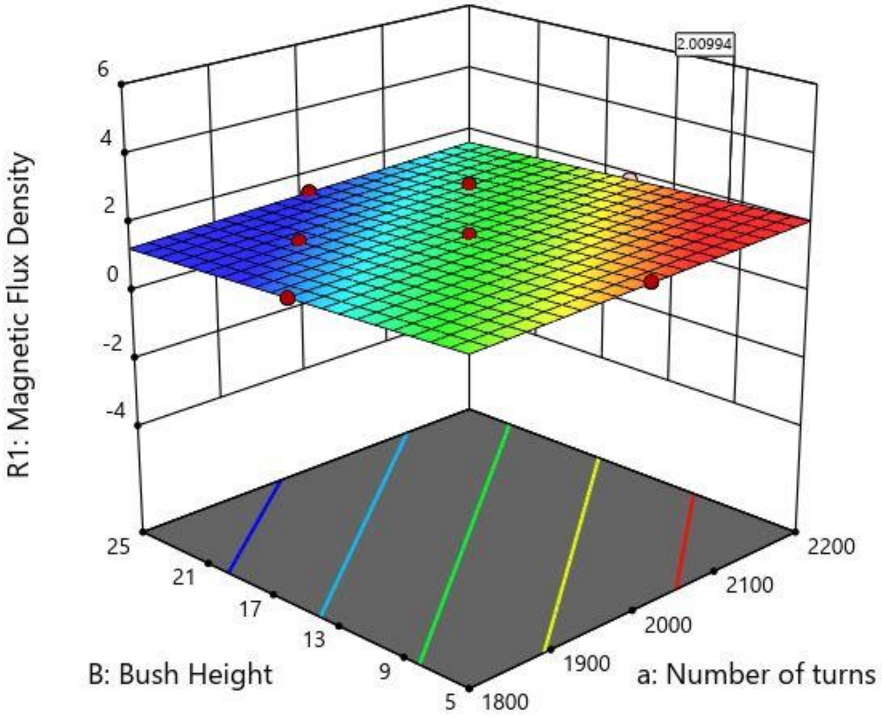

Figure 6.6: 3 D Response Surface plot of Magnetic Flux Density between Bush Height and Number of turns

6.3 RESULT OPTIMIZATION

The crucial aspect involves optimizing the outcome of the experiment. The process of optimizing various response parameters is detailed as follows:

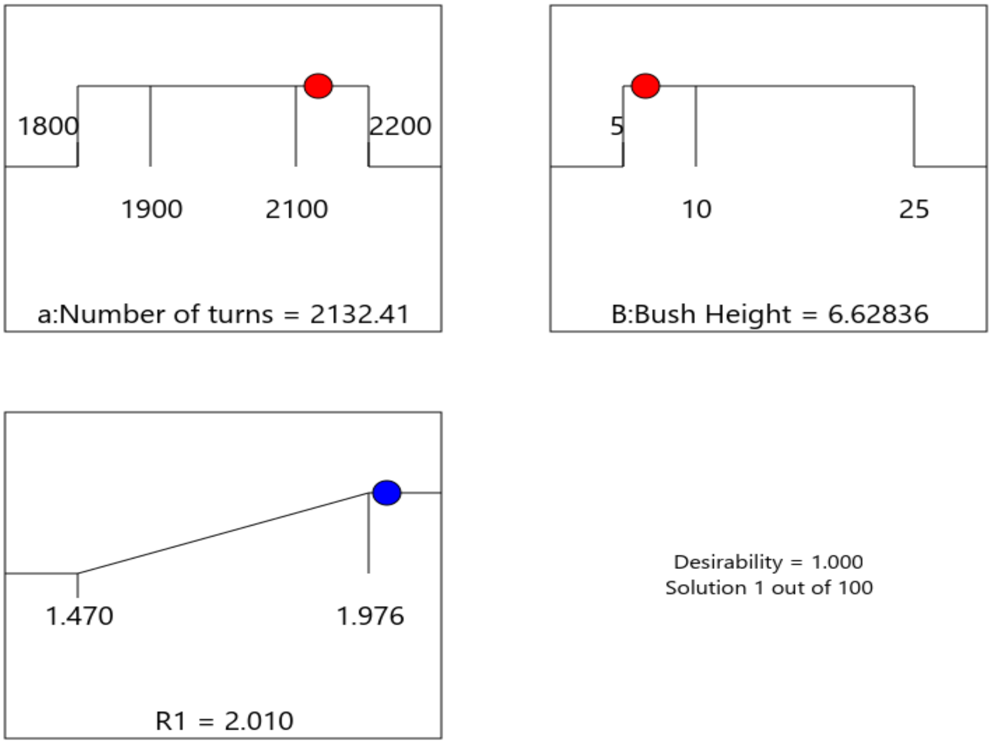

Figure 6.7: Optimum result of considered factors

The best outcome was achieved by considering a range of bush height values between 5 mm and 25 mm, and a range of turns between 1800 and 2200. The optimal values for R1 were found to be 2.010 Tesla, with a bush height of 6.63 mm and a number of turns equal to 2133.

6.4 POINT PREDICTION

Table 6.1 presents a description of the predicted values for the mean of the response parameter, standard deviation, lower 95% confidence interval for the mean, and upper 95% confidence interval for the mean. These predictions are based on the data points of the responses. The specific point predictions for the responses can be found in Table 6.1.

Table 6.1: Predict the mean of Response parameter

Response	Predicted Mean	Std Dev	95% CI low for Mean	95% CI high for Mean
R1	2.010	0.027	1.969	2.051
R1(POE)	2.00994	1.733	-0.599	4.619

CHAPTER 7

CONCLUSION AND FUTURE SCOPE OF STUDY

7.1 CONCLUSION

This dissertation introduces a study that focuses on simulating, optimizing, and analyzing a magnetorheological (MR) tool using ANSYS Maxwell 3D simulation software. The main objective was to examine the behavior and performance of the MR tool under different magnetic field conditions and enhance its functionality by optimizing its design. The simulation and analysis process yielded valuable insights and outcomes, summarized as follows:

1. By utilizing the Maxwell 3D simulation software, the MR finishing tool was successfully modeled and simulated. This software accurately represented how the tool responded to varying magnetic fields, enabling the evaluation of its real-world performance.
2. The workpiece material, which is not ferromagnetic, did not initially attract the magnetic field lines. However, once the permanent magnet was placed below the workpiece, the magnetic field lines started being drawn towards the surface of the workpiece, resulting in an increase in the strength of the magnetic field.
3. The maximum magnetic flux density after running the simulation in ANSYS Maxwell is found to be 1.976 Tesla at bush height 5 mm and number of turns 2000, whereas the maximum magnetic flux density by numerical optimization method is 2.010 Tesla at bush height 6.63 mm and number of turns 2133 and it's predicted value is 2.0094 Tesla. The optimum and predicted value of magnetic flux density is close enough which validates the model.
4. After conducting simulations on three different MR fluids, it was determined that the highest magnetic flux density achieved was 1.740 Tesla. This occurred specifically with the MRF-122EG fluid, when the bush height was set to 5 mm and the number of turns was 2000.
5. The ability to accurately predict and understand the MR tool's behavior through simulation offers a cost-effective and efficient approach to design optimization, reducing the reliance on extensive physical prototyping and testing.

7.2 FUTURE SCOPE OF STUDY

The dissertation presented in this study enhances the progress of magnetorheological tool design and optimization through the utilization of Maxwell 3D simulation software. The findings obtained from this research open new avenues for future studies and advancements in this field, ultimately resulting in the creation of MR tools that are more effective and dependable, and can be applied across various industries. The incorporation of this software exhibits great potential in influencing the future of MR tool development, empowering engineers to explore innovative ideas and push the limits of this captivating domain.

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