Design and Analysis of a Polishing Tool for Different MRP Fluid in the Magnetic Field Assisted Finishing (MFAF) Process

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Abstract — *Finishing of a surface is the most important aspect for many industries and thus a lot of research has been going on in this area for decades. Many non conventional machining processes have been developed to get a more effective finished surface. One such surface finishing and polishing process is the Magnetic field assisted finishing process (MFAF process). It is best used to finish the free form surfaces. A Magneto-rheological fluid is used as a finishing medium in this process. The permanent magnet controls the rheological properties of the MR fluid. Finishing forces consist of normal forces which help in getting the required indentation and tangential forces which are responsible for the removal of the material through indentation. As magnetic flux density plays an important role in deciding the finishing forces in magnetic field assisted machining processes and to access the required magnetic field on the tool tip , a polishing tool is considered. In this study, an optimised finishing tool for MFAF process has been designed using a simulation software package (ANSYS) and then a critical analysis of variation of magnetic flux density at the tip of the tool for four different MR fluids is performed. Lord Corporation is a company that commercially manufactures these MR Fluids. The above analysis helps in determining the best MR fluid for further research in this vast field of finishing processes.*

Keywords — *MR Fluid, Magnetic assisted finishing process, Polishing tool, Nanofinishing, Smart fluid, Ansys simulation.*

I. INTRODUCTION

The surface quality of most of the products or parts manufactured in the industry plays an essential role in enhancing the overall functionality and the life of the entire product and due to this the industry today is having an inclination towards a highly finished product and particularly those linked with advanced engineering applications such as in the field of nanoscience, aeronautical systems and medical equipment. However, it is challenging to produce such a highly finished surface by manual polishing or by using the conventional finishing methods. Even it is quite evident in processes like welding, forging and other operations, the part after the process is left with some roughness which eventually decreases part efficiency and the overall efficiency of the product as a whole. Conventional finishing processes such as grinding, honing, lapping require both skill, intensive labour, causing a lot of error and damages the sub surface. Apart from these, the non conventional processes also don't have a proper mechanism to guide the slurry or fluid which acts as cutting fluid. To overcome all these problems with the conventional and non conventional finishing processes and to get an effective surface finish, a lot of research from the past few decades have been going on in the area of magnetically controlled super fluid based finishing techniques. These processes use the rheological properties of the magneto-rheological fluid under the magnetic field applied externally to control the forces which cause the finishing on the target zone. S.Jha et al.[1] have developed a new and a very effective finishing process that could reach the intricate corners of any complex part or geometry. The process used was the magneto-rheological abrasive flow finishing (MRAFF).

MR polishing fluids are the fluids that consist of small particles which are magnetically charged like the carbonyl iron, immersed in a medium like water or viscoplastic base of mineral oil. As shown in Fig 1When magnetic flux is applied on the MR fluid, the CIPs acquire magnetic dipole moments, which is directly related to the strength of the magnetic field and when this magnetic interaction among the CIP particles attains more than their excitation energy, the particles collide into chains of dipoles. They get formed into chain-like structures with abrasives amidst them. Experiments were performed on stainless steel work pieces so as to obtain an inference from its influence on the surface finish. However, the key observation was that for the same number of cycles on increasing magnetic field strength, roughness value decreased along with increasing strength. It is quite evident that while the magnetizing current is increased, the magnetic field strength also increases which makes the CIP particles hold the abrasives together and thus resulting in the improved finishing process.

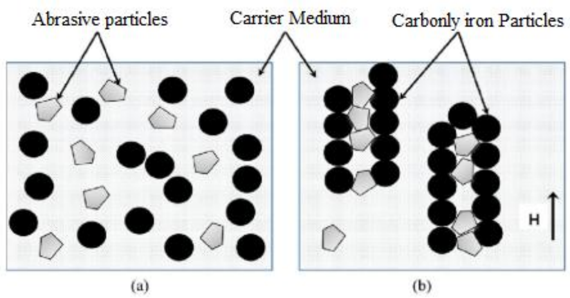


Fig 1: Abrasive particles (a) Without applied force field (b) With force field

The increase in the field's strength is not linear when the magnetic field is increased as the particles being ferromagnetic and the field strength thus occurs non uniformly in different parts. For the study on the behaviour of different MR Fluids for the same working gap chosen tool geometry according to the MFAF process was chosen. Magnetic field-assisted finishing, sometimes called MAF process is a process in which using a magnet and its field to force the rough particles, basically the abrasives against the aimed surface. It is a modern and very effective technique. The material removal, a finished surface is obtained due to the relative motion between the material surface and the tool .This process avoids the direct contact with the tool, the particles can reach the intricate corners of the geometries.

II. LITERATURE REVIEW

A recent finishing process which uses magnetic abrasives and pressure indentation for stock removal and surface finishing having diamond coated magnetic abrasives were employed to finish Si_3N_4 fine ceramics and its finishing abilities were backed by T. Shinmura, K. Takazawa et al.[2]. It actually helped in giving a direction and laying the guidelines for the magnetic assisted finishing process. W. Kordonski, D. Golini et al.[3] presented the basic working of the magneto-rheological fluid (MR) and its finishing process in magneto-rheological finishing (MRF) processes. They have presented the flow of abrasive fluid flow in the converging gap of the work-piece and the moving wall for precise material removal finishing. They paved the path for further enhanced magneto-rheological finishing processes like B-MRFF, MFAF and other processes. Other applications are being considered integrated circuits and advanced ceramics. MRF is now widely used in many applications and in many fields like automotive industry, household applications, prosthetics, brakes and clutches etc. It can also be used in reducing the effect of gun recoil. Application of MRF is innumerous and widely used nowadays. J. Rabinow et al.[4] devised a new passive clutch with use of magneto-rheological fluid. In their setup they have induced eddy currents on a conductive material and electromagnetic torque is formed. This torque formed is used in engagement of the clutch using MR fluid. The device has been analyzed using the FEM code and some set of operations were performed and simulated using Ansys. V.K. Jain, S.G. Abdul et al.[5] have analyzed and focussed on the basic non-conventional method of surface finishing abrasive flow machining in which semi-solid medium containing visco-elastic polymer and abrasive particle mixed in a definite fraction. It is thrusted under pressure through and across the work piece to obtain the surface finishing. K Saraswathamma et al.[6] in the ball end magneto rheological finishing process stated that the rheological properties such as field induced yield stress and viscosity are a function of CIP volume and flux density which has a direct dependence and another observation made was that the shear thinning behaviour was seen more in CIP-OS (coated with silicon dioxide) with and without exterior magnetic flux density, Sidpara, A. et al.[7] have worked on the magneto-rheological forces obtained using the magneto-rheological fluid.MRF are used in nanofinishing. A model was prepared depicting the three forces, normal force, tangential force and squeeze force for in depth understanding of the nanofinishing process using the magneto-rheological fluid. Das M, et al.[8] proposed a more recent finishing process named as "rotational–magneto-rheological abrasive flow finishing (R-MRAFF)" The study of Barman A. et al.[9] who worked on the spot nanofinishing of surfaces which plays an important role in improving the surface quality of small optical components and mechanical devices.

III. DESIGNING OF POLISHING TOOL

The designing of a polishing tool is done to predict the finishing performances of the cutting forces. Knowledge of magnetic flux density is important to understand the finishing mechanism. In the study an effort to develop an understanding towards the parameters that can affect the final magnetic flux density in the working gap and for that an in depth analysis is done over designing every part of the polishing tool.

A. *Modelling of Permanent Magnet*

Firstly, a replica of permanent magnet is prepared without specifying any dimensions using Ansys for verification of the behaviour as listed for Nd-Fe-B (grade 48). The Permanent Magnet used here is a linear hard magnetic material type permanent magnet of cylindrical geometry. The

Table I Properties of permanent magnet Nd-Fe-B(N48)

Magnetic properties	Units	Minimum	Nominal	Maximum
Br, (ResiduaInduction)	mT	1370	1400	1430
HcB, Coercivity	kA/m	836	963	1090
HcJ, Coercivity	kA/m	955	-	-
BH ,Maximum energy product	Kj/m^3	358	374	390

Properties considered during modeling of permanent magnet are listed
Table I. The following assumptions were taken into consideration during the finite element simulation set up:-

- Only stationary magnetic fields are considered during computation.
- The objects considered during simulations are stationary.
- Nd-Fe-B(N48) permanent magnet is the only source of magnetic field lines for the whole apparatus.
- An enclosure is also provided as a cushion for the whole apparatus with air as environment.
- The enclosure act as the working environment for the whole polishing tool
- Apart from enclosure everything is vacuum.
- Specific polarization coordinates are specified during designing of the permanent magnet.

Here MRP fluid occupies the whole space between the magnet and work piece, known as the working gap, and for this study the working gap is kept fixed as 1 mm. A line is plotted running through the magnetic axis from magnet tip till point B at the work piece surface and then from B to the edge of the work piece i.e. till A another line has been drawn as can be seen in the Fig 2, so as to get a defined variation of magnetic field with the increasing gap from the tip of the magnet to the edge of the surface. The distribution of magnetic field is one of the basic parameter which will further lead to the designing of the optimum tool design. Height and diameter are the two main features of the magnet dimension. While simulations were run, one of the parameters was fixed and the other was varied. The diameter range is varied between 5 mm-20 mm and the height range is varied between the 50mm-100 mm.

Firstly, the diameter is kept fixed at 10mm and then the height is varied from 70 mm to 100 mm. The simulation result can be seen in Fig 3 and it can be observed that the height of the magnet does not have much impact on the workpiece and also the flux density doesn't deviate much and remains the same almost as evident in the graph. So, 70 mm is the height taken for the magnet. Now, the diameter is varied with keeping the height fixed at 70 mm and simulation results are shown in Fig 4. It can be observed from the distribution that a non uniform magnetic flux density is generated for the 5 mm diameter while it has a maximum density at the tip but it falls down very rapidly when observed away from the centre, which isn't suitable as it is desired to have a larger radius of the working fluid with maximum flux density. Now, the distribution curves for 20 mm diameter magnet in Fig 4 shows that 20 mm diameter is also not appropriate for the optimum tool design as the maximum magnetic flux density observed is around 0.1 T, which is not a desirable outcome because as per the requirements it is needed to have a high and good strength flux density at the tip of the optimized tool. Finally it is seen in Fig 4 that magnets with diameter ranging between 10mm to 15 mm are suitable as they show the variation of magnetic flux density as per the required level.

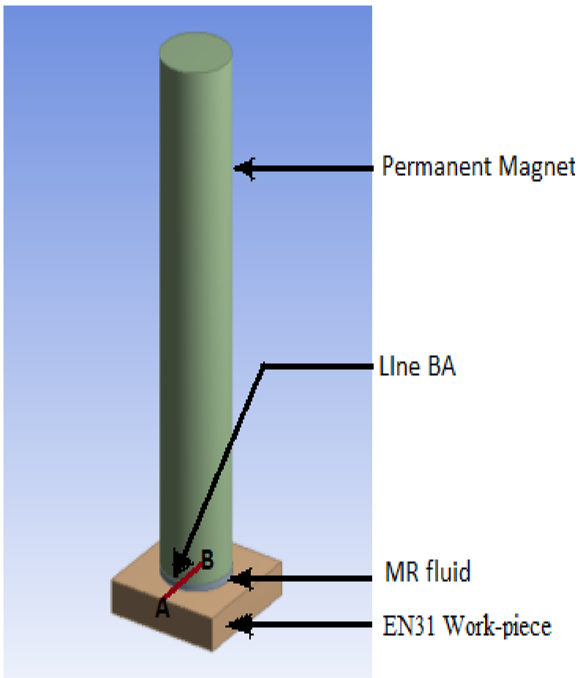


Fig 2 Simulation set up of the polishing tool

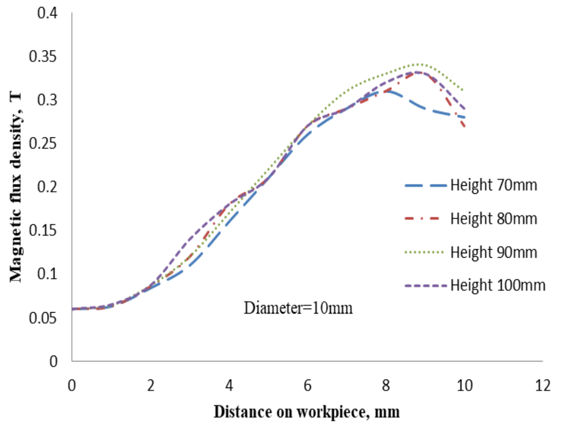


Fig 3 Magnetic flux variation for different heights with diameter fixed at 10 mm

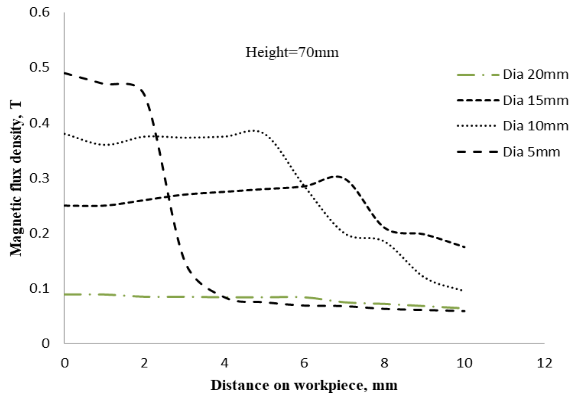


Fig 4 Magnetic flux variation for different diameters with height fixed at 70 mm

B. Modelling of Magnetic Holder

The tool comprises of a permanent magnet and tool holder, the shape and geometry of permanent magnet have been discussed in section 3.1. The literature [11] have focused on optimizing the tool holder design so as to get a highly concentrated magnetic flux density at the workpiece and those results have been verified in the present study by analysing the optimum tool holder design suggested [11].

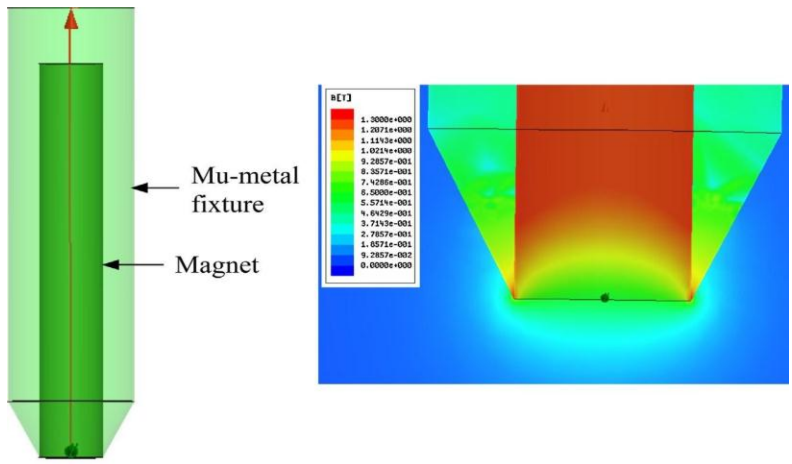
The key features considered during simulation set up for the magnet holder are as follows:

- The permanent magnet needs to be surrounded by magnet holder completely.
- The holder should aid in concentrating the magnetic flux lines towards the tip of the tool.
- The holder should act as a shield for MR polishing fluid to any outside environment particle or magnetic material.

Mu metal is the material employed for magnetic shielding. It is an iron-nickel based alloy and a high permeable magnetic material. For designing the shape of the magnet fixture and gripping of the magnet, different dimensions and shape of the holder are taken into consideration in [1]. The idea behind the study is based on the contour plots of magnetic flux distribution just so all the magnetic field lines can be polarized towards a particular direction. The dimensions of the magnetic holder were adjusted according to the study done in section 3.1.

The main aims of the study are

- To find out the best and the appropriate shape of the magnetic fixture that will give out the maximum magnetic field on the surface of the workpiece.
- To obtain a point of contact on the workpiece, thus aiming for spherical shaped fluid in the targeted zone and generating a circular magnetic field distribution.



(a) (b)

Fig 5 (a) The shape of the optimum configuration and (b) Contour plot of optimum configuration

During study the two main factors which were taken into account are magnetic flux distribution on the surface and the shape of the contour plots at the bottom of the magnet with centre as magnetic axis. Fig 5 (a) shows the shape considered for magnet holder and Fig 5 (b) shows the contour plot for the magnetic flux density distribution at the bottom of the magnet, thus verifying that a spherical shaped zone is formed. In Fig 6 is shown, which indicates that the configuration is providing appropriate magnetic flux distribution in the finishing zone and hence can be used for further analysis.

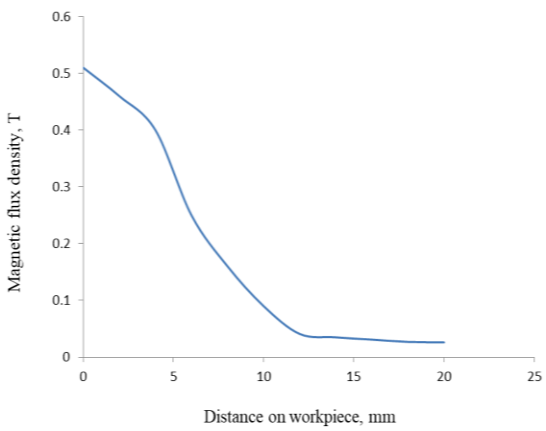


Fig 6 Magnetic flux distribution over the line AB

C. Properties of MR polishing fluid

J.D. Carlson et al.[12] have discussed the controllable magneto-rheological fluids and their applications . These fluids have found their application in a wide range of devices controlling vibrations, aerobic exercise equipment, finishing freeform surfaces as well as complex structures and in line with that the present study has considered these 4 magneto-rheological fluids, MRF-122EG, MRF-132DG, MRF-126LF, MRF-140CG. The data for defining the properties of different MR Polishing Fluid are taken from Lord Corporation, which produces MR Polishing Fluid.

IV. EXPERIMENTATION

In line with the optimum design condition discussed above a magnet fixture is fabricated as shown in Fig 7 (b) . A milling machine as shown in Fig 7 (a) is used in which a mu-metal magnetic holder and a permanent magnet is fixed. 1 mm is the gap between the workpiece and tool..EN31 is taken as the workpiece in both experimentation and simulations during magnetic flux density analysis. The comparison of the experimental and simulations are then done for different MR fluids. The comparison is based on the maximum magnetic flux obtained at the tip. The tool developed is temporarily fixed to a 4-axis CNC milling machine head. A permanent magnet (Nd-Fe-B of grade N48) of proportion 10mm x 70mm is attached to the tool holder, with the properties listed on the table. The MRP fluids used in the experiment have properties as listed above in Table II.

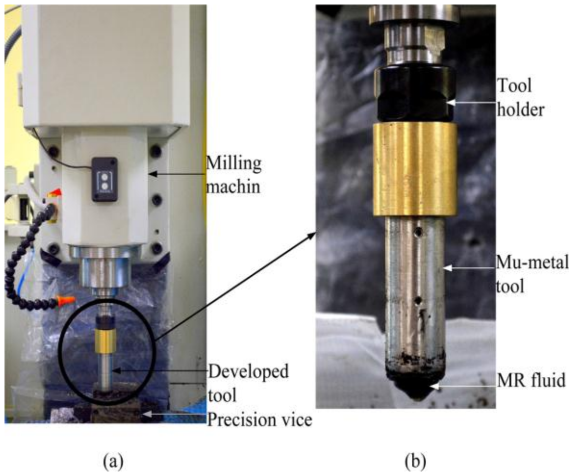


Fig 7 (a)milling machine with the tool and (b)an enlarged view of the tool.

V. SIMULATION SETUP

Analysing the effect of magnetic field on MRP fluid during finishing in MFAF process is necessary in order to simulate the whole processing tool. The design considered for simulation set up in this study is shown in Fig 9 and a close view on how abrasive particle will indent the workpiece is shown in Fig 10. The MR fluid shows non-linear magnetic properties and thus it is fabricated in Ansys as a non -linear magnetic material. After this, another important property for MRP fluid is B-H curve which are shown in Fig 8. VSM provides the data for the BH curve of MR fluid. After this, the BH curve data is given as input in MR fluid material property. For the better interpretation of magnetic field lines behaviour in the Magnetic field assisted finishing (MFAF) process, a 3 dimensional finite element study is done. In the present study the dimensions considered for the cylindrically shaped Nd-Fe-B permanent magnet of grade N48 is 15 mm x 70 mm. The magnet is held by a magnet fixture made of Mu metal during finishing. In the beginning, a distance of 1 mm is taken between the tool and work-piece to receive the MR fluid. Some validation experiments are performed at different process parameter conditions after the simulation study is completed. Now in the end of simulation study, a point contact is defined between work-piece surface and abrasive. After this some trial runs were performed with some of the parts activated with the required material configuration and in the last with whole polishing tool activated.

Table II Properties of MRP Fluids.

Properties	MR Polishing Fluids			
	MRF-122EG	**MRF-132DG**	**MRF-126LF**	**MRF-140CG**
Solid content conc. (% by weight)	72	80.98	78	85.44
Viscosity (Pa-s @ 40°C)	0.042 ± 0.020	0.112 ±0.02	0.70± 0.02	0.280±0.070
Density (g/cm³)	2.28-2.48	2.95-3.15	2.64-2.84	3.54-3.74
Ignition point (°C)	above 150	above 150	above 150	above 150
Temperature range (°C)	-30 to 120	-30 to 120	-30 to 120	-30 to 120
Texture	dark greyish liquid	dark greyish liquid	dark greyish liquid	dark greyish liquid

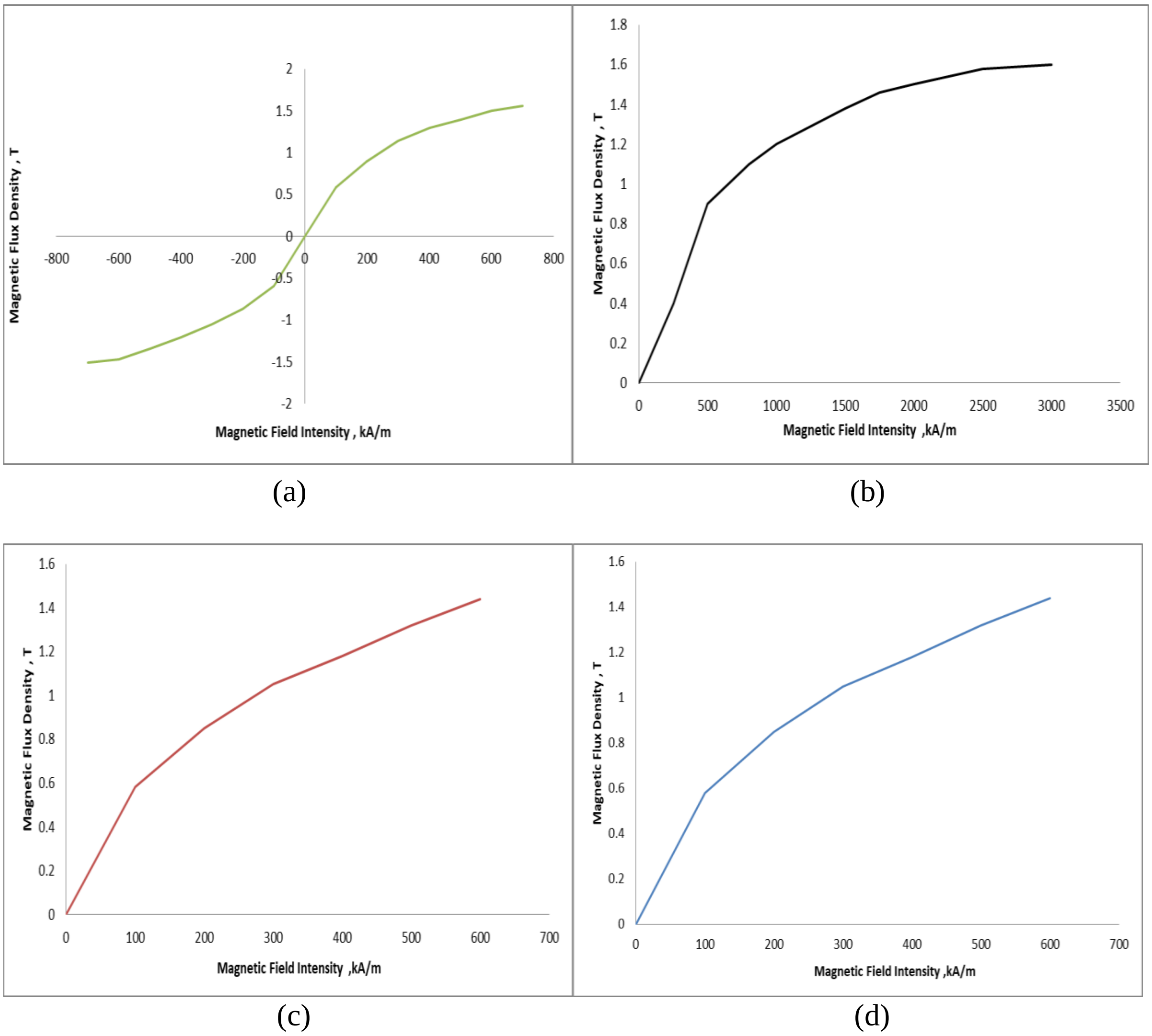


Fig 8 B-H curves for the MR Polishing fluid used (a) MRF 132DG (b) MRF 126LF (c) MRF122EG (d) MRF 140CG

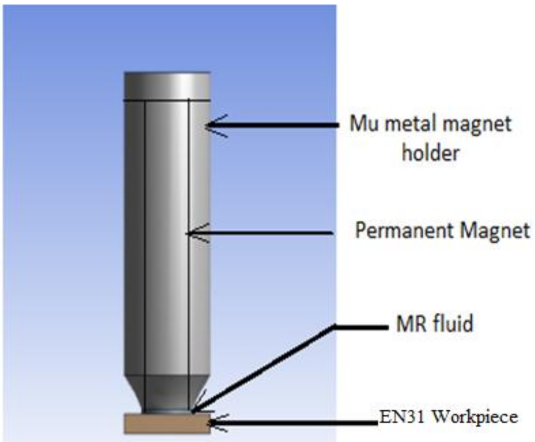


Fig 9 Basic framework of finalised tool

VI. RESULTS AND DISCUSSION

The 4 MRP fluids discussed in Table II were simulated in the Ansys environment in accordance with the B-H curve and the properties shown in Fig 8. Now after designing both the MFAF polishing tool and MRP fluids the variation of magnetic flux density is observed and it was found that the maximum flux density in case of every fluid was on the tip of the tool. The various results obtained from Ansys software magnetostatic simulations for 4 MR Polishing Fluid are listed in Table III. From the respective simulations as shown in Fig 11, it can be seen that the maximum flux density is at the tip in each case, and the vectors represent the flow of the magnetic field lines that originate from the permanent magnet and then pass through the respective MRP fluid. In the present study Al alloy is chosen as the workpiece material, which is a non ferrous alloy, if a ferrous alloy is used then there will be deviation from the results.

Table III Simulation result for different MRP Fluid

S.No	MRP Fluid	Maximum Flux Density(T)	Minimum Flux Density(T)
1	MRF-122EG	0.98099	0
2	MRF-132DG	0.7518	0
3	MRF-126LF	0.57392	0
4	MRF-140CG	0.73879	0

The Table IV is showing the results obtained by both experiments and simulations for different MRP fluids used and it also shows a close agreement between the values obtained from both experiment and simulations. The error observed between the experimental and simulated values might be due to the different environment conditions (surrounding). During experimentation, the surrounding air may have different properties and in experimental results there are various other sources of disturbances which are not accounted for in the simulations. Above all there are magnetic materials in the milling machine

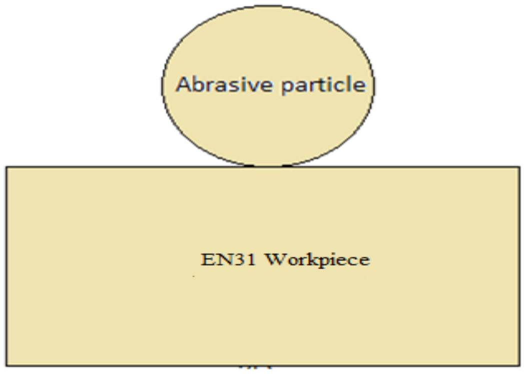


Fig 10 Interaction between abrasive particle and workpiece

whose effect cannot be ignored, but at the same time cannot be fabricated in a simulation environment.

Table IV The comparison of simulation and experimental results.

MRP Fluid	Simulation	Experimental
MRF-122EG	0.98099	0.857
MRF-132DG	0.7518	0.624
MRF-126LF	0.57392	0.462
MRF-140CG	0.73879	0.615

VII. CONCLUSIONS

In this current study, a novel polishing tool designed by [11] is studied and used to study the variation of magnetic flux density for various MR polishing fluids so as to find the best MR polishing fluid for the tool designed to finish the freeform surfaces. The various parts of the tool are magnet, magnetic holder. Initially working dimensions for the magnet are defined, after that an in depth analysis on the design of magnet holder is performed and then the optimized tool is used to study the variation of magnetic flux for different MR polishing fluid used. The properties of various MR polishing fluid used are listed in Table II. For Finite element analysis, Ansys software package was used, using which simulations of different designing shapes and dimensions of the polishing tool were obtained and could also design the appropriate environment for compassion of a different MR polishing fluid. The magnetic holder was made of mu-metal because of its excellent magnetic field shielding. From this study, it is concluded that MRF-122EG shows the maximum flux density magnitude at the tip of the tool, thus it also tells about the MR fluid, which is best suited for finishing of free form surfaces using the polishing tool.

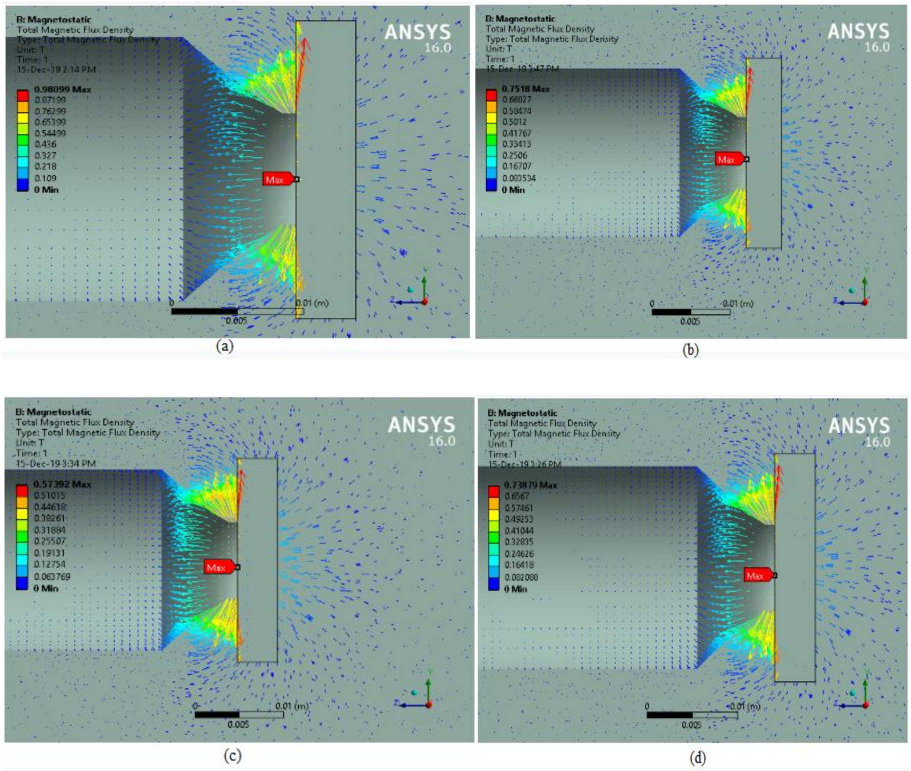


Fig 11 The Magnetic flux density Simulation result for (a) MRF-122EG, (b) MRF-132DG, (c) MRF-126LF, (d) MRF-140CG

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