SELECTION OF OPTIMUM DESIGN OF MR FINISHING TOOL AND ITS ANALYSIS FOR FINISHING OF EN-31 WORKPIECE SURFACE.

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY

IN

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Submitted by

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CANDIDATE'S DECLARATION

I, **Kunal Krishna**, 2K21/PRD/06 hereby declare that the major project dissertation titled "**SELECTION OF OPTIMUM DESIGN OF MR FINISHING TOOL AND ITS ANALYSIS FOR FINISHING OF EN31 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 previously formed the basis for the award of any degree, diploma, fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the major project entitled here **"SELECTION OF OPTIMUM DESIGN OF MR FINISHING TOOL AND ITS ANALYSIS FOR FINISHING OF EN31 WORKPIECE SURFACE",** in partial fulfillment of the requirements for the award of the Degree of **Master of Technology** in **Production Engineering** and submitted to the Department of Mechanical Engineering of Delhi Technological University has been an authentic record work of **Mr. Kunal Krishna (2K21/PRD/06)** carried out under my supervision.

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ABBREVIATIONS

MRF	Magneto Rheological Finishing
ANOVA	Analysis of Variance
MRR	Material Removal Rate
RSM	Response surface methodology
BP	Bingham Plastic
HP	Herschel–Bulkley
CF	Casson Fluid
MR	Magneto Rheological
EIPs	Electrolytic Iron Particles
CIPs	Carbonyl Iron Particles

ABSTRACT

Magneto-rheological finishing (MRF) is a novel and promising technique used for precision machining and polishing of various workpiece materials. Present work is aimed to design MR finishing tool in ANSYS Maxwell 3D simulation software for finishing variety of workpiece materials. Design of experiment has been used with two parameters such as bush height and number of turns to develop the experimental plan using design expert software. Modelled MR finishing tool has been tested with different experimental run to observe the shape and intensity of magnetic field at MR finishing tool tip. Statistical analysis has been done to see the effect of bush height and number of turns on magnetic field intensity at MR finishing tool tip. Linear model has been selected in the analysis and analysis of variance (ANOVA) has been done with model p values less than 0.0001 along with F value 566.41 which indicates that the model selected is significant and lack of fit with p value 0.1265 indicates insignificant. Regression equation has been obtained in coded form as well as actual form to see the effect of bush height and number of turns on response intensity of magnetic field at MR finishing tool tip. It has been observed that the predicted intensity of magnetic field at tool tip is found 1.99885 T for bush height 6.63 mm and number of turns 2133. After obtaining predicted intensity of magnetic field, numerical optimization has been carried out and found that maximum intensity of magnetic field is obtained 1.999 T for bush height 6.628 mm and number of turns 2132 which is very close to the predicted value of magnetic field intensity.

Keywords: Magnetorheological Finishing, MR fluid, Maxwell 3D Simulation, Analysis of Variance.

CHAPTER 1

INTRODUCTION

1.1 MAGNETORHEOLOGICAL FINISHING

Magneto-rheological finishing (MRF) is a deterministic material removal process that employs magnetorheological fluids (MRFs) to achieve high-quality surface finishes on various optical, ceramic, and metallic components. MRF has gained significant attention in recent years due to its versatility and effectiveness in producing precision finishes on a wide range of materials.

1.1.1 Magnetorheological Fluids

Magneto-rheological fluids consist of magnetizable particles dispersed in a carrier fluid. These fluids exhibit a unique property of changing their rheological behavior in the presence of a magnetic field, transitioning from a low-viscosity state to a semi-solid state. The controllable viscosity of MRFs allows for precise material removal during the finishing process.

1.1.2 MRF Setup

The MRF setup typically consists of a polishing head, magnet assembly, workpiece holder, and control systems. The process parameters, including magnetic field strength, polishing head pressure, MRF composition, rotational speed, and feed rate, play a crucial role in determining the material removal rate and surface finish quality.

1.1.3 MRF Process Parameters

The process parameters play a crucial role in determining the effectiveness and efficiency of MRF. By carefully controlling these parameters, manufacturers can achieve the desired surface finish, form accuracy, and material removal rate.

1.1.3.1 Magnetic Field Strength

The magnetic field strength is a key parameter in MRF as it controls the behaviour of the abrasive fluid. By adjusting the magnetic field strength, manufacturers can regulate the viscosity and stiffness of the fluid. Higher magnetic field strengths lead to an increase in the yield stress of the fluid, resulting in a more rigid abrasive medium. This can affect the material removal rate and surface finish. Therefore, optimizing the magnetic field strength is essential for achieving the desired finishing results.

1.1.3.2 Abrasive Particle Concentration

The concentration of abrasive particles in the MRF slurry is another critical parameter. The abrasive particles interact with the workpiece surface during the finishing process, determining the material removal rate and surface quality. A higher concentration of abrasive particles typically leads to a higher material removal rate. However, it can also result in increased surface roughness. Therefore, finding the right balance between material removal rate and surface finish is important by adjusting the concentration of abrasive particles in the slurry.

1.1.3.3 Slurry Viscosity

The viscosity of the MRF slurry affects the flow characteristics and the behaviour of the abrasive particles. Controlling the slurry viscosity is crucial for ensuring uniform distribution of the abrasive particles across the workpiece surface. It also affects the stability and predictability of the finishing process. Higher viscosity can enhance the stability of the process but may result in reduced material removal rate. Conversely, lower viscosity can increase material removal rate but may lead to a less predictable process. Adjusting the slurry viscosity helps in optimizing the process for achieving the desired finishing outcomes.

1.1.3.4 Workpiece Speed and Pressure

The rotational speed of the workpiece and the applied pressure during MRF are important parameters that influence the material removal rate and surface quality. Higher rotational speeds and pressures generally lead to increased material removal rates. However, excessively high speeds or pressures can result in surface defects, such as waviness or subsurface damage. It is essential to carefully balance the workpiece speed and pressure to achieve the desired finishing results without compromising the surface quality.

1.1.3.5 Polishing Time

The polishing time in MRF refers to the duration for which the workpiece is subjected to the finishing process. It is an essential parameter that determines the total material removal and the final surface finish. Longer polishing times generally result in a smoother surface but may increase the processing time. Shorter polishing times can lead to faster processing but may not achieve the desired surface finish. Optimization of the polishing time is crucial to strike a balance between productivity and quality.

In conclusion, the magneto-rheological finishing process parameters, including magnetic field strength, abrasive particle concentration, slurry viscosity, workpiece speed and pressure, and polishing time, play a vital role in achieving the desired surface finish, form accuracy, and material removal rate. Careful control and optimization of these parameters are necessary to ensure efficient and effective MRF operations, leading to high-quality finished components.

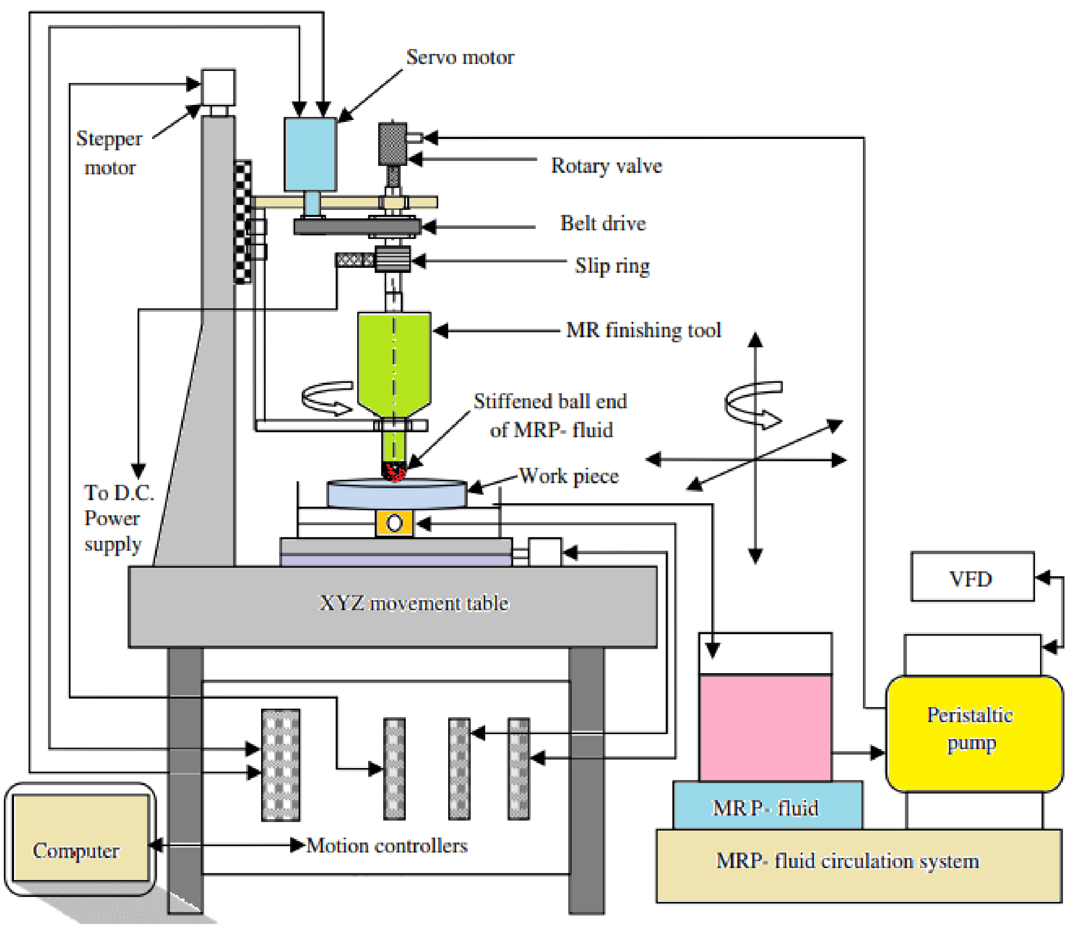

Figure 1.1: Schematic diagram of MRF setup [1]

1.1.4 Working Principle of MRF Process

During the MRF process, the MR fluid is applied between the workpiece and a polishing tool. The polishing tool is usually a magnetorheological ball or a flexible magnetic abrasive ball. When a magnetic field is applied to the MR fluid, the particles align themselves and form chains or clusters within the fluid. This causes the fluid to exhibit a shear thickening behaviour, increasing its viscosity and stiffness. As the workpiece and polishing tool come into contact, the MR fluid trapped between them forms a stiff polishing layer due to the increased viscosity. The polishing layer behaves like a solid material and removes material from the workpiece through a combination of mechanical abrasion and chemical reactions, depending on the abrasive particles present in the MR fluid.

The material removal mechanism in MRF can be attributed to several factors:

1.1.4.1 Mechanical abrasion

The stiff polishing layer formed by the aligned particles in the MR fluid acts as an abrasive material. It abrades the surface of the workpiece, causing the removal of a thin layer of material. The hardness and size of the abrasive particles in the MR fluid play a significant role in the abrasive action.

1.1.4.2 Hydrodynamic pressure

The shearing action of the polishing tool and the presence of the aligned particle chains in the MR fluid create a hydrodynamic pressure between the tool and the workpiece. This pressure assists in material removal by dislodging loose particles and debris from the workpiece surface.

1.1.4.3 Chemical reactions

In some cases, the MR fluid can be formulated to include chemical agents or abrasives that react with the workpiece material. These chemical reactions can enhance the material removal rate and improve the surface finish.

Overall, the material removal mechanism in magneto-rheological finishing of metals involves a combination of mechanical abrasion, hydrodynamic pressure, and, if applicable, chemical reactions. The process allows for precise control over material removal, making it suitable for achieving high-quality surface finishes and correcting surface defects.

1.1.5 Advantages of MRF

Some advantages of using magneto-rheological finishing for metals:

1 *High precision*

MRF enables precise control over the material removal process, resulting in highly accurate finishing of metal surfaces. It can achieve surface roughness in the nanometer range, making it suitable for applications where precision is crucial.

2 *Uniform finishing*

MRF provides uniform and consistent finishing across the entire surface of the metal workpiece. The magnetorheological fluid adapts to the contours of the surface, ensuring that all areas receive the same level of treatment. This helps to eliminate localized defects and inconsistencies.

3 *Flexibility*

MRF can be used for finishing a wide range of metal materials, including both ferrous and non-ferrous metals. It is effective on various shapes and sizes of workpieces, making it a versatile process for different applications and industries.

4 *Material preservation*

Unlike traditional finishing techniques that can generate excessive heat, vibration, or mechanical stress, MRF is a relatively gentle process. It minimizes the risk of introducing structural damage to the metal, such as heat-induced distortion or surface cracking. This makes it particularly suitable for delicate or sensitive materials.

5 *Process automation*

MRF can be easily integrated into automated manufacturing systems. It allows for precise control and adjustment of process parameters, such as magnetic field strength, fluid composition, and removal rate. Automation reduces human intervention and improves repeatability, efficiency, and productivity.

6 *Reduction in surface defects*

Magneto-rheological finishing can effectively remove surface defects like scratches, pits, and microcracks, improving the overall quality of the metal surface. It can also smoothen out irregularities and remove material from complex geometries, resulting in improved functional performance and aesthetic appearance.

7 *Time and cost savings*

MRF offers the advantage of reduced processing time compared to traditional finishing methods. It can achieve the desired surface quality in fewer steps, thereby reducing the overall production time. Additionally, the ability to automate the process can lead to cost savings in labor and improved production throughput.

While magneto-rheological finishing has numerous advantages, it is important to note that the specific benefits may vary depending on the application, material, and desired surface finish.

1.1.6 Limitation of MRF

While MRF offers several advantages, it has few disadvantages when applied to metals.

1. *Surface Quality Limitations*

   While MRF can achieve excellent surface finishes, it may struggle to remove certain types of surface defects, such as deep scratches or large burrs. These defects often require more aggressive material removal methods, which MRF may not be capable of providing efficiently.

2. *Limited Material Compatibility*

   MRF is typically more effective for softer materials like glass and ceramics. When it comes to metals, especially hard metals like steel or titanium, the material removal rate can be relatively slow. This limits the applicability of MRF for certain metal components.

3. *Time-consuming Process*

   MRF is generally a slow process compared to traditional grinding or polishing methods. It often requires multiple iterations and extended processing times to achieve the desired surface finish. This limitation can be a drawback, particularly in industries that demand high production rates or quick turnaround times.

4. *Complexity and Cost*

   Implementing MRF can be technologically complex and expensive. It requires specialized equipment, including a magnetic field generator and control systems, as well as MR fluid formulations. The setup and maintenance costs associated with MRF can be significant, making it less accessible for smaller-scale operations or industries with budget constraints.

5. *Environmental Considerations*

   MRF involves the use of MR fluids containing abrasive particles. Proper disposal or recycling of these fluids can pose environmental challenges due to the presence of contaminants. Managing the waste generated during the process requires careful attention and adherence to environmental regulations.

6. *Process Control and Variability*

   Achieving consistent results with MRF can be challenging due to the complex interaction between the magnetic field, fluid properties, and material being processed. Controlling the material removal rate, surface roughness, and other finishing parameters may require significant expertise and careful optimization, which adds complexity to the process.

1.1.7 Applications of MRF

Here are some applications of the MRF process:

1. *Optics Manufacturing*: MRF is extensively used in the optics industry for polishing and finishing optical components such as lenses, mirrors, prisms, and filters. The process enables the production of precise surface shapes, removal of sub-micron-scale defects, and achievement of exceptional surface smoothness, which are critical for optical performance.
2. *Semiconductor Industry*: MRF finds applications in the manufacturing of semiconductor devices, including silicon wafers and photomasks. It is used for planarization, removal of surface defects, and obtaining ultra-smooth surfaces required for high-resolution lithography and device performance.
3. *Precision Mechanics*: MRF can be applied to various precision mechanical components, such as bearings, gears, and sliders. By precisely controlling the MRF process, manufacturers can achieve tight tolerances, improve surface quality, and reduce friction and wear on these components, leading to enhanced performance and longevity.
4. *Medical Device Manufacturing*: The MRF process is employed in the production of medical devices that require exceptional surface finishes, such as implants, surgical tools, and diagnostic equipment. MRF helps in achieving precise geometries, reducing surface roughness, and minimizing the risk of contamination or bacterial adhesion.
5. *Aerospace and Defence*: In the aerospace and defence industries, MRF is utilized for the fabrication of critical components, such as turbine blades, optical systems for surveillance

and targeting, and aerospace mirrors. The process aids in achieving aerodynamic efficiency, optical clarity, and durability by polishing and refining the surfaces to stringent specifications.

6. *Automotive Industry*: MRF can be applied in the automotive sector for the manufacturing of precision components, including engine parts, transmission components, and fuel injection systems. By using MRF, manufacturers can improve the surface finish, reduce friction and wear, enhance fuel efficiency, and optimize performance.

   Overall, the magneto-rheological finishing process has wide-ranging applications in industries where precise surface finishing, superior surface quality, and controlled material removal are crucial. Its ability to achieve sub-micron-level accuracy makes it a valuable technology.

CHAPTER 2
LITERATURE REVIEW

The presented literature review consists of the polishing fluid used in magneto rheological finishing process, methods used in performing MRF process and various other research work aligned in the area of the topic of this project work.

2.1 POLISHING FLUIDS IN MRF

The composition of the various components in MR fluid affects the final surface finish. Ajay S. et al. [1] conducted statistical analysis that characterized various rheological properties of magneto rheological fluid. For characterizing author used three models viz. BP, HB and CF. Later, by using RSM, author predicted the effect of change in various composition of the fluid on its properties and performance. CIPs are preferred magnetizing particles because of its lower magnetic remnant and higher permeability. In case of carrier fluid water, silicon oil, mineral oil etc. are available. But among the above water-based fluid is better for finishing of metallic surfaces [2].

The one that contributes in higher material removal rate are abrasive particles as the soft spherical CIPs does not contributes much in material removal from the work surface [3]. The various types of abrasives used are SiC, diamond, alumina, cerium oxide etc. Ajay S. et al. [1] polished silicon surface by using ceria and alumina and later noted the differences in using two different abrasives. In another study by Jang et al. [4] authors finished brass work piece by using diamond abrasives. Surface roughness of the brass surface reduced from 192nm to 34nm.

Later, Nagdeve et al. [5] in a study concluded that various sizes of abrasives had an impact on toughness and strength of MR fluid. This is since MR fluid when in magnetic field, the abrasives are trapped into the CIPs chain. When size of abrasives that are trapped in CIPs chain are large then they result in decrease in magnetic force interaction. But when they are smaller the force interaction increases and MRR is higher.

Various compositions of MR fluid

Different compositions of MR fluid are used by different researchers depending upon the type of work material [6]. Generally, CIPs ranges from 20% to 45% by volume fraction.

Carrier fluid ranges between 47% and 67% by volume fraction. Stabilizers like glycerol are between 1% and7% [6-7]. When the abrasives are in large quantity in MR fluid then percentage change in roughness decreases this is because CIPs limit to grasp the abrasive are over after a limit. This was reported in a study by Maan et al. [8].

Rheological properties of MR fluid

The rheological effects of MR fluid were affected majorly by the intensity of magnetic field and also by the concentration of MR fluid. Jain et al. [9] reported that on increasing abrasive and CIPs content, surface roughness decreases but MRR in MRF process increases.

2.2 MRF METHODS

To super finish various shapes and types of material researchers developed different methods to perform MRF operations. These include method with rotating wheel or tool or disk.

Rotating tool

In this method, MR fluid sticks at tip of finishing tool (made up of magnetic material) and hemispherical shape flexible tool is developed at tool tip [10]. The shape of the tool at the tip can be controlled by controlling the intensity of induced magnetic field. The MR fluid at the tool tip stiffened when exposed to the magnetic field. The material is removed from the surface whenever the tool tip rotates on it. Ball end magneto rheological finishing is one of this.

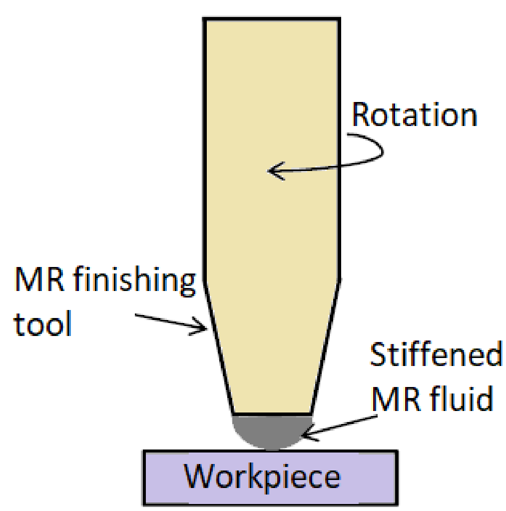

Figure 2.1: Rotating tool mechanism.

Rotating wheel

In this type, a rotating wheel (made up of magnetic material) acts as a carrier for MR fluid. When MR fluid goes through small gap between the wheel and workpiece, it becomes as stiffened ribbon. This ribbon further with movement over work surface removes materials. Wang et al. [11] finished flat, spherical and 3D shape using dual rotating mechanism to achieve surface roughness value as low as 0.58nm.

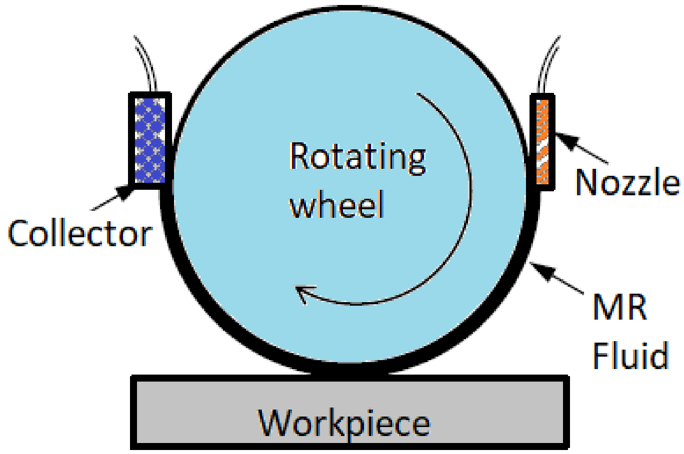

Figure 2.2: Rotating wheel mechanism.

Rotating disk

In this method, workpiece is submerged in the MR fluid in a container and either disk rotates or workpiece rotates or both disk and workpiece rotate. By this the polishing action takes place and material is removed. Wang et al. [12] finished a workpiece by utilizing rotation of both polishing disk and workpiece together.

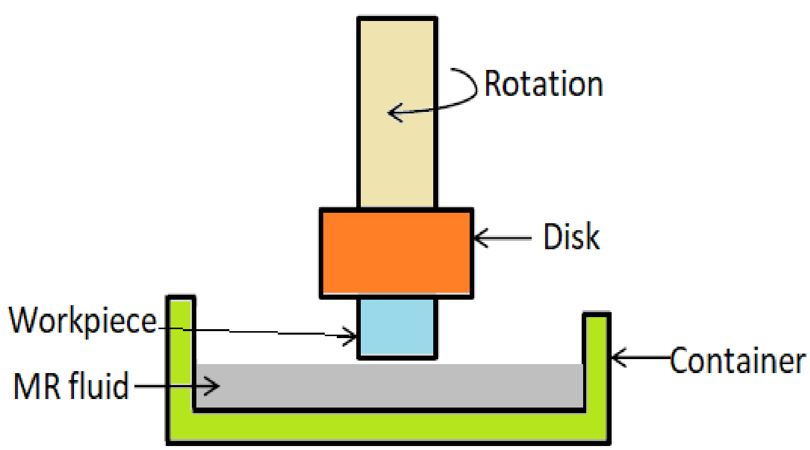

Figure 2.3: Rotating disk mechanism.

2.3 FINISHED SURFACE QUALITY

There are several factors that contributes to the quality of surface finish in magnetorheological finishing process. Some of the notable ones being intensity of magnetic field, magnetizing current, tool workpiece gap, speed of wheel rotation, size of abrasives composition of MR fluids etc.

The effect of magnetizing current, tool workpiece gap and speed of wheel in surface finish of silicon was studied and demonstrated by Khatri et al. [13]. Later Khan et al. [14] studied the effect of different composition of MR fluid in surface roughness of copper workpiece. The result showed abrasive particles with 14% of volume fraction to be the optimum in finishing copper surface.

2.4 OTHER NOTABLE RESEARCHES

Jinchuan et al. [16] improved efficiency of polishing using ball end MRF by increasing temperature of MR fluid. Authors noted that with increase in temperature of MR fluid, the relative velocity of finishing increases accordingly, which promotes the improvement of MRR. But accordingly, there is decrease in shear stress which reduces the previous improvement of MRR. This decrease is rather small when compared with improvement. The result showed that when MR fluid temperature increases to 60°C, there is 108.4% improvement in MRR and the finished surface roughness has value 14.9 nm. So, increasing the MR fluid temperature significantly improves the finishing efficiency of MRF process.

Khan et al. [17] analysed magnetic field intensity simulation over ferromagnetic and anti-ferromagnetic copper workpiece and found that on copper magnetic field were irregular and density of magnetic field declined on its surface. In a study by Khurana et al. [18] authors demonstrated the use of two different types of rotating tool, one having central hole and the other being solid. In the results it was found that magnetic flux density was more uniform in case of solid tool when compared with the one having central hole.

Iqbal et al. [19] developed an arrangement to aid MR polishing process to finish and clean the workpiece and measure surface roughness with an automated feedback control. To clean the workpiece various methods like water jet, air sprays, kerosene jets etc. were used and it was found that kerosene jet was best option for complete cleaning of MR fluid. Alam et al. [20] in year 2019 tried to fully automate the ball end MRF process. And they were successful in doing so.Iqbal et al. [21] made a setup to measure the tilt or taper on work surface. A constant working gap is maintained for the same and this is essential to maintain uniform surface throughout to eliminate any tilt or taper on surface. A mild steel workpiece was finished by using bidisperse and monodisperse MR polishing fluid during ball end MRF process. The result showed that bidisperse MR polishing fluid when used on mild steel workpiece, achieved superior reduction in surface roughness (%ΔRa) [22].

Saraswathamma et al. [23] studied about the influence of different process parameters like working gap, current, rotational speed etc. on surface finish in terms of decrease in percentage surface roughness of silicon surface using ball end MRF process. Polishing fluid consisted of cerium oxide abrasive and deionized water as base fluid. Analysis of variance (ANOVA) was applied to see individual effect of various parameters on surface finish. The conclusion from the study showed the working gap as the most critical parameter for super finishing silicon using ball end MRF process. Kumar et al. [24] came up with analytical and experimental study about the effect of MR fluid composition and finishing time of polyactic acid (PLA) material using ball end MRF. The three types of abrasives used were Al_2O_3 (1000 mesh size), SiC (1000 mesh size), and B_4C (1000 mesh size) mixed with EIPs and water (base fluid). Out of these Al_2O_3 was found to be best suited for finishing of PLA workpiece. Finally, optimum composition of MR fluid having 16.7% abrasives by volume, 25% EIPs by volume and 58.83% distilled water by volume was selected for finishing of PLA workpiece from the conducted experimental results.

Singh et al. [25] analysed the effect of varying mesh size and change in volume percentage of abrasives in MR fluid on surface finish of ferromagnetic material using ball end MRF process. SiC abrasives with mesh size varying from 400 to 1200 were used. Changes in volume percentage of abrasives were from 5% to 25% by volume. The results showed that the percentage change in surface roughness varies inversely with abrasive mesh size and it reduced with the increase in volume percentage. Finally surface finish value of 82nm was achieved from an initial value of 214nm. Niranjan et al. [26] attempted to enhance the surface roughness of mild steel workpiece by using sintered magnetic abrasive in MR fluid.

20% CIPs (CS grade) by volume and 25% SiC by volume were sintered in ball mill to develop these abrasives. 600 rpm was found to be the optimum speed. Result showed minimizing tool aging effect by using these sintered abrasives. In another study by Niranjan et al. [27] authors found working gap to be the primary parameters affecting the percentage reduction in surface roughness. While, secondary factors influencing surface roughness were tool rotational speed and magnetizing current. Alam et al. [28] modeled material removal mechanism to predict surface roughness and then verified it using ball end MRF on mild steel surface. Theoretical and experimental data were analyzed and error of about 7% to 31% was found.

Iqbal et al. [29] super finished EN31 steel using ball end MRF and found that the reduction in surface roughness over a period is gradually decreasing one. Alam et al. [30] studied the effects of change in composition of MR fluid on normal forces and shear forces. Variation in magnetic abrasives y volume were from 5% to 25% and non-magnetic abrasives by volume were from 5% to 20%. Manjesh et al. [31] experimentally and theoretically analyzed how the material removal mechanism takes place during MRF process in a poppet valve. The result showed 23.1nm roughness value on poppet surface. However, there was an error of 12.87% between experimental and theoretical MRR. Xu et al. [32] recently made a study to investigate the mechanism of lateral assembly in magnetic particles of MR fluid. For the study they used finite element method and arbitrary LE method to establish a 2D model. The result showed that the experimental result corelated with model developed. Iqbal et al. [33] automated the finishing process of ball end MRF by using confocal sensors. The result of the study showed that by using insular finishing the surface roughness of 289 was achieved from its initial value of 352nm.

2.5 RESEARCH GAP

Based on the above literature survey some research gap can be extracted:

1. Concept of MR finishing is well established in the current scenario. The optimum design and development of MR finishing tool by using latest software is to be explored.
2. The development of accurate models and simulations can aid in predicting and optimizing the MR finishing tool design. Modelling of MR finishing tool design is to be explored.

2.6 RESEARCH OBJECTIVE

Based on the literature survey, following research objectives are drawn:

The main objective of this research is to design and simulate a magnetorheological tool. The specific goals are as follows:

1. To design magnetorheological finishing tool using ANSYS Maxwell 3D simulation software.
2. To simulate the designed MR finishing tool using Maxwell 3D software and analyze the effect of various parameters taken into considerations.
3. To study the effect of three different MR fluid on intensity of magnetic field at tool tip by considering the properties of MR fluid.
4. To statistically analyze the effect of bush height and number of turns on magnetic field intensity at MR finishing tool tip.

CHAPTER 3

DESIGN & SIMULATION

3.1 DESIGN OF MRF TOOL

A tool is designed taking in account previous researches. The tool is designed in ANSYS Maxwell 3D simulation module. The total length of tool is kept to be 100cm. The inner core radius being 25mm, EM coil radius of 55mm and finally outer core radius of 80mm. A 5mm pore is kept for the MRF fluid passage. A brass bush of thickness 2mm and varying height is placed at bottom part of tool to help in concentrating the magnetic field at tool tip. The dimension of workpiece being 110mm in length, 100mm in breadth and 10mm height.

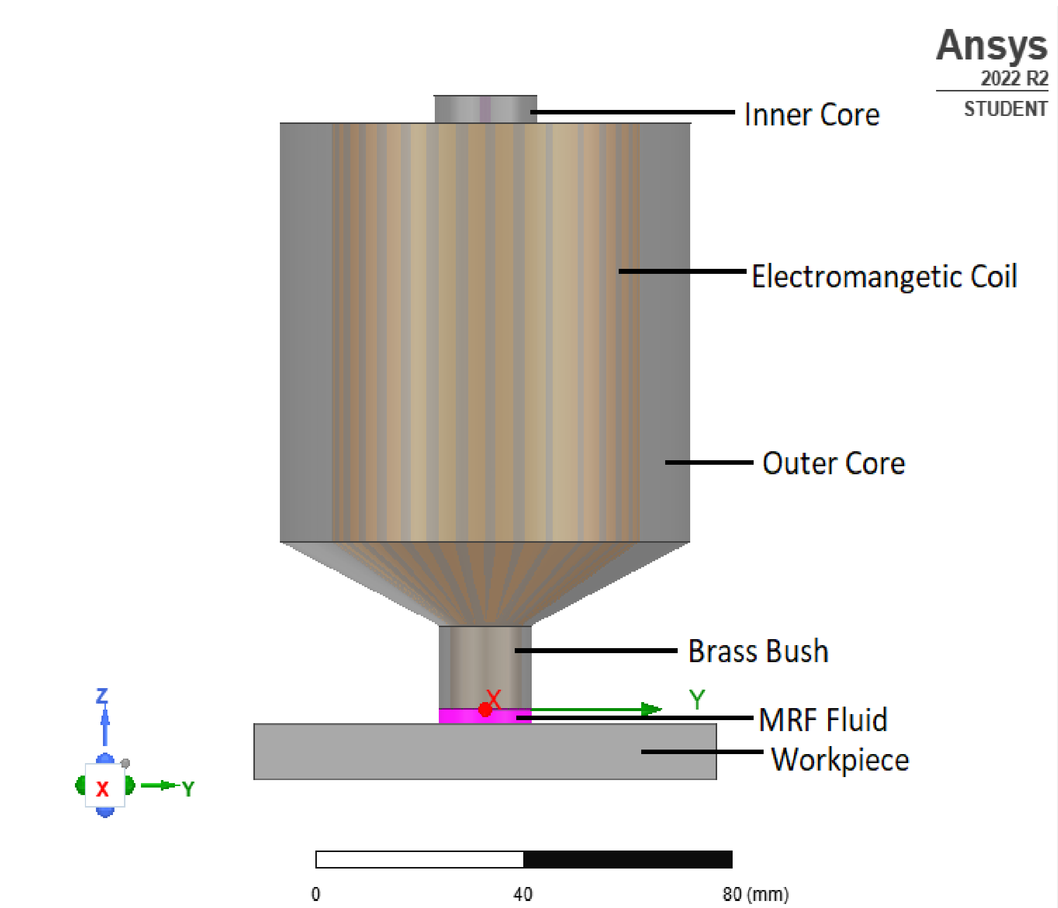

Figure 3.1: Designed MRF tool (2D View)

Table 3.1: Dimensions and material used in tool design.

Sl. No.	Parameter	Diameter	Material	Permeability
1	Inner coil	25mm	Iron	4000
2	Outer coil	80mm	Copper	1
3	Electromagnetic coil (Current 2A)	55mm	Iron	4000
4	Bush	22mm	Brass	1

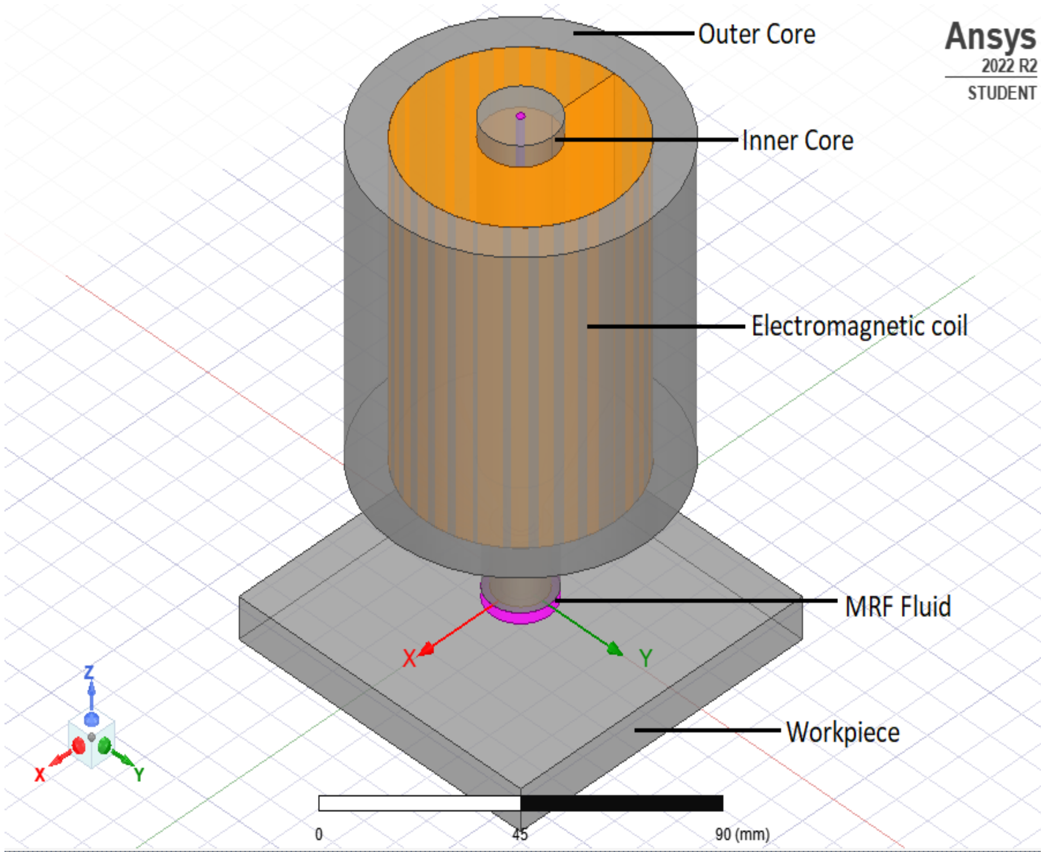

Figure 3.2: Designed MRF tool (3D View)

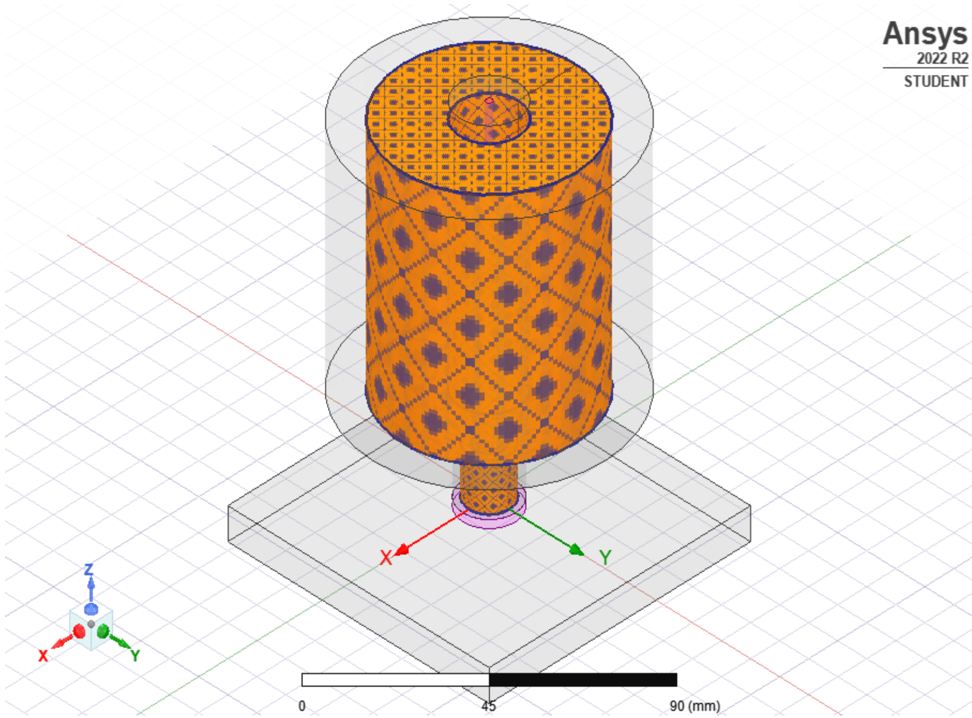

Figure 3.3: Insulation of electromagnetic coil (3D View).

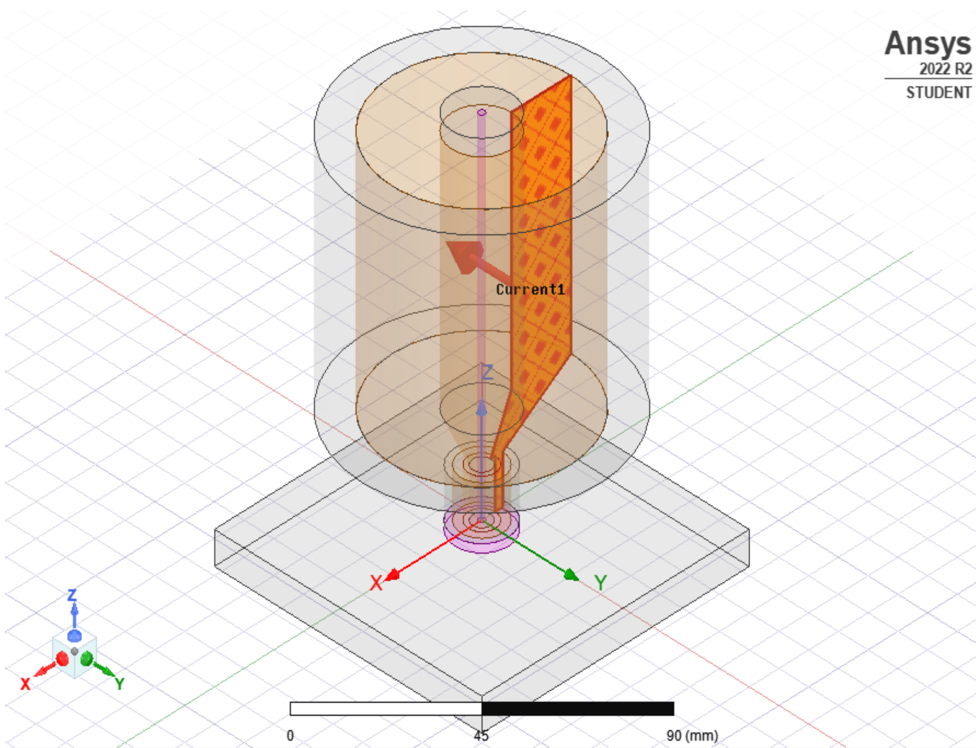

Figure 3.4: Current excitation in coil (3D View).

3.2 DESIGN OF EXPERIMENT (DOE)

In the detailed literature survey, it is quite evident that MRF process parameters such as intensity of magnetic field, magnetizing current, working gap etc. play a crucial role to super finish various work surfaces. Traditional design technique is generally applicable to areas where there is variation in a single parameter and its impact is envisaged, which implies a requisite to perform a handful of experiment in order to investigate its importance. This entire process is quite monotonous and languidly.

Basically, the DOE process consists of 3 fundamentals:

Randomization: Experimental runs are arranged in any random order to neutralize the impact of noise factors.

Replication: For each factor combination it foresees to accomplish analogous experimental runs that helps in estimation of experimental errors. For identifying if the stated differences in the data are mathematically alterable; error measurement is the decisive element.

Blocking: This parameter helps to soothe the impact of various factors that influences the response and is quite of minor importance for our purpose. These are generally known as noise factors. Analogous experimental conditions are usually referred as block, in which the user partitions the inspection from the mathematical design into various groups that conform each block [34].

The above process is carried further to investigate input parameters and then develop required statistical model to understand the liaison among the various parameters.

Following are the steps to accomplish the above stated condition:

i. Identification of key factors in process control.
ii. Deciding about the working scope of control factors: Bush height, No. of turns.
iii. Design matrix development.
iv. Conducting the test in accordance with the design matrix.
v. Taking down the reactions viz. Intensity of magnetic field at tool tip.
vi. Developing the essential numerical models.
vii. Checking the acceptability of the developed models.
viii. Locating the importance of coefficient.
ix. Advancing the proposed models.

x. Plotting of graphs and conclusion.

xi. Discussion about the final outcomes.

3.2.1 Identification of various process control parameters

In nano-finishing surface using MRF process basically three parameters which need to be considered are the numbers of turns, magnetizing current and bush height. For the simulation purpose the considered parameters decided are bush height and number of turns.

3.2.2 Deciding the span of the process parameters

Initial runs are performed by changing one parameter while maintaining others as constant. Working range is kept steady by observing the MRF tool geometry.

The limits were coded as -2, -1, 0, +1, +2. The coded estimation for mid esteems is then calculated, Where, Zi is the required coded estimation of any variable Z, when Z is the estimate of the variable from Z_{min} to Z_{max}; Also, Z_{min} and Z_{max} are the extreme levels of the factors. The followed procedure parameters with their lower and upper restrains are shown in table below.

Table 3.2: Process control parameters and their levels.

Sl. No.	Parameters	Unit	-2	-1	0	+1	+2
1	Bush Height	mm	5	10	15	20	25
2	Number of turns in EM coil	-	1800	1900	2000	2100	2200

3.2.3 Developing the design matrix

A two factor 5 level composite design matrix was employed for the analysis. Table below demonstrates the various sets of coded orders utilized to frame an outline. The bush height in millimeter and the number of turns is considered as varying factors and the DOE table is developed. The standard order, run order along with coded values for bush height and coded values for number of turns are shown in the table 3.3. Along with the coded values, the actual values of bush height and number of turns in electromagnetic coil is also incorporated in the table. The actual value of bush height is taken in mm.

Table 3.3: Design matrix

Stand. Order	Run Order	Coded Values (Bush Height)	Coded value (No. of turns)	Actual value (Bush Height)	Actual value (No. of turns)
10	1	0	0	15	2000
13	2	0	0	15	2000
2	3	-1	+1	10	2100
3	4	+1	-1	20	1900
6	5	0	+2	15	2200
4	6	+1	+1	20	2100
7	7	-2	0	5	2000
12	8	0	0	15	2000
1	9	-1	-1	10	1900
9	10	0	0	15	2000
11	11	0	0	15	2000
5	12	0	-2	15	1800
8	13	+2	0	25	2000

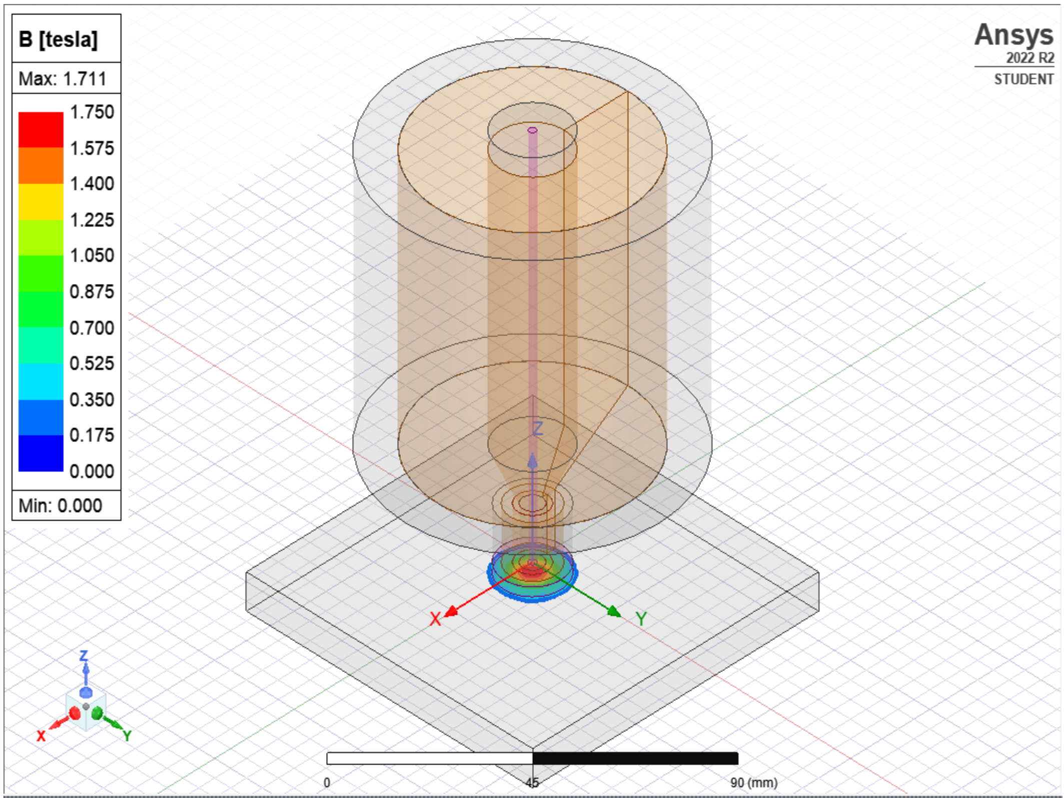

Figure 3.5: Magnetic field intensity at tool tip when bush height 15mm & No. of turns 2000

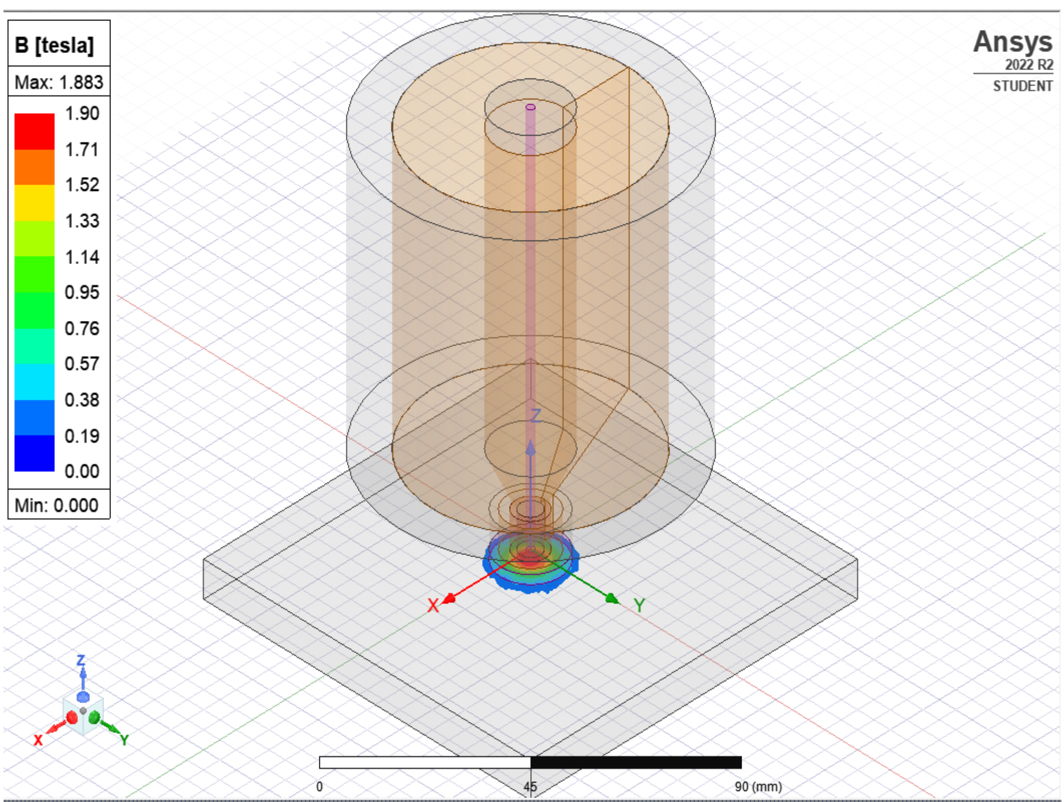

Figure 3.6: Magnetic field intensity at tool tip when bush height 10mm & No. of turns 2100

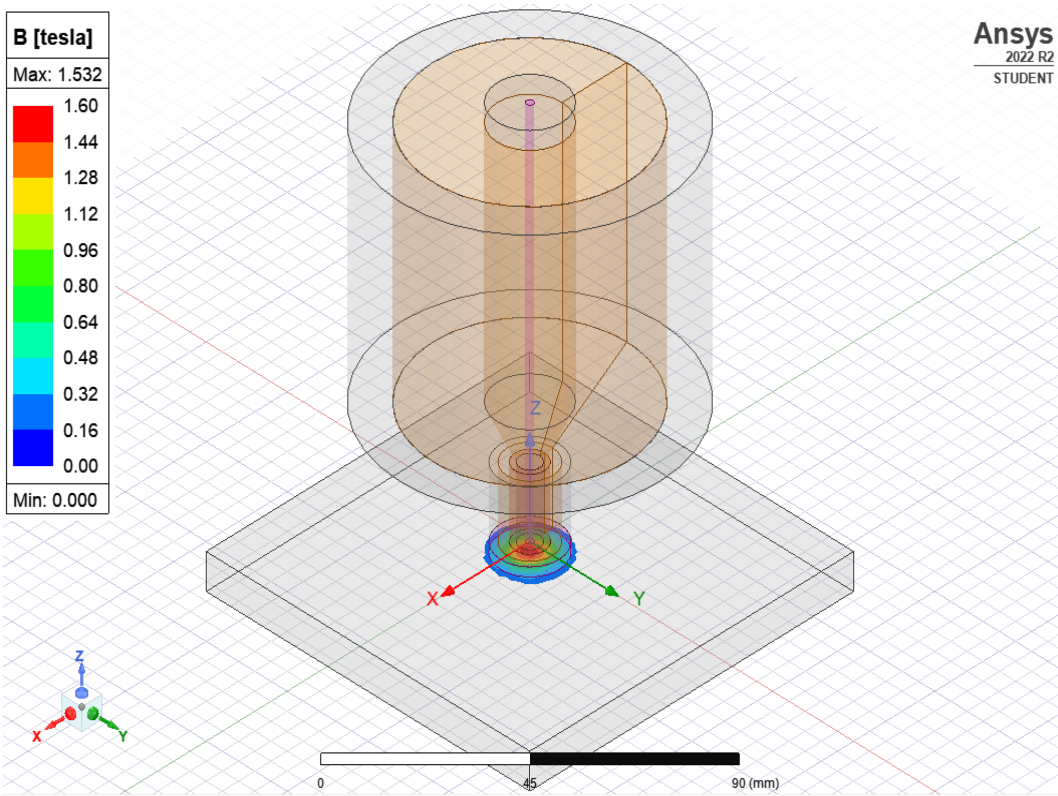

Figure 3.7: Magnetic field intensity at tool tip when bush height 20mm & No. of turns 1900

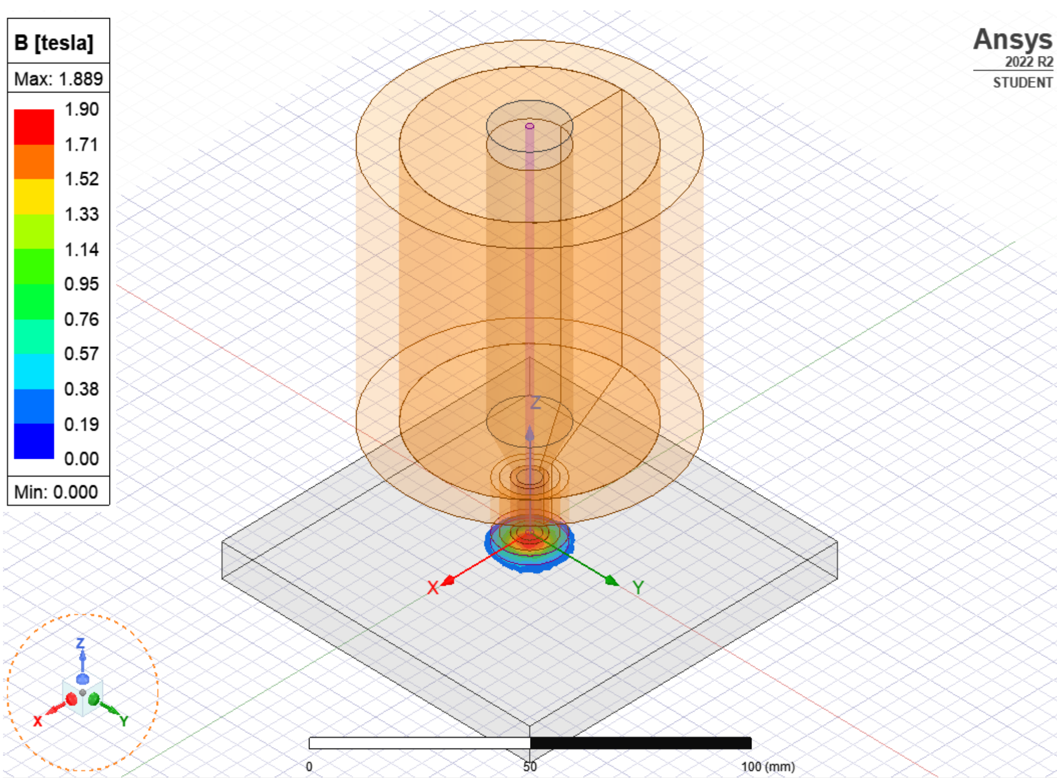

Figure 3.8: Magnetic field intensity at tool tip when bush height 15mm & No. of turns 2200

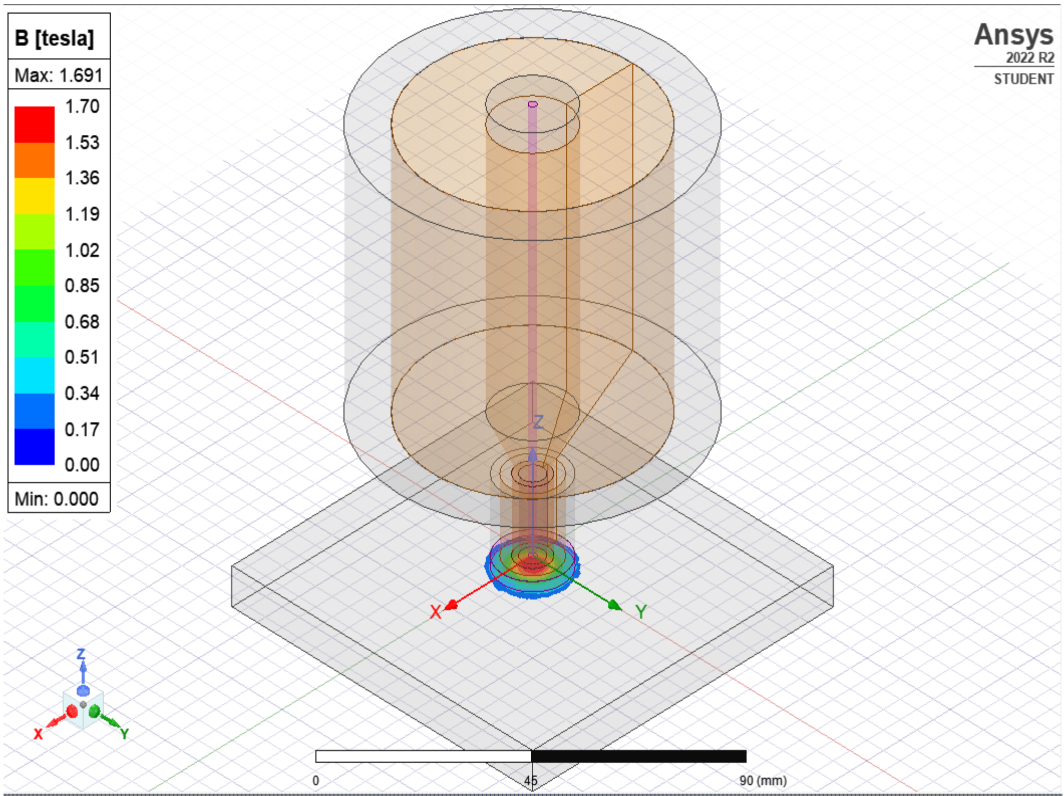

Figure 3.9: Magnetic field intensity at tool tip when bush height 20mm & No. of turns 2100

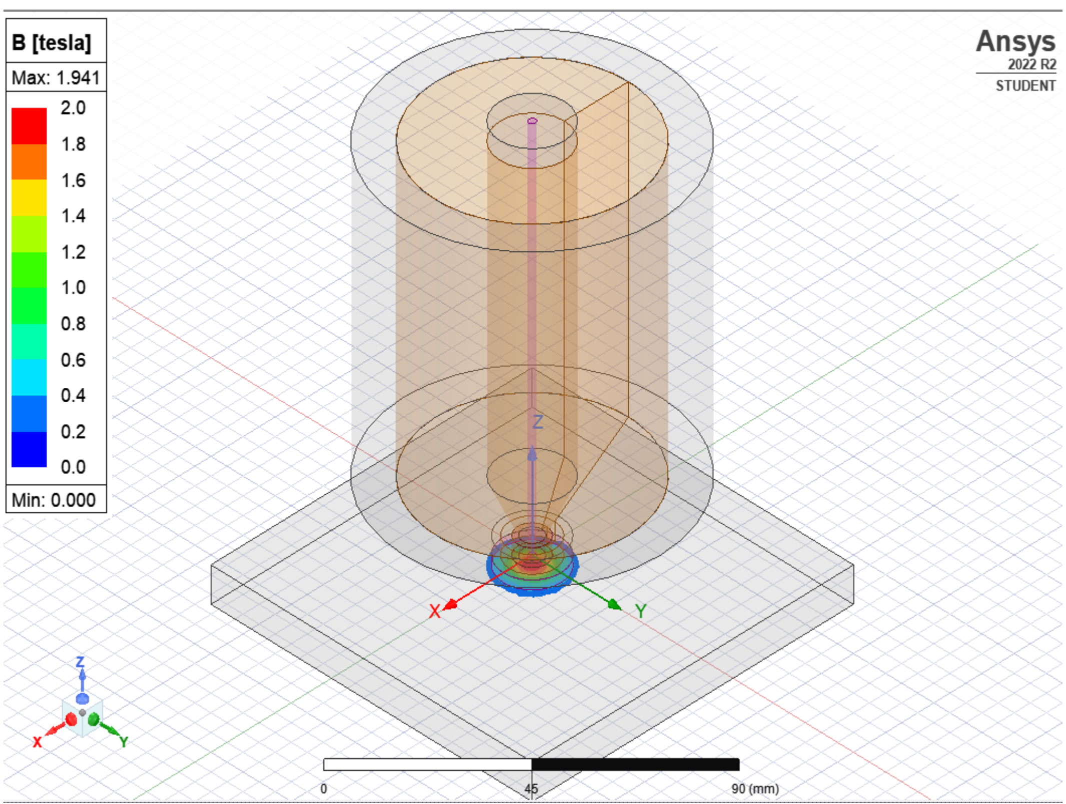

Figure 3.10: Magnetic field intensity at tool tip when bush height 5mm & No. of turns 2000

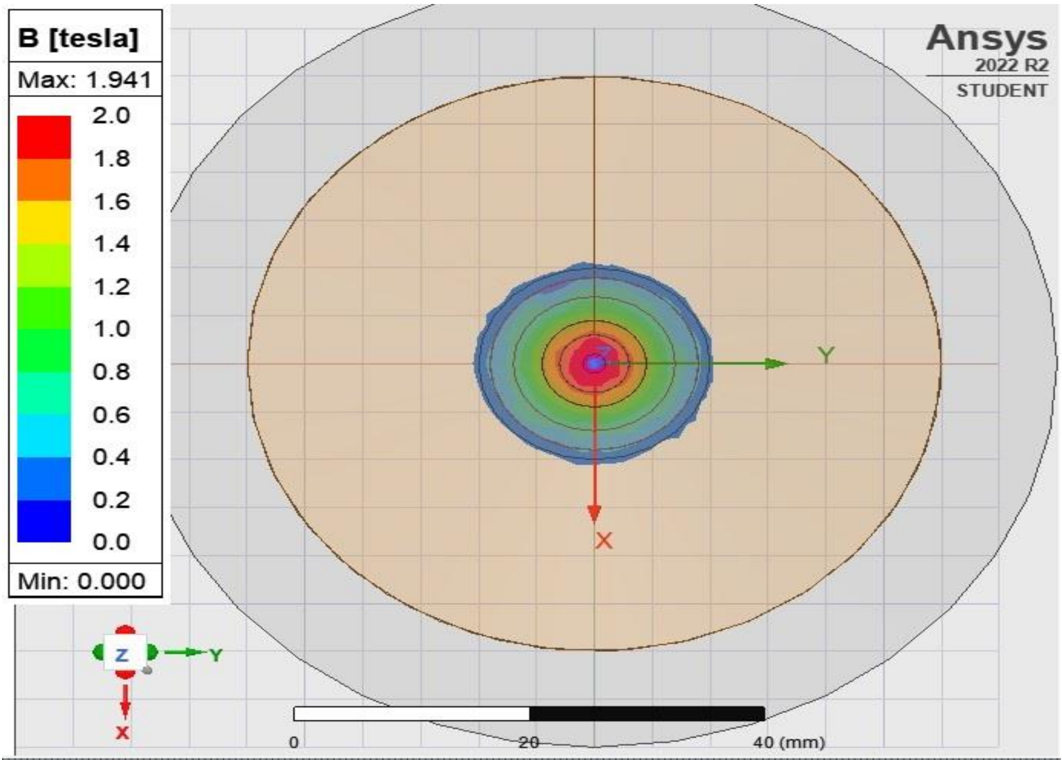

Figure 3.11: Top view of magnetic field intensity at tool tip when bush height 5mm & No. of turns 2000

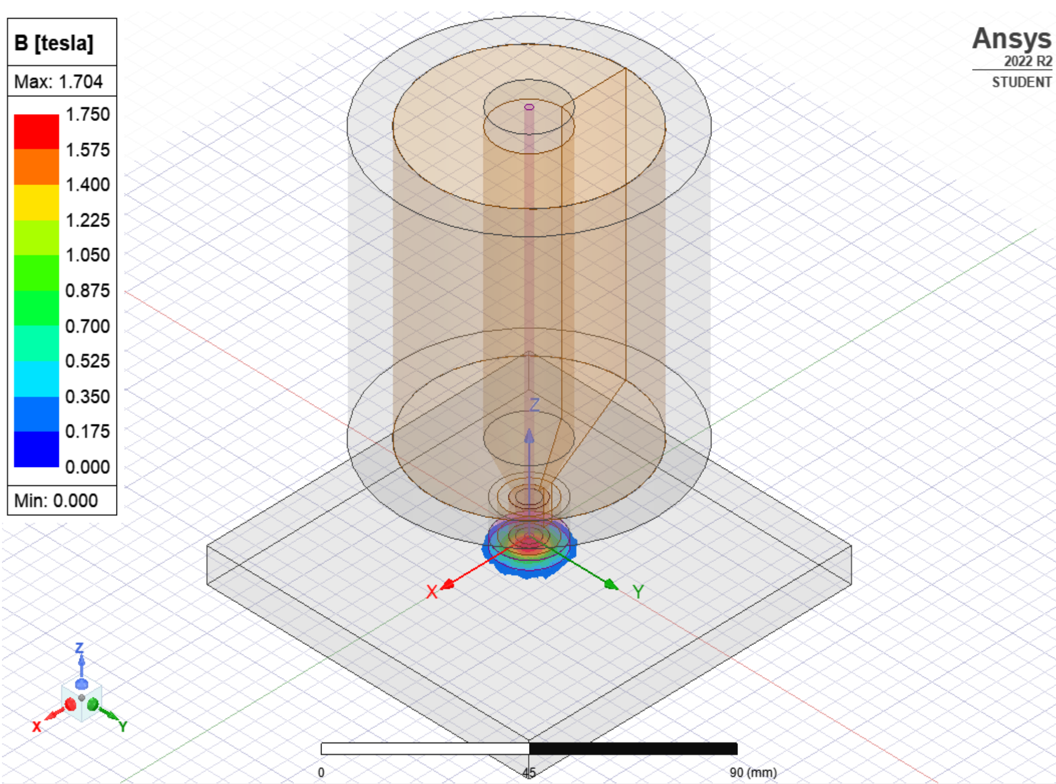

Figure 3.12: Magnetic field intensity at tool tip when Bush height 10mm & No. of turns 1900

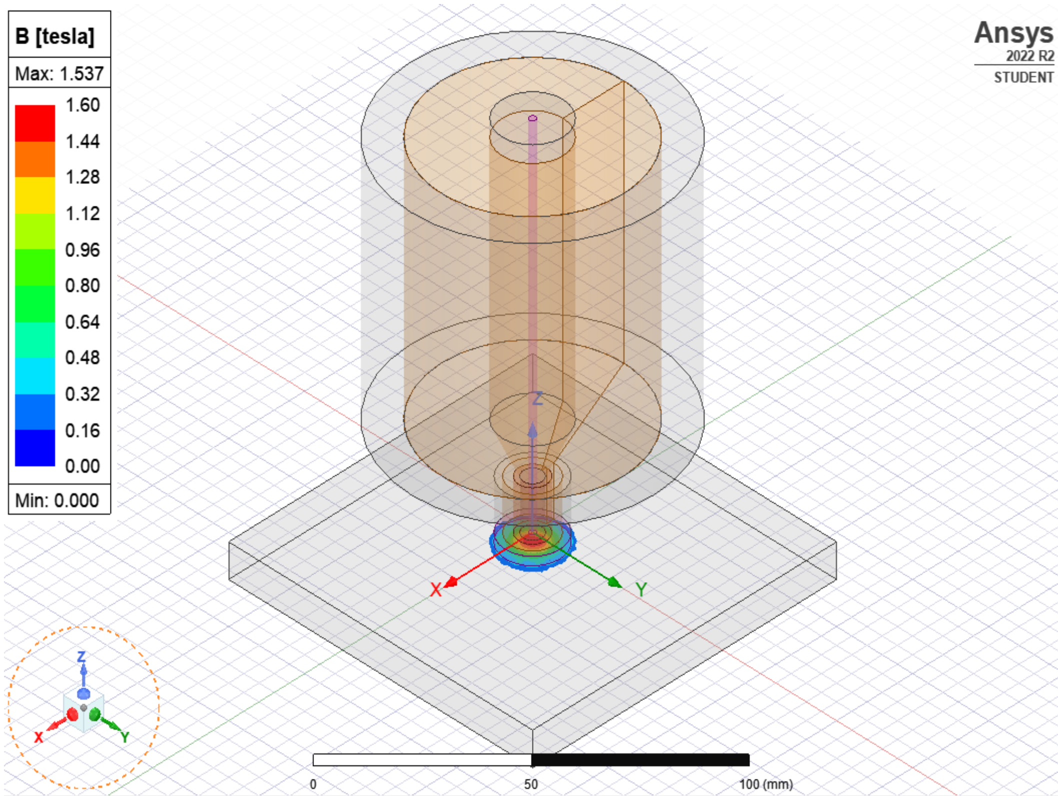

Figure 3.13: Magnetic field intensity at tool tip when Bush height 15mm & No. of turns 1800

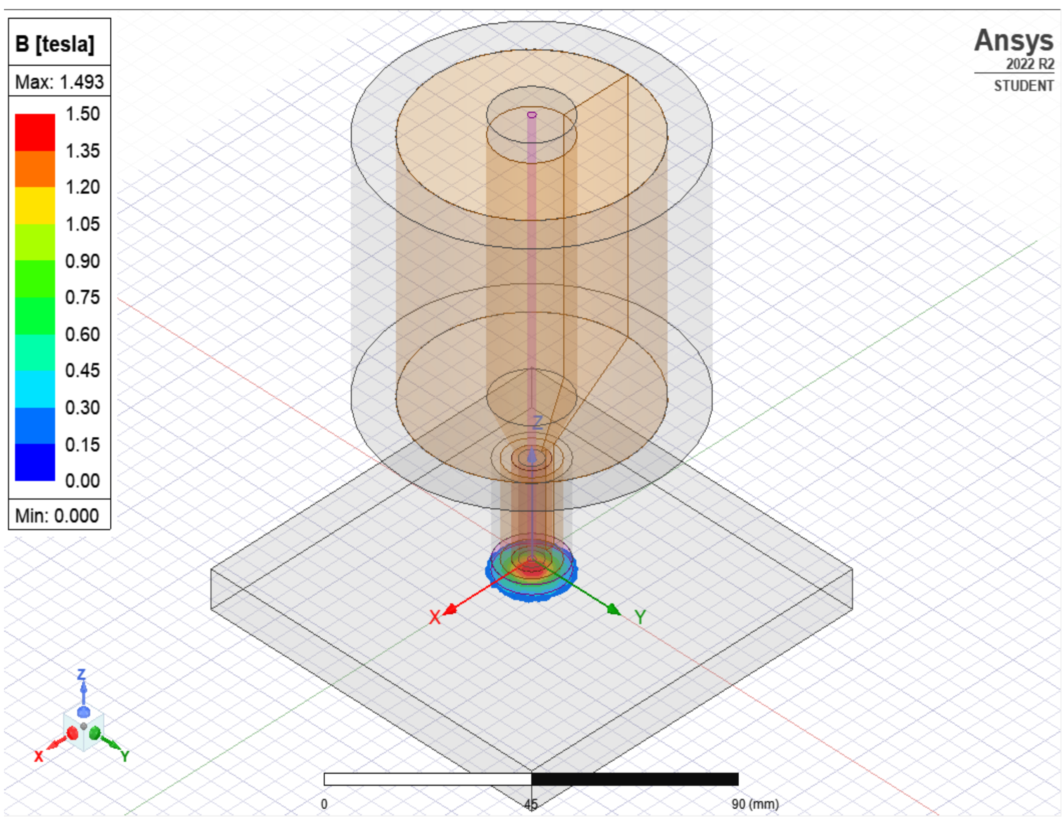

Figure 3.14: Magnetic field intensity at tool tip when Bush height 25mm & No. of turns 2000

After the simulations the value of magnetic field intensity at each MR finishing tool tip is entered manually in the designed matrix table. This table is shown in table 3.4. From the table it is observed that the maximum magnetic field intensity obtained at tool tip is 1.941 T in case when bush height being 5mm and number of turns is 2000.

Table 3.4: Design matrix with results.

Stand. Order	Run Order	Coded Values (Bush Height)	Coded value (No. of turns)	Actual value (Bush Height)	Actual value (No. of turns)	Intensity of Magnetic Field (Tesla)
10	1	0	0	15	2000	1.711
13	2	0	0	15	2000	1.711
2	3	-1	+1	10	2100	1.883
3	4	+1	-1	20	1900	1.532
6	5	0	+2	15	2200	1.889
4	6	+1	+1	20	2100	1.691
7	**7**	**-2**	**0**	**5**	**2000**	**1.941**
12	8	0	0	15	2000	1.711
1	9	-1	-1	10	1900	1.704
9	10	0	0	15	2000	1.711
11	11	0	0	15	2000	1.711
5	12	0	-2	15	1800	1.537
8	13	+2	0	25	2000	1.493

3.3 USE OF DIFFERENT MR FLUID

The tool with maximum intensity of magnetic field at its tip as obtained in fig.3.10 is now considered with three different magnetorheological fluid namely MRF-140, MRF-126 and MRF-122. Since the MR fluid shows non-linear magnetic behavior so the same has been exported in ANSYS Maxwell 3D simulation software. The data points of B-H curve is then imported to study the effect of magnetic flux density at the tip of MR finishing tool.

3.3.1. MRF 140 Magneto-Rheological Fluid

MRF 140 is hydrocarbon-based fluid having suspensions of magnetizable particles in a carrier fluid. When subjected to a magnetic field, the rheological property of MRF-140 immediately transforms from a free-flowing liquid to a semi-solid with manageable yield strength. By varying the intensity of the applied magnetic field, the consistency or yield strength of the fluid can be controlled.

When no magnetic field is present, MRF-140 fluid flows freely. But when subjected to magnetic field, the fluid particles align themselves like chain in the direction of the magnetic field, hence limiting the fluid movement in the gap and this limit is in proportion to the intensity of the applied magnetic field [35].

3.3.1.1. Features and Benefits

• Quick response time – responds immediately to changes in a magnetic field.

• Dynamic yield strength – offers high yield strength when subjected to a magnetic field and negligible yield strength when no magnetic field present.

• Temperature resistant – performs effectively though a wide range of temperature.

• Hard settling resistant – opposition to hard settling; gets dispersed easily.

• Non-abrasive – does not affect the devices in which it is used.

3.3.1.2. MRF-140 Properties

Table 3.5: Properties details MRF-140 [35]

Sl. No.	Name	Details
1	Appearance	Dark gray liquid
2	Viscosity	0.280 ± 0.070 Pa-S
3	Density	3.54 gm/ cm^3
4	Working Temperature	-40 to +130ºC
5	Solid content	85.44% by weight

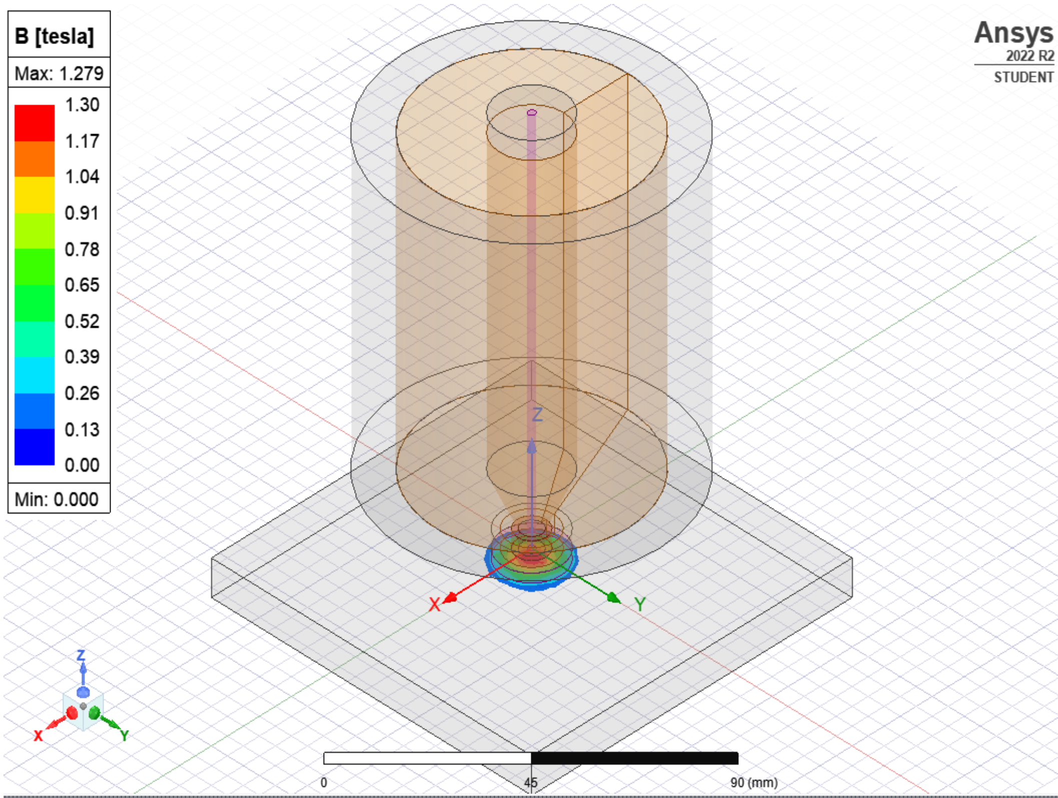

Figure 3.15: Magnetic field intensity at tool tip, using MRF 140 fluid, with bush height 5mm & No. of turns 2000

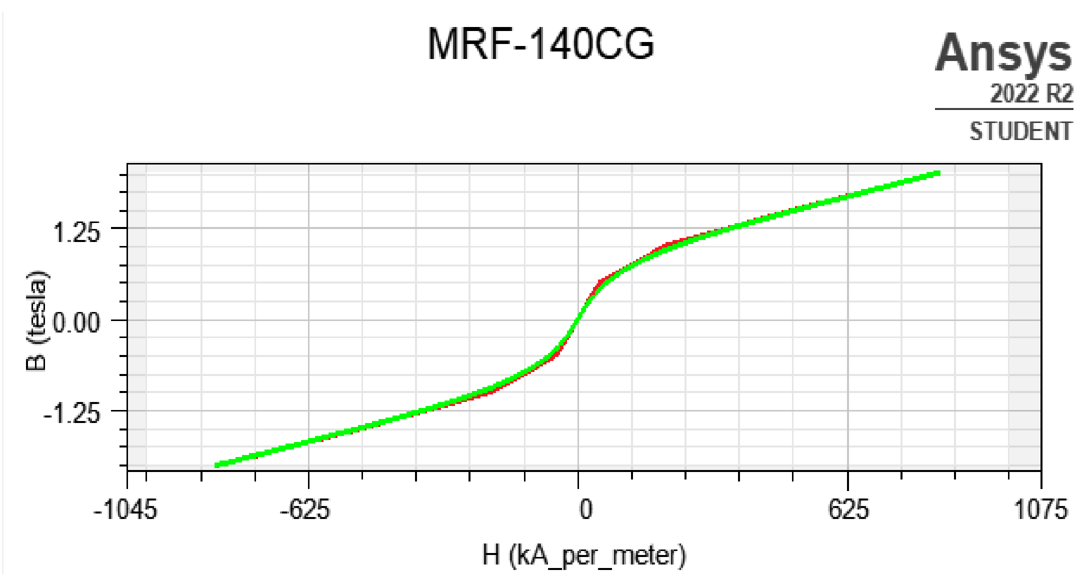

Figure 3.16: Magnetic Properties MRF 140

3.3.2 MRF 126 Magneto-Rheological Fluid

MRF 126 a magnetorheological fluid having micron sized suspensions of magnetic particles in a carrier fluid. When subjected to a magnetic field, the rheological property of MRF-126 changes from a free-flowing liquid into a semi-solid with commendable yield strength. By varying the intensity of the applied magnetic field, yield strength of the fluid can be controlled.

In magnetic field absence, MRF-126 fluid flows freely. But in its presence, the fluid particles align themselves in the direction of the magnetic field, thereby limiting the fluid motion in the gap and this restriction is in proportion to the intensity of the applied magnetic field. [36]

3.3.2.1 **Feature and Benefits**

- Quick response time – responds immediately to changes in a magnetic field.
- Low friction – provides lessen boundary friction.
- Dynamic yield strength – offers high yield strength when subjected to a magnetic field and negligible yield strength when no magnetic field present.
- Temperature resistant – performs effectively though a wide range of temperature.
- Non-abrasive – does not affect the devices in which it is used.

3.3.2.2 **MRF 126 Properties**

Table 3.6: Properties details MRF-126 [36]

Sl. No.	Name	Details
1	Appearance	Dark gray liquid
2	Viscosity	0.070 ± 0.020 Pa-S
3	Density	2.64 gm/ cm^3
4	Working Temperature	-40 to +130ºC
5	Solid content	78% by weight

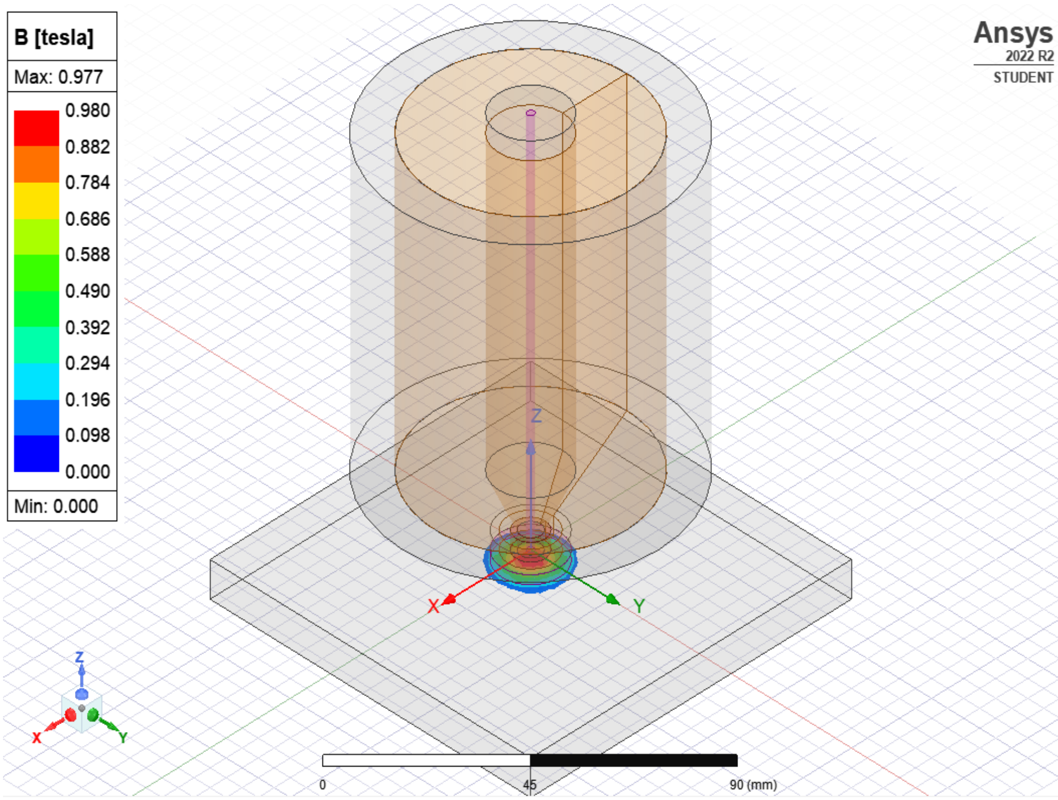

Figure 3.17: Magnetic field intensity at tool tip, using MRF 126 fluid, with bush height 5mm & No. of turns 2000

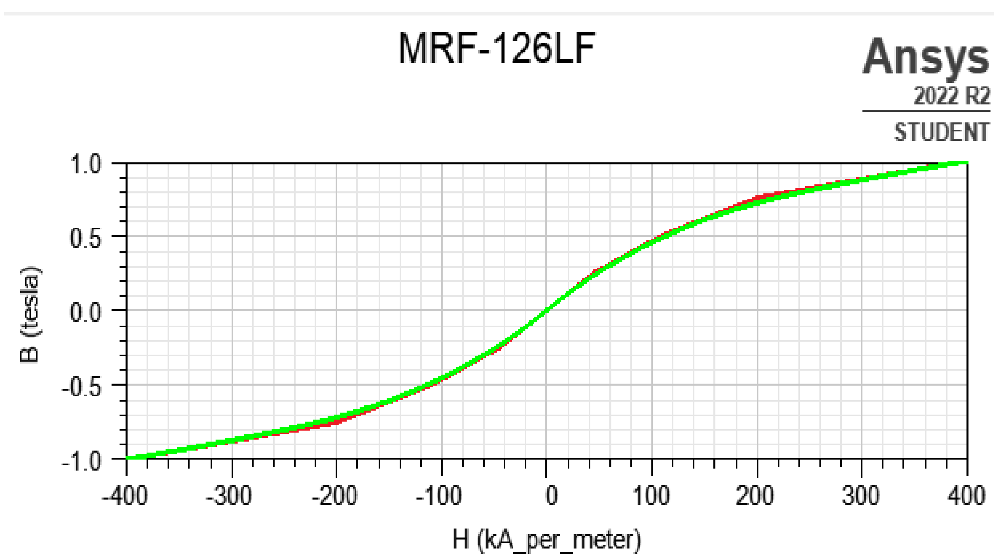

Figure 3.18: Magnetic Properties MRF 126

3.3.3 MRF 122 Magneto-Rheological Fluid

MRF 122 is also a hydrocarbon-based fluid having micron sized suspensions of magnetic particles in a base fluid. When put through a magnetic field, the rheological property of MRF-122 fluid quickly transforms from a free-flowing liquid to a semi-solid with controllable yield strength. By varying the intensity of the applied magnetic field, the yield strength of the fluid can be controlled.

When no magnetic field is present, MRF-122 fluid flows freely. But when put through magnetic field, the fluid particles arrange themselves in the direction of the magnetic field, so limiting the movement in the gap and this restriction is in proportion to the intensity of the applied magnetic field. [37]

3.3.3.1 Features and Benefits

- Rapid response time – responds immediately to changes in a magnetic field.
- Dynamic yield strength – offers high yield strength when subjected to a magnetic field and negligible yield strength when no magnetic field present.
- Temperature resistant – performs effectively though a wide range of temperature.
- Non-abrasive – does not affect the devices in which it is used.

3.3.3.2 MRF-122 Properties

Table 3.7: Properties details MRF-122 [37]

Sl. No.	Name	Details
1	Appearance	Dark gray liquid
2	Viscosity	0.042 ± 0.020 Pa-S
3	Density	2.28 gm/ cm^3
4	Working Temperature	-40 to +130ºC
5	Solid content	72% by weight

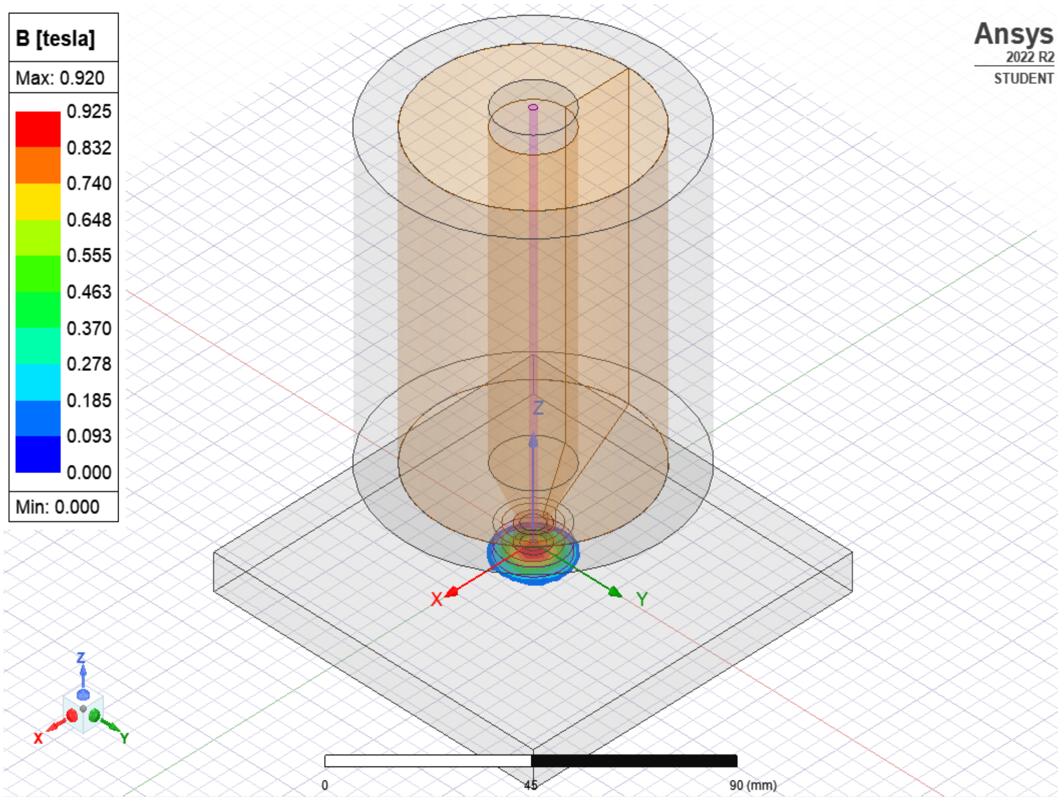

Figure 3.19: Magnetic field intensity at tool tip, using MRF 122 fluid, with bush height 5mm & No. of turns 2000

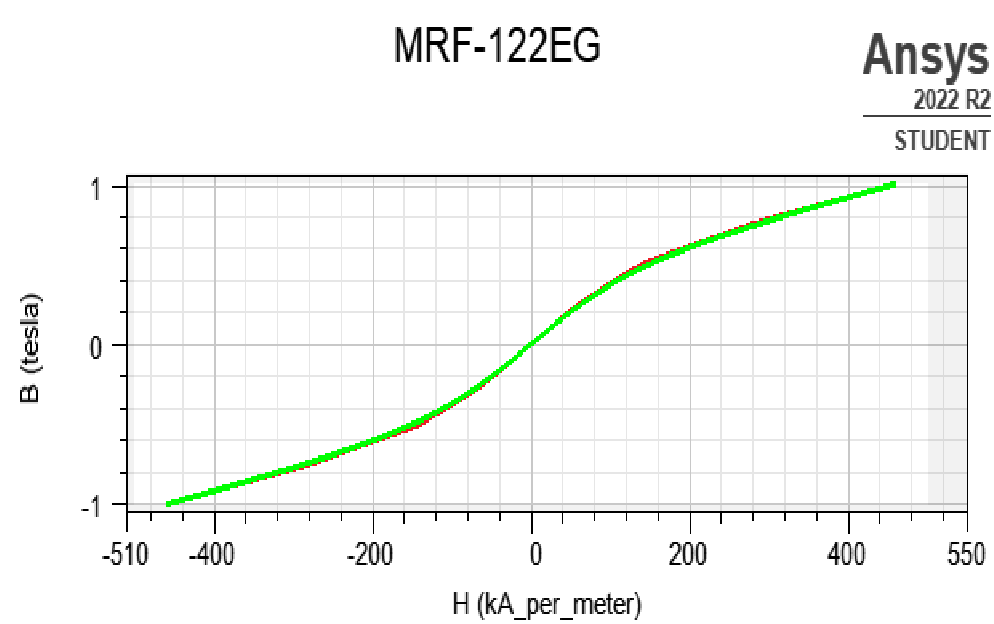

Figure 3.20: Magnetic Properties MRF 122

CHAPTER 4

STATISTICAL ANALYSIS

4.1 INTRODUCTION

Models of magnetorheological tools are developed in ANSYS Maxwell 3D simulation software to check the intensity of magnetic field at tool tip. The variable parameters taken in account were height of bush and number of turns in electromagnetic coil. The various outcomes were listed in DOE table. Later these data were utilized to analyze the non- linearity of the developed models and then the feasibility of the model is checked using Analysis of Variance (ANOVA) and graphical plots.Design expert 6.0.8 software (trial version) was utilized for the purpose.

4.1.1 Developments of statistical models

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

B = f (Bush height, Number of turns)

B = Intensity of magnetic field at tool tip

4.1.2 DESIGN EXPERT 6.0.8 Software (Trial Version)

This software is quite useful in leap forward changes to any parameter or a procedure. We can monitor for necessary elements, as well as find perfect process fixture for top implementation and find ideal parameter details. We can also see response surfaces from all points. It provides options to set flags as well as investigate forms on invasive 2D diagrams; and makes use of capacity to enhance it numerically so as to discover most extreme functions for reactions at the same time.

4.2 INVESTIGATING THE FEASIBILITY OF THE MODEL

Analysis of Variance (ANOVA) technique is utilized for investigation of the feasibility of the model proposed. As per ANOVA:

i. F ratio marks the base for assessing the confidence test, here the similarity between the calculated and the reference tabulation is tested.

ii. Prime condition for feasibility checking is,

Calculated f ratio should be smaller than the reference value, this indicates that model is quite suitable for feasibility.

Table 4.1: ANOVA for Response Surface Model.

Source	**Sum of Squares**	**DF**	**Mean Square**	**F-value**	**P-value**	**Remarks**
Model	0.22	2	0.11	566.41	< 0.0001	*Significant*
A: No. of turns	0.090	1	0.090	460.09	< 0.0001	
B: Height of bush	0.13	1	0.13	672.74	< 0.0001	
Residual	0.001967	10	0.001967			
Lack of Fit	0.001647	6	0.002744	3.43	0.1265	*Not Significant*
Pure Error	0.003200	4	0.0080			
Cor Total	0.22	12				

The model f-value of 566.41 means that the subjected model stands significant. There is very rare chance of 0.01% model f-value this extent may be occurring due to noise.

In order to remain significant, P value should not exceed 0.0500. So, in above case A and B are significant terms. The model terms are insignificant when their values are greater than 0.1000. If in any model, the number of non-significant terms are high, it is suggested to trim the model by reduction in number of parameters to make improvement in the model.

Finally, the Lack of fit f-value of 3.43 suggests that lack of fit is not significant in comparison to pure error. There is less chance (12.65%) that a large lack of fit value may occur due to noise factor.

Table 4.2: Model Statistics Summary

Source	**Standard Deviation**	**R^2**	**Adjusted R^2**	**Predicted R^2**	**PRESS**	**Comment**
Linear	0.014	0.9912	0.9895	0.9825	0.00393	*Suggested*
2FI	0.014	0.9917	0.9889	0.9743	0.00576	
Quadratic	0.016	0.9923	0.9868	0.9371	0.0140	
Cubic	0.10	0.9977	0.9945	0.8949	0.0240	*Aliased*

Table 4.3: Fit Statistics

Standard Deviation	0.014	**R^2**	0.9912
Mean	1.71	**Adjusted R^2**	0.9895
C.V. %	0.82	**Predicted R^2**	0.9825
		Adeq. Precision	62.345

The Predicted R^2 having value 0.9825 is nearby the Adjusted R^2 value of 0.9895 with small variation of 0.007.

Adequate Precision enables the author to calculate the S/N ratio.

This ratio should be more than 4, which is 62.345 in this case, hence the signal obtained is desirable. Further, this model entitles to set itself in the design area.

In terms of coded factors for magnetic field, the final equation:

B = +1.71 + 0.087*A **-** 0.11*B

These equations in terms of coded factors are apt in making assumptions regarding data for each level of all parameter. Generally, the higher parameters are marked as +2 while the lower as -2

In terms of actual factors for magnetic field, the final equation:

B = +0.28641 + 0.00086833*****Number of turns **-** 0.021000*****Height of bush

The equation in terms of actual parameters can be applied in making assumption about the output data for specified level of all parameter. This equation must be relieved from examining the relative effect of all parameter because initial coefficient is enlarged to settle up with units of all parameter while the intercept to the center of the design is not modified.

CHAPTER 5

RESULT AND DISCUSSION

5.1 ANALYSIS OF ANSYS MAXWELL SIMULATION RESULT

The various combinations developed using DOE were developed and simulated in ANSYS Maxwell 3D simulation software. The one modelled MR finishing tool with best magnetic field intensity at tip of MR finishing tool is shown in figure 5.1. The value of this magnetic field at tip of MR finishing tool is obtained to be 1.941 T.

The shape of the magnetic field intensity developed near tool tip is nearly semi hemispherical. The intensity at the center of this hemispherical ball is maximum (indicated by red area) and then gradually decreases to its outer periphery and finally to zero at edges (indicated by blue area). The red zone experiences the maximum magnetic flux and hence contributes most stiffened part to material removal in magnetorheological finishing process.

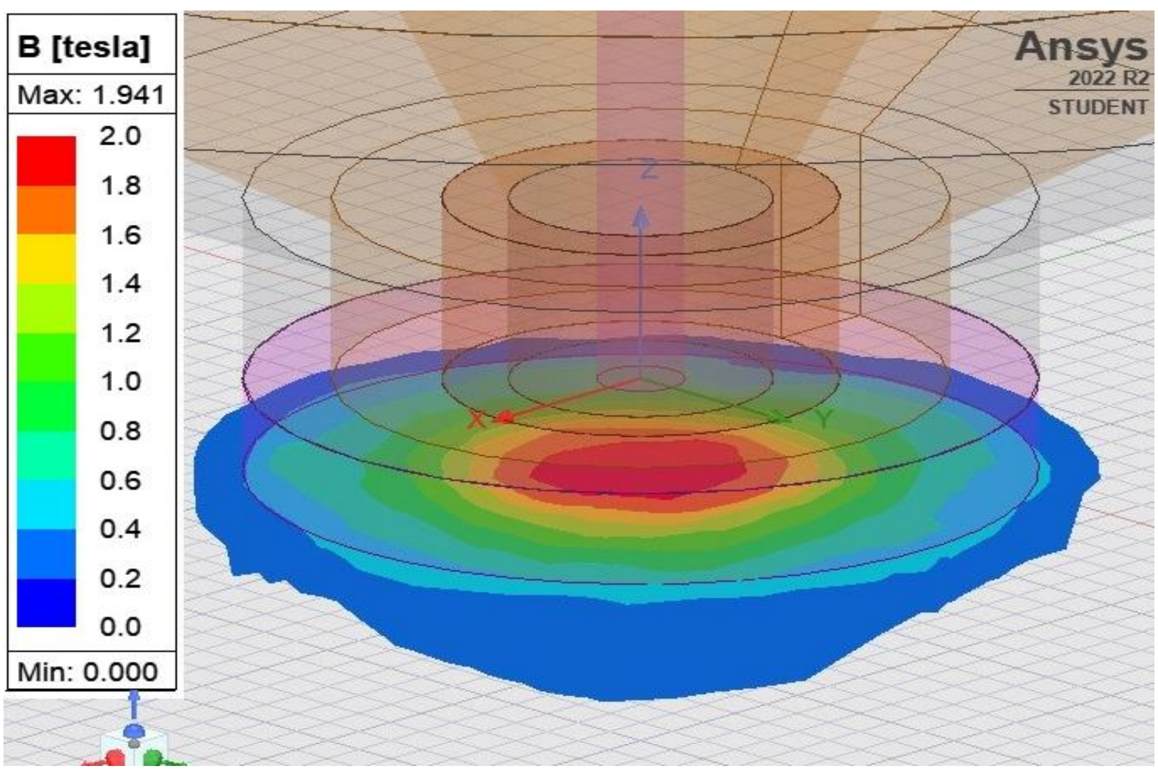

Figure 5.1: Maximum magnetic field obtained on one of the designed tools.

5.2 STATSTICAL ANALYSIS

5.2.1 Effect of analysis on Magnetic Field Intensity

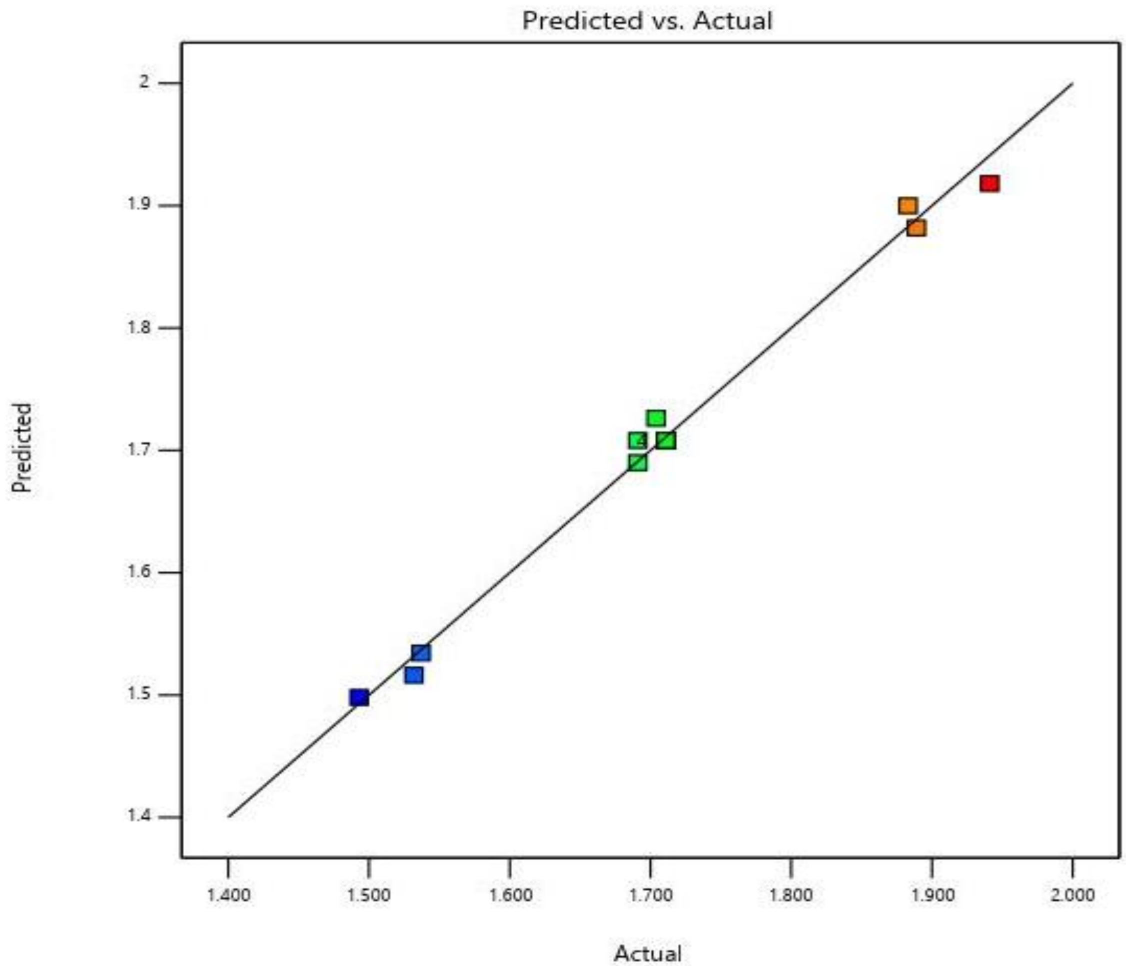

Figure 5.2: Graph between predicted vs actual points of magnetic field intensity

The above graph depicts predicted data of magnetic field intensity at MRF tool tip on the y-axis and actual data of magnetic field intensity at MRF tool tip on x-axis. The red dots corresponding to 1.999 represent highest value of magnetic field intensity at tool tip while navy blue dot corresponding to 1.49 represents the least values of magnetic field intensity at tool tip. From the above graph, it is obvious that actual data is nearby the predicted one. The graph above shows a clear correlation between predicted data points and actual data points.

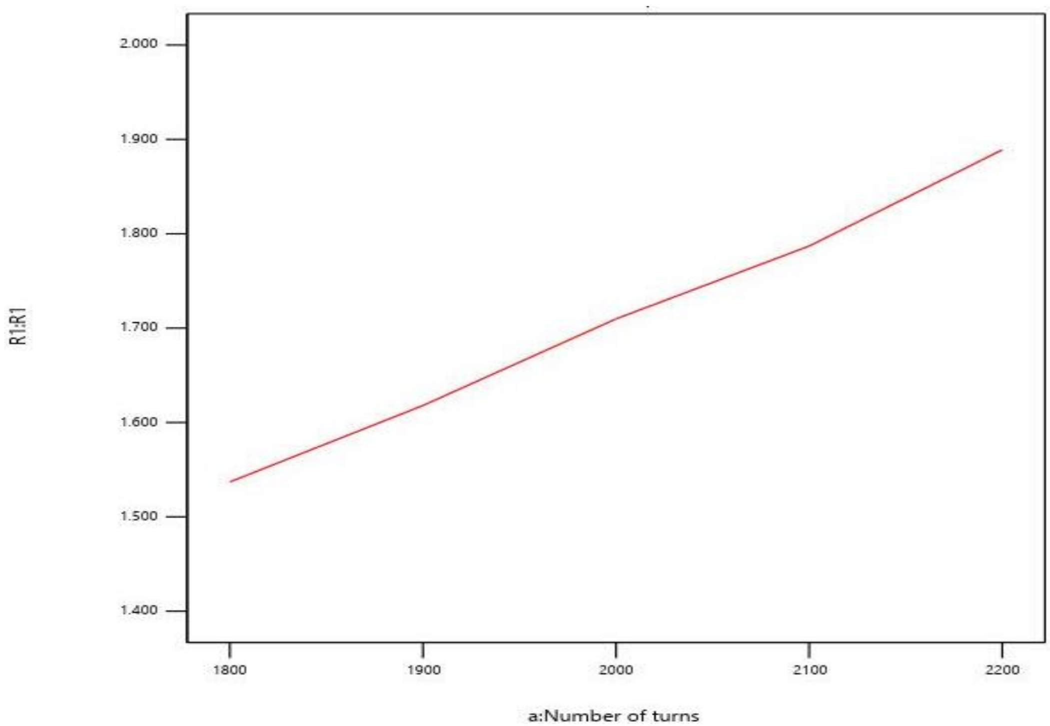

Figure 5.3 Line graph showing variation of magnetic field with change in number of turns.

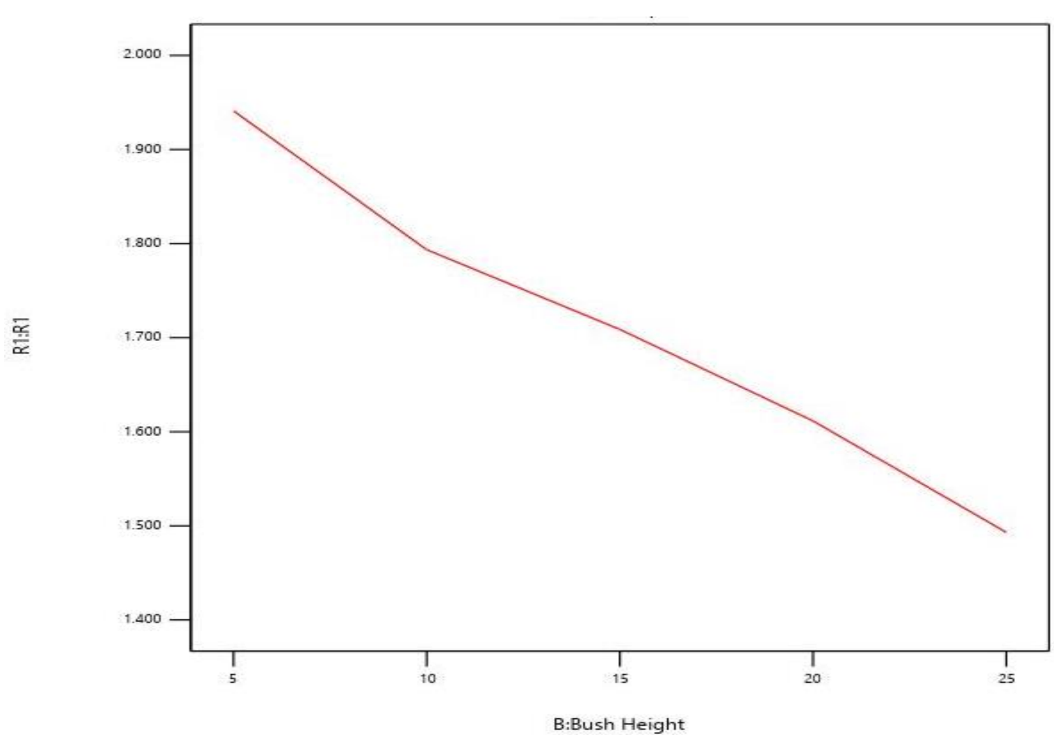

Figure 5.4 Line graph showing variation of magnetic field with change in height of bush.

The above graphs (figure 5.2 and 5.3) depict variations of magnetic field intensity at magnetorheological tool tip. It is evident from the figure 5.2 that as number of turns in electromagnetic coil increases the intensity of magnetic field increases. Further from figure 5.3 it is concluded that when height of bush increases the magnetic field intensity decreases. This is because the distance between the work surface and tool tip increases. Limit points in both case is shown in above figure.

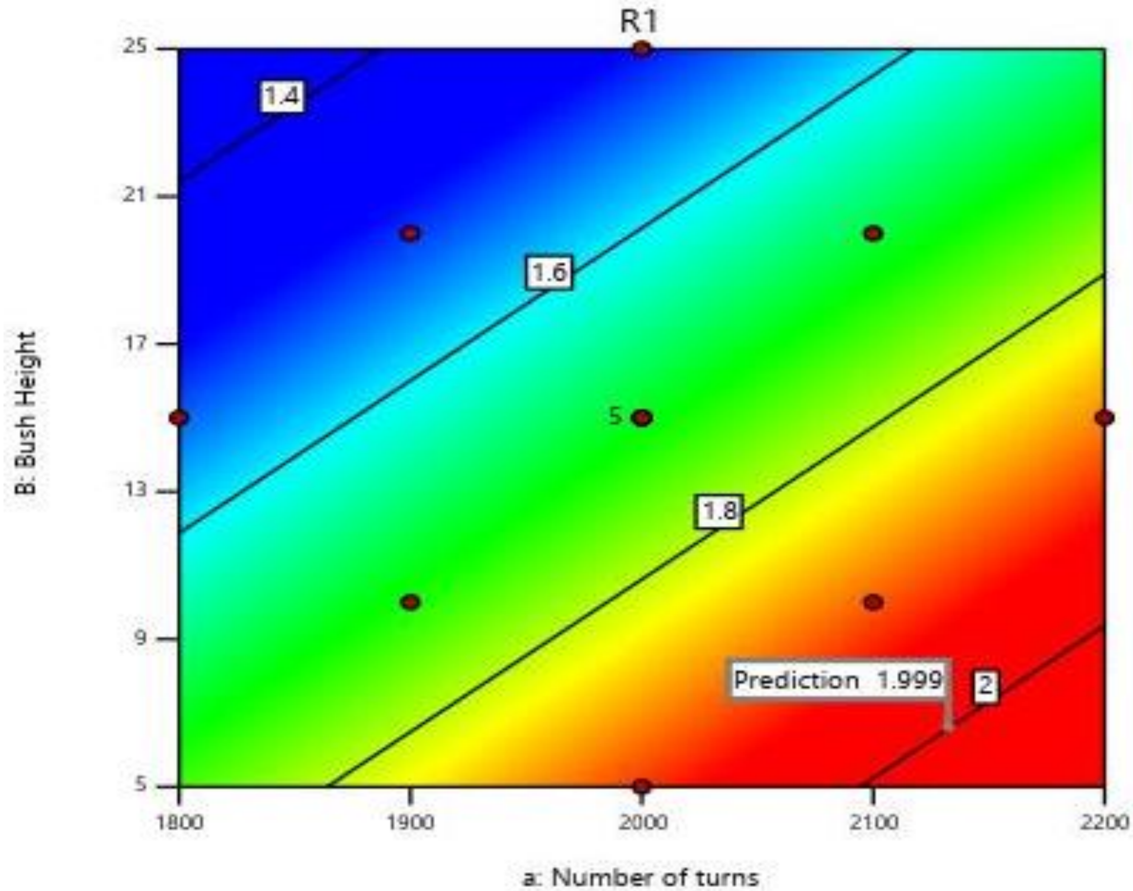

Figure 5.5: Contour plot showing magnetic field variation (2D View).

The contour plot (figure 5.4 and figure 5.5) depicts variation in magnetic field intensity at MR finishing tool tip with variations in height of bush and number of turns in electromagnetic coil. The height of bush (mm), the number of turns and the resultant magnetic field intensity on three different axes. The response surface geometry is 3-D in nature. 1.99 T is the highest magnetic field developed at the tool of MR finishing tool tip, (indicated at bottom right corner in 2D and at top right corner in 3D graph).

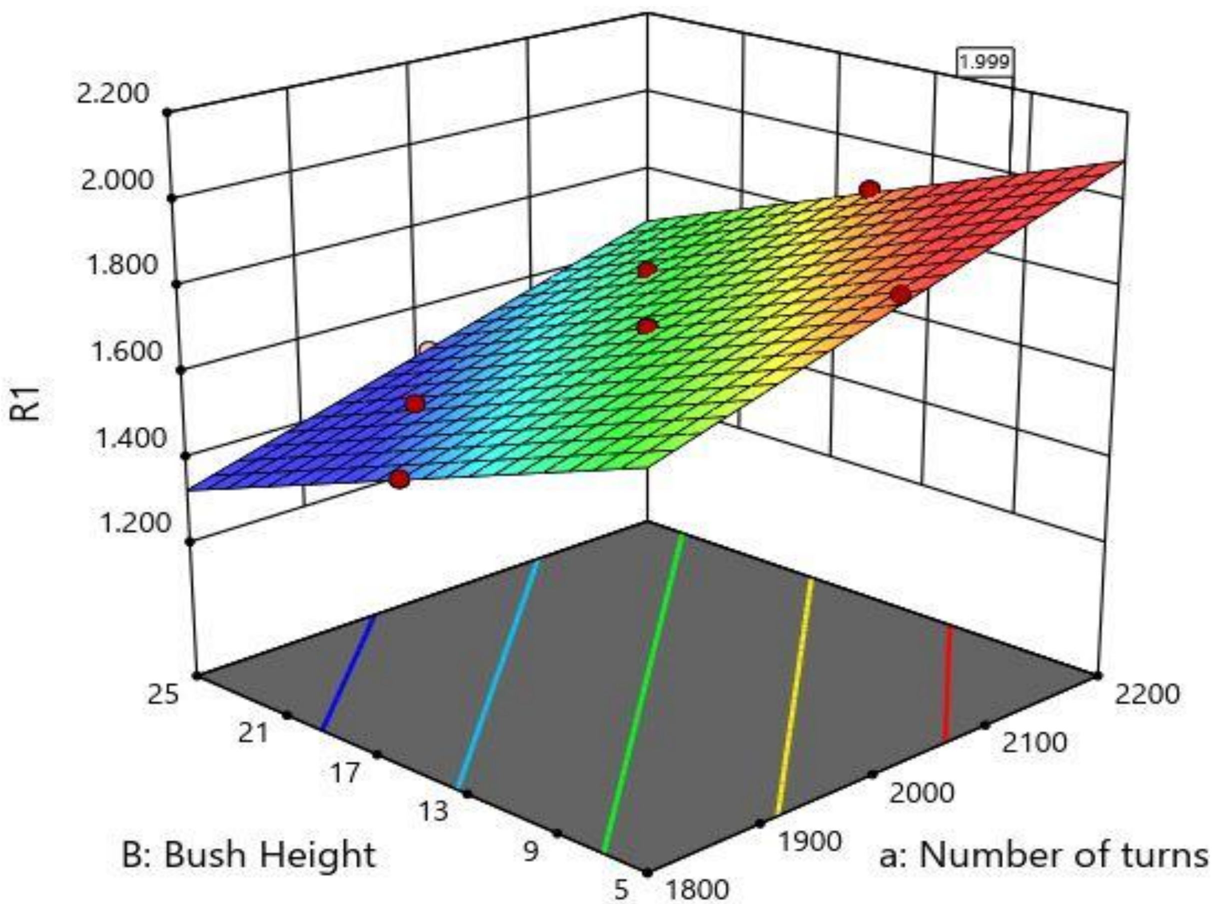

Figure 5.6: Contour plot showing magnetic field variation (3D View).

5.2.2 Effect of MR fluid variations

When three different MRF fluid is used for analysis, due to variation in the magnetic properties of these fluid, different intensity of magnetic field is obtained at tool tip in all three cases. The values of magnetic field intensity at tool tip, when MRF 140, MRF 126 and MRF 122 are used, is shown in table 5.1

Table 5.1: Magnetic field developed using different MR fluid.

Sl. No.	Type of MR fluid used	Magnetic field at tip [Tesla]
1	MRF-140	1.279
2	MRF-126	0.977
3	MRF-122	0.920

From the table 5.1 it is evident that in case of MRF 140 the maximum magnetic field is obtained at the tip of MR finishing tool. So, out of these three MRF-140 gave the best result. Hence it is concluded that if these three are available as option one must go for MRF-140.

5.3 OPTIMIZATION OF RESULT

The ramp model for number of turns (a) and bush height (B) is shown below. Their optimized value is indicated by red dot. The blue dot shows the maximum value of magnetic field intensity (R1) obtained after optimization.

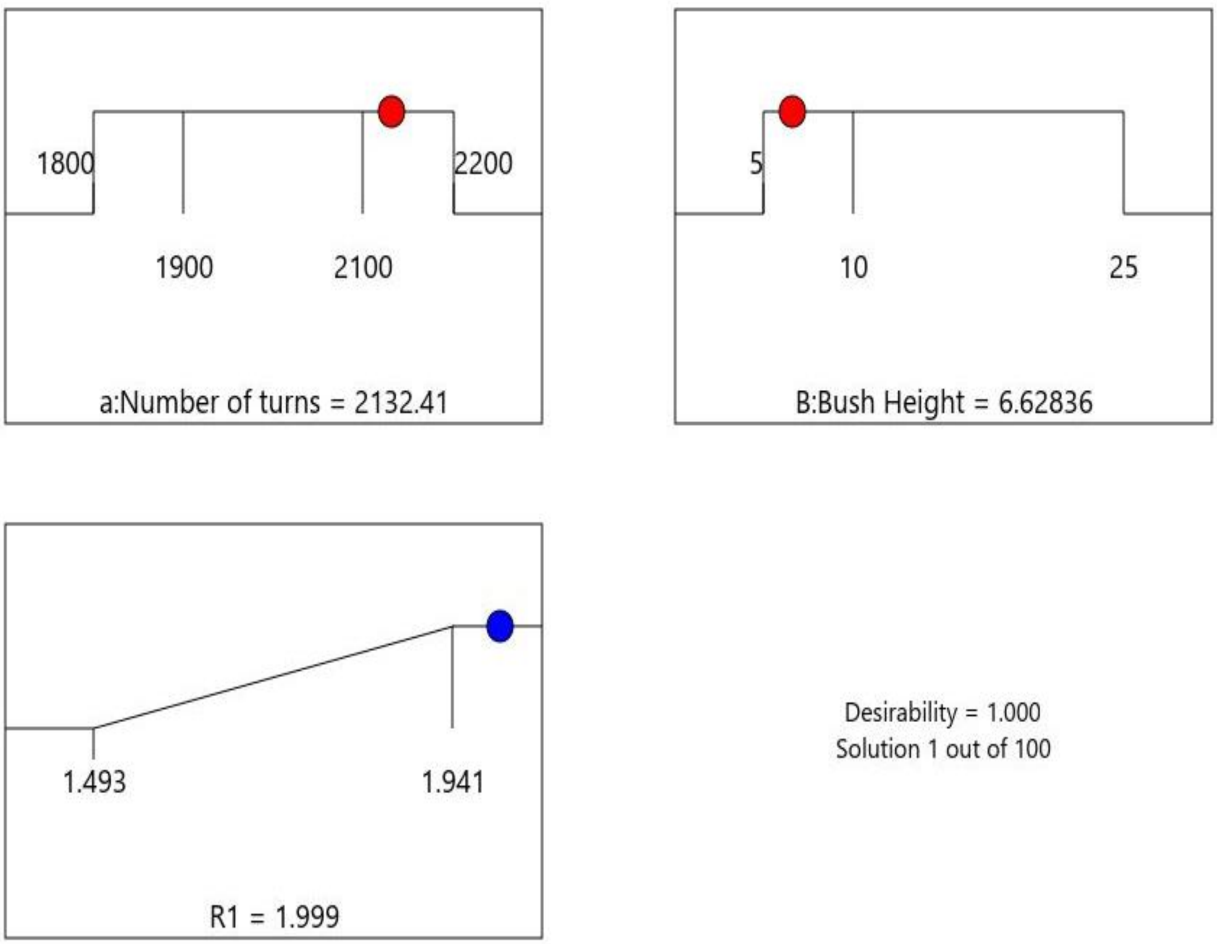

Figure 5.7: Optimum values of a, B and R1.

The optimum result obtained with value of number of turns in electromagnetic coil being 2133 and height of bush being 6.63mm. The optimum value of intensity of magnetic field at tip of MR finishing tool obtained as 1.999 T with the desirability 1.000

5.4 POINT PREDICTION

The table 5.2 below helps to predict the response parameter B (magnetic field intensity at MR finishing tool tip) mean, standard deviation, 95% CI low as well as 95% CI high with help of data points of response with 95% confidence and 99% population. The point predictions of responses are as follows:

Table 5.2: Response parameter for predicting mean.

Response	Predicted Mean	Std deviation	95% CI low for Mean	95% CI high for Mean
Magnetic Field (B)	1.99885	1.765	0.659	4.656

CHAPTER 6
CONCLUSION AND FUTURE SCOPE OF STUDY

6.1 CONCLUSIONS

This dissertation presents the design and simulation of MR finishing tool using ANSYS Maxwell 3D simulation software as well as statistical analysis and optimization using Design Expert software. The study aimed to investigate the intensity of magnetic field developed at the tip of MR finishing tool under various bush height and varying number of turns. Later, the effect of three different MR fluid namely MRF 140, MRF 126 and MRF 122 on magnetic field intensity is analyzed. By performing the study following valuable insights and outcomes are drawn:

- Through the utilization of Maxwell 3D simulation software MR tool was successfully modeled and simulated. The software provided an accurate representation of the tool's response to varying magnetic fields, enabling to evaluate its performance in real-world operating conditions.
- The maximum magnetic field intensity was found to be 1.941 T among the various combination of tool designed by taking into consideration the numeric parameters i.e. bush height and number of turns in electromagnetic coil.
- The optimized magnetic field intensity using ANOVA approach was found to be 1.999 T whereas, the predicted value for magnetic field intensity was 1.99885 T. The optimized and predicted value are close enough to validate the developed MR finishing tool.
- The optimized tool when used with three different MR fluid yield the maximum magnetic field intensity for MRF-140 and this was most significant fluid among the three used.

6.2 Future Scope of Study

The presented dissertation contributes to the advancement of magnetorheological tool design and optimization by leveraging the capabilities of Maxwell 3D simulation software. The insights gained from this study pave the way for future research and development in the field, ultimately leading to ease in creation of more efficient and reliable MR tools with a wide range of industrial applications. The integration of this software holds immense potential for shaping the future of MR tool development, enabling engineers to explore novel concepts and push the boundaries of this exciting field.

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