

A review on magnetically assisted abrasive finishing and their critical process parameters

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Received: 26 May 2018 / Accepted: 28 July 2018

Abstract. Magnetically assisted abrasive finishing (MAAF) processes are the precision material removal processes that have been applied to a large variety of materials from brittle to ductile and from magnetic to non magnetic. The MAAF process relies on a unique “smart fluid”, known as Magnetorheological (MR) fluid. MR fluids are suspensions of micron sized magnetizable particles such as carbonyl iron, dispersed in a non-magnetic carrier medium like silicone oil, mineral oil or water. The MAAF processes overcome the limitation of abrasive flow machining by deterministically control the abrading forces by applying magnetic field around the workpiece. MAAF process is divided into two parts; one is magnetorheological finishing (MRF) and another is magnetorheological abrasive flow finishing (MRAFF). The MRAFF process gives better results as compared to results of MRF because it has additional reciprocating motion of MR fluid. In this article the attempt has been made to review various technical papers related to MRF and MRAFF. The experimental setups, process parameters, MR fluid, modeling & optimization and applications are discussed in this paper. This review article will be useful to academicians, researchers and practitioners as it comprises significant knowledge pertaining to MAAF.

Keywords: magnetically assisted abrasive finishing (MAAF) / magnetorheological finishing / magnetorheological abrasive flow finishing / magnetorheological fluid / flexible brush

1 Introduction

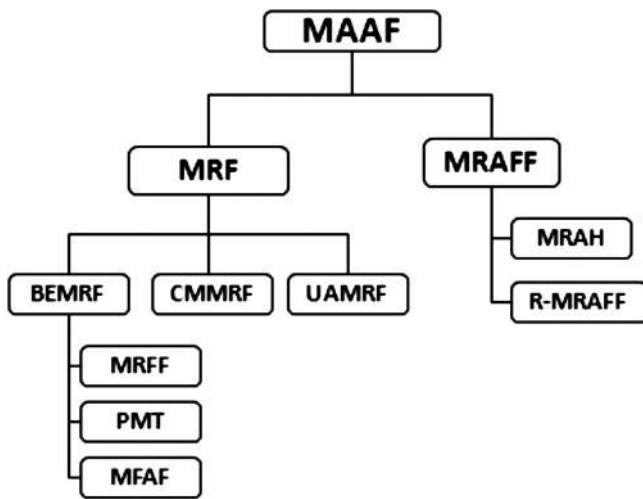
Material removal is the principal operation carried out by a majority of manufacturing industries. Every product we use in day to day life has used machining process either directly or indirectly. In the past three decade, researchers were always striving to enhance the surface roughness up to nanometric level [1,2]. Surface finish is achieved traditionally by Grinding [3], Lapping [4] and Honing [5] by the use of abrasives. The main limitation of traditional processes: (i) shape and size of workpiece is fixed in grinding. There is no flexibility of choosing the workpieces other than cylindrical and plane. (ii) Honing is only for internal finishing [6]. (iii) Lapping is very slow process [7]. Low machinability with a new material is the main problem associated with these traditional machining processes. Moreover, the above processes have no control on finishing process. The problems associated with above mentioned methods for surface finishing has been successfully overcome by advanced nanofinishing techniques during the last decade. Comparison of surface finish obtainable by different finishing processes is given in Table 1 [7].

Nano-finishing is the most important area of micro manufacturing and it is widely used for fabrication of highly precise and accurate components. Surface roughness of the finished surface is important because it carries the functional properties such as wear resistance and power loss due to friction [8]. The ultimate precision is achieved when the chip size approaches sub-nanometer size ~ 0.3 nm [9]. In the nanometer range material is removed in the form of atoms or molecules individually or in groups. Advanced processes are classified according to removal of atoms and molecules from there surface. Some processes such as elastic emission machining [10] and ion beam machining [11] work on the principal of removing atoms and molecules directly from the surface. Other processes based on abrasive wear remove them in cluster. Abrasive flow machining (AFM) is also one of the advanced abrasive based finishing. But the main limitation of AFM process is incapability to control the finish surface value. Deterministic control over in-process finishing forces is an important consideration for Nano-finishing with close tolerances and without damaging surface topography. The major bottleneck in existing finishing technologies lies in the incapability controlling the final surface finish by deterministically controlling abrading forces. The nature and strength of bonding material used to hold the abrasive

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Table 1. Surface finish achievable by different finishing processes [7].

Sr. No.	Finishing process	Workpiece	Ra value (nm)
1	Grinding	–	25–6250
2	Honing	–	25–1500
3	Lapping	–	13–750
4	Abrasive flow machining (AFM) WITH SiC abrasives	Hardened steel	50
5	Magnetic abrasive finishing (MAF)	Stainless steel	7.6
6	Magnetic Float Polishing (MFP) with CeO ₂	Si ₃ N ₄	4.0
7	Magnetorheological Finishing (MRF) with CeO ₂	Flat BK7 Glass	0.8
8	Elastic Emission Machining (EEM) with ZrO ₂ abrasives	Silicon	<0.5
9	Ion Beam Machining (IBM)	Cemented carbide	0.1

**Fig. 1.** MAAF, its types and their variants.

particles together determine the extent of abrasion and quality of the finished surface. Advanced fine finishing processes in which efforts were made to precisely control the abrading forces are magnetic abrasive finishing (MAF) [12], magnetorheological abrasive honing (MRAH) [13], magnetorheological finishing (MRF), magnetorheological jet finishing (MRJF) [14], magnetorheological abrasive flow finishing (MRAFF) [15]. In MAF, MFP, MRAFF and MRJF, the magnetic field is used to control the abrading forces.

Surface roughness and material removal rate are the responses mainly measured in these magnetically assisted abrasive finishing (MAAF) processes [16–18]. These responses depend on the operating conditions, Magnetorheological (MR) fluid, workpiece geometry and type of electromagnet used. These MAAF processes are the new advanced techniques. In the present article, MAAF is classified into two types of finishing processes; MRF and MRAFF as shown in Figure 1. These processes are explained below with their variants.

Due to paucity of literature available regarding MAAF process, continuously work has been progressed regarding this process. Researchers have developed a variety of experimental setup for MRAFF process according to the complexity of the job. Today the demand of society is

nanofinishing of the freeform surfaces owing their use in the aerospace sector, moulds and dies, medical implants, automotive components, etc.

The present article attempts to report various experimental setup of MRF and MRAFF. Process parameters of MAAF processes have been studied and their comparison among them was also done. This review is based on the reported experimental works and future research issues.

2 MRF process

Magnetorheological finishing (MRF) is the nano surface finishing technology. Mostly the optical surfaces are polished in a MR finishing slurry [19–23]. Researchers developed several MR fluids, each consisting of micron size magnetic carbonyl iron particles (CIP) and nonmagnetic polishing abrasives suspended in a carrier liquid [24–28]. Solid's concentration in excess of 42 vol% makes these MR fluids highly viscous. Carbonyl iron (CI) is important for the stiffness it brings to the MR fluid in the magnetic field, the polishing abrasive is necessary for high removal rates and smoothing of the part surface, and the carrier liquid is critical for establishing the correct polishing chemistry and the rheology necessary for fluid stability. Optical surfaces are usually made of brittle materials such as glass which tends to crack while it is machined with conventional process like grinding, honing and lapping [29–36]. The main advantages of the MRF process is that it carries away the heat and debris away from the polishing zone, does not load up as in grinding wheel and it is flexible and adapts the shape of the part of the workpiece which is in its contact [37]. In MRF process, the MR fluid shape and stiffness can be magnetically manipulated and can be controlled by magnetic flux density [38]. The mechanism involved in MRF of material removal and surface finish is basically comprises three different modes as shown in Figure 2.

- The abrasive particle held by chains of iron particles;
- the bunch of iron and abrasive particles move in the forward direction and shears/removes a very small amount of material in the form of micro-chip;
- when this bunch of iron and abrasive particles moves further, it separates the micro-/nano-chip from the work piece.

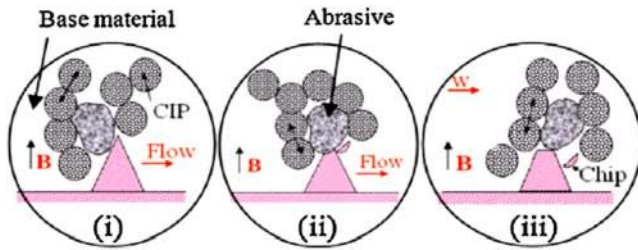


Fig. 2. Mechanism of material removal in MRF [38].

For the optical surfaces like lens center for optics manufacturing, in Rochester, N.Y. has developed a technology to automate the lens finishing process known as MRF [39]. Figure 3 shows that a convex, flat or concave workpiece can be positioned above a reference surface in the MRF process.

A MR fluid ribbon is deposited on the rotating wheel rim. Transient work zone or finishing spot is created by stiffened region by applying magnetic field [40]. When the lens rotates on a spindle at a constant speed about its radius of curvature through the stiffened finishing zone there is surface smoothing, removal of subsurface damage and figure correction are accomplished [41,42]. Converging gap between the part and carrier surface created a shear stress which is mainly responsible for material removal. The zone of contact is restricted to a spot, which conform perfectly to the local topography of the part [43].

2.1 Variants in MRF

The MRF is a MR fluid based finishing process so that most of their parameters are fluid based. The variants of MRF have been developed for betterment in the process to get improved results [44–52]. The researchers have done various experiments in terms of types of magnet used, shape of flexible ball created at the tip and combination of MRF with other conventional machining processes like chemical and ultrasonic machining. There are two ways to classify the variants of MRF machining process:

- processes in which all constituent processes are directly involved in the material removal and surface finish.
- the processes which only assist in removal/finishing by changing the condition of machining in a positive direction.

The MAAF processes can be classified into two parts; one is MRF process and another one is MRAFF process. In MRF, earlier magnetorheological slurry is used to finish the surface topography. But this process can finish only the concave, convex and flat surfaces due to restriction on relative movement of finishing medium and workpiece. The MRF is incapable to finish 3D intricate shaped surfaces. To overcome the above mentioned limitation a new precision nanofinishing process of 3D surfaces using ball end MR finishing (BEMRF) tool was developed. Thus, BEMRF process is the one of the variants of MRF process. The other process called MRFF was also developed with use of different type of MR fluid. However, the process mechanism remained almost the same as BEMRF process. In other variant of MRF named MFAF process for concen-

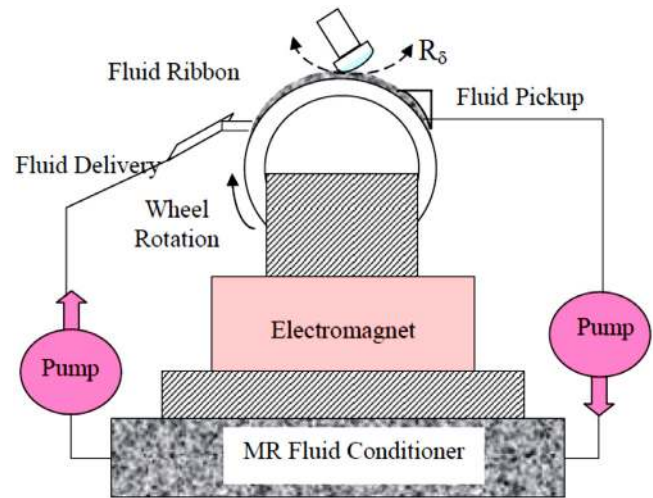


Fig. 3. Vertical MRF machine set-up [39].

trating the magnetic lines at the center of workpiece magnetic fixture is developed. Two types of magnets: permanent and electromagnet were used by the researchers [53–57]. Heating of electromagnet coil reduces the viscosity of MR fluid which can be avoided by using permanent magnet in place of electromagnet. The MRF process was hybridized by using chemical machining and ultrasonic machining to improve the finishing [58–61]. Variety of materials can be finished by MRF from hardness varies from 140–160 VHM. Both magnetic and non magnetic material can be finished upto roughness value 8 nm.

Table 2 shows the developments occurred with time in MRF process. To describe the process technology four elements are considered; machine, MR fluid, type of magnet used and type of workpiece used. In the ‘Machine’ element; parameters like total time taken by the process, working gap and feed rate is explained. The total time taken by the process depends on hardness of the process and type of process used during machining [62]. When the working gap is increased the magnetic flux density at the workpiece surface is decreased. Types of CIP used, their concentration and size, types of abrasive used and their concentration & size are explained in the element called ‘Medium’. The machine decides the extent of abrasion, the media decides the kind of abrasion and the magnet determines the magnetic flux used during the MRF processes. Type of workpiece also affects the response in MRF process. Material removal rate (MRR) and surface finish are the main response measured during the MRF process.

2.2 Ball end magnetorheological finishing

BEMRF is one of the variant of MRF in which ball end is created at the end of polishing tool. It overcomes the limitation of the earliest developed MRF process by finishing the intricate 3D surfaces with more finishing rate and surface accuracy. In BEMRF process the ball end shape of MR polishing fluid is generated at the tip of rotating tool which is used as a finishing spot. To stiffen this MR fluid and to create the flexible ball at the tip of the tool,

Table 2. Recent MRF processes with process parameters.

Process	Machine	Medium	Magnet	Workpiece	Response	Reference
BEMRF	t_{EN31} -100 min & t_{copper} - 60 min, z-2 mm	20 vol% CIP, 20 vol% SiC abrasive (#EN31-600 and #copper-800), 60 vol% base medium	Electromagnet coil V_{DC} - 30 V, I - 2.6A and B - 0.2 T, N_{EN31} -100 rpm and N_{copper} -300 rpm	EN31, Copper (50 × 30 × 5 mm)	R_a decrease from 414.1 nm to 70 nm in 100 min for EN31 and from 336.8 to 102 nm in 60 min for copper	[63]
MRFF	t - 64.7 hr, z-1 mm, F-4 mm/min	40 vol% CIPs, (6 μ m), 3.5 vol% diamond abrasive (6 μ m), 56.5 vol% Paraffin oil (oil based), 48.5 vol% water, 8 vol% glycerol	Sintered Nd-Fe-B permanent magnet, BH_{max} - 48-51 MGOe, N-1000 rpm, F-4 mm/min, B-0.3 to 0.5T	Knee joint implant (titanium)	Total Average % ΔR_a 39.76, R_a decreased from 268 nm to 28 nm	[64]
CMMRF	t- 5 to 100 min, z-1 mm, F- 10 mm/min	60 vol% Water, 30 vol % CIP (HQ grade), 5 vol% Alumina (#2500), 2 vol% Glycerine, 3 vol% Glycine	Sintered Nd-Fe-B permanent Magnet, B_{max} - 0.6T	Al6061-T6 (20 × 20 × 10 mm)	Final R_a is 8.4 nm	[65]
UAMAF	z-0.8 mm	75 wt% Fe (49 μ m) and 25 wt% SiC (22 μ m)	ν - 20000 Hz, λ - 20 μ m of ultrasonic horn	SS304 (100 × 100 × 2 mm)	R_a decreased from 240.8 to 44.9	[66]
MFAF	t - 6.30 h, z-0. 18 mm	40 vol% CIP, 3.5 vol% diamond abrasive (6 μ m), 56.5 vol% base medium	Magnet fixture: mu metal, Cylindrical magnet (Φ - 5-20 mm, H- 50-100 mm), B- 0.4T, N: 1200 rpm	Titanium	(1) Surface roughness change from 180 nm to 10 nm (2) % ΔR_a -94.44%	[67]
PMT	t-7.5 min, z-1.5 mm	23 vol% SiC (21-19 μ m), 17 vol% CIP (19 μ m), 60 vol% base medium	Permanent magnet attached with rotating shaft	Diamagnetic copper alloy	R_a , R_{q1} , R_z from 273.6 nm, 347.2 nm and 1769 nm to 28.8 nm, 38.1 nm and 269 nm resp.	[68]

T - Time, z - working gap, WM - workpiece material, Φ - diameter, H - height, N - rotational speed, B - Magnetic flux density, R_a - surface roughness, V - volt, I - current, F - feed, ν - frequency, λ - amplitude, μ m - micrometer, mm - millimeter, # - mesh size, BH_{max} - maximum magnetization energy.

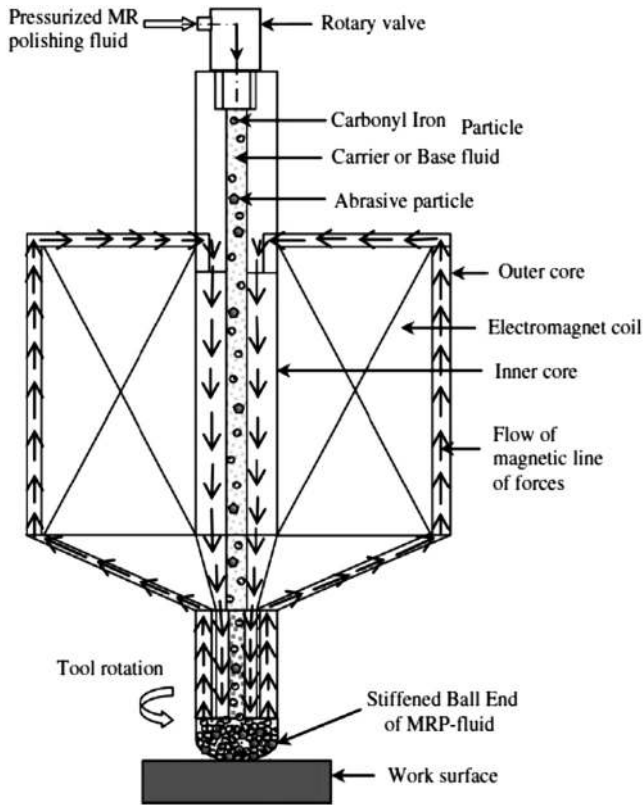


Fig. 4. Mechanism of formation of the stiffen ball end of MR polishing fluid at the tip of the tool [63].

the electromagnet coil was designed for this setup to obtain varying magnetic flux at the tip of tool. MR fluid was supplied through the core material of the electromagnet coil. The pressurized MR fluid enters axially from the upper end of the MR finishing tool. Once the magneto-rheological polishing (MRP) fluid reaches the tip of the tool, the magnetic CI particles of MRP fluid are aligned in the line and formed a chain like structure along with magnetic field direction available at the tip of the MR finishing tool as shown in Figure 4. The experiment was performed on two types of material, one is magnetic and another one is nonmagnetic. This method is superior for finishing the magnetic material as compared to nonmagnetic material because the magnetic lines of force are attracted towards the workpiece, form a very good shape of ball end of MR polishing fluid. But in case of nonmagnetic material these magnetic lines of force are diverted from inner core to outer core at the tip of the tool. More no. of cycles is required for finishing the nonmagnetic material. With this set-up, the roughness value decreased from 141.1 nm to 70 nm in finishing time of 100 min for ferromagnetic material. Results are shown in Figure 5.

The finishing of freeform surfaces is mostly done by CNC milling process and manually. Manual finishing processes are costly, tedious, inaccurate, labor intensive, and time consuming, and it relies mainly on the worker's skill. There is need to automate the finishing for freeform surfaces has become the most important issue to increase productivity and quality.

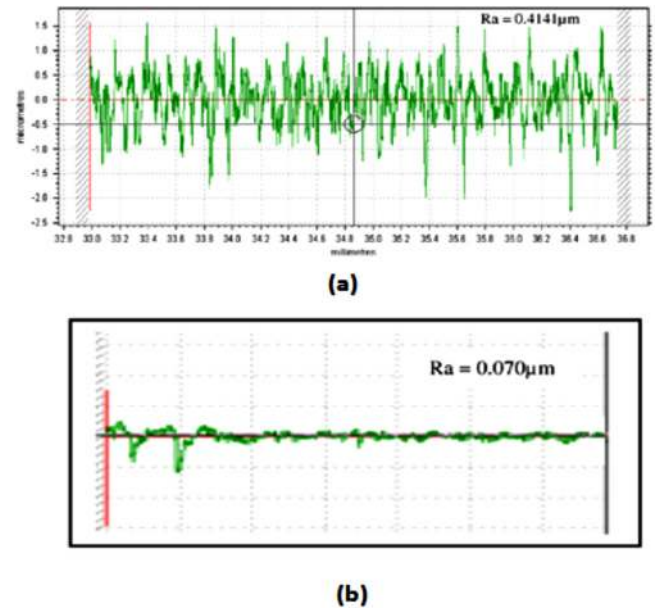


Fig. 5. SEM experimental images for EN8 workpiece before and after experiment [63].

Sidpara et al. [64], developed a magnetorheological fluid-based finishing tool for finishing the knee joint implant which has complex shape.

Different types of magnetorheological fluids are used to reduce finishing time. Three different kinds of MR fluids (oil based, water based and chemical) have been used to finish the knee joint implant. Firstly, the finishing of knee joint with oil based MR fluid was done. With this oil based MR fluid, the initial surface roughness value decreases faster owing to high initial sharp peaks that are comparatively easily removed with oil based MR fluid. After oil-based MR fluid, water-based MR fluid was used to further reduce the surface roughness. There is a little improvement in roughness value that is already finished with oil based MR fluid. There was a need to soften the surface by adding the chemical (HF and nitric acid) with water based MR fluid. It is observed that the surface roughness value decreases but the surface becomes dull owing to the chemical reaction between the MR fluid and workpiece. Hence, again water based MR fluid was used to improve surface reflection. Sidpara et al. [64] reported the best surface finish achieved through this process is of the order of 28 nm. Most of MR processes make use of electromagnet for generating magnetic field. The coil of electromagnet at high current causes heating problem. Due to heating of coil, viscosity of MR fluid decreases. There is no provision for continuous use of electromagnet without chilling effect. This problem can be eliminated by use of permanent magnet [68]. It reduces the cost of apparatus and simplifies the setup. Two cylindrical magnets were selected for making the flexible brush at the tool end as shown in Figure 6. Those have been used to finish the diamagnetic copper alloy workpiece. Copper is diamagnetic in nature and difficult to finish at nano-level in shorter time. Here surface roughness from 273.6 nm to 28.8 nm in 7.5 min was achieved. To avail sufficient magnetic field in the finishing zone, Barman et al. [67], designed a magnet fixture to concentrate

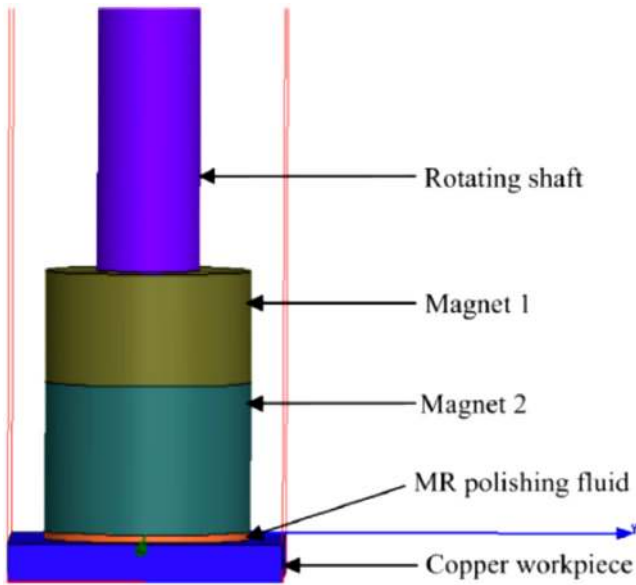


Fig. 6. Magnetic model of permanent magnets finishing tool along with MR polishing fluid and copper workpiece [68].

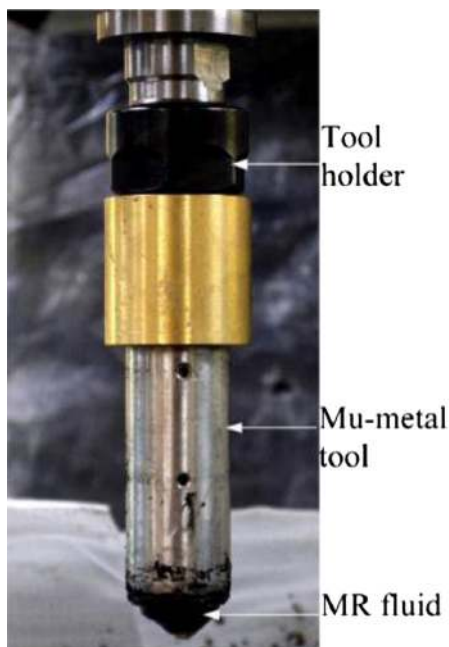


Fig. 7. Experimental set-up of MAFF process with Mu metal fixture [67].

all magnetic lines on the workpiece as shown in Figure 7. Mu metal is selected for magnet fixture due to its magnetic-field shielding property. The experimental results of MAFF process show that the optimum dimensions of permanent magnet are 15 mm diameter and 70 mm length.

2.3 Chemical based MRF process

To make the MRF process fast and to overcome the limitations of chemo-mechanical polishing (CMP) to finish the flat and cylindrical surface, the chemo-mechanical magneto-rheological finishing (CMMRF) [65] process was

developed. It has combined essential aspect of both CMP [69] process and MRF process for surface finishing of silicon and copper. Chemical reactions are performed on the surface for making the soft layer on brittle materials e.g. Si, SiO₂, Al₂O₃, etc. and formation of brittle layer on ductile materials [70] e.g. copper, aluminum etc. These chemical reactions protect the parent metal by making passive layer on the surface and alter the surface properties of the workpiece. Figure 8 shows the initial and final plot achieved during CMMRF process. Roughness value was reduced from 54 nm to 8 nm.

2.4 Ultrasonic based MRF process

Various researchers performed experiments and found that the rate of material removal can be increased by giving vibration to the workpiece. The UAMRF is one of the hybridized process of MRF. It has advantages of both ultrasonic vibration and MRF. In ultrasonic assisted magnetic abrasive finishing (UAMAF) [66] process surface finish is achieved by a flexible magnetic abrasive brush [71] developed by ferromagnetic iron and non ferromagnetic abrasive particles (called magnetic abrasive powder or MAP) in presence of magnetic field and ultrasonic vibrations. Ultrasonic vibration increases the relative velocity of MR fluid, hitting the workpiece surface asperities. This results in improvement in the surface finish and material removal as compared to MRF process. The schematic diagram of UAMAF as shown in Figure 9 which comprises power source, piezoelectric transducer with a horn constituted a complete unit of an ultrasonic vibration generator setup which produce electrical signals. The transducer converts the electric signal upto 20 kHz into mechanical vibration of work-piece. Researchers also developed a theoretical model of UAMAF process for normal force and horizontal force [72–75]. Normal force on the particles helps in indenting the particle on the work surface whereas horizontal force provides finishing torque that in-turn helps the particle to perform micro-machining.

3 MR fluid

MR fluids are the magnetic field-controllable fluids, their rheological behavior depends on the strength of the magnetic field. Normally, the rheological properties like viscosity and shear stress change with the physical properties of MR fluid such as chemical composition and temperature. In the “off” state of magnetic field, MR fluids appear similar to liquid paints and exhibit comparable levels of apparent viscosity (0.1 to 1 Pa s at low shear rates) [76]. Their apparent viscosity changes significantly (10^5 – 10^6 times) within a few milliseconds when the magnetic field is applied. Condition of MR fluid is shown in Figure 10 below with and without magnetic field.

The change in the viscosity is completely reversible when the magnetic field is removed. Once the magnetic field is applied, it induces a dipole in each of the magnetic particles. This dipolar interaction is responsible for the chain like formation of the particles in the direction of the

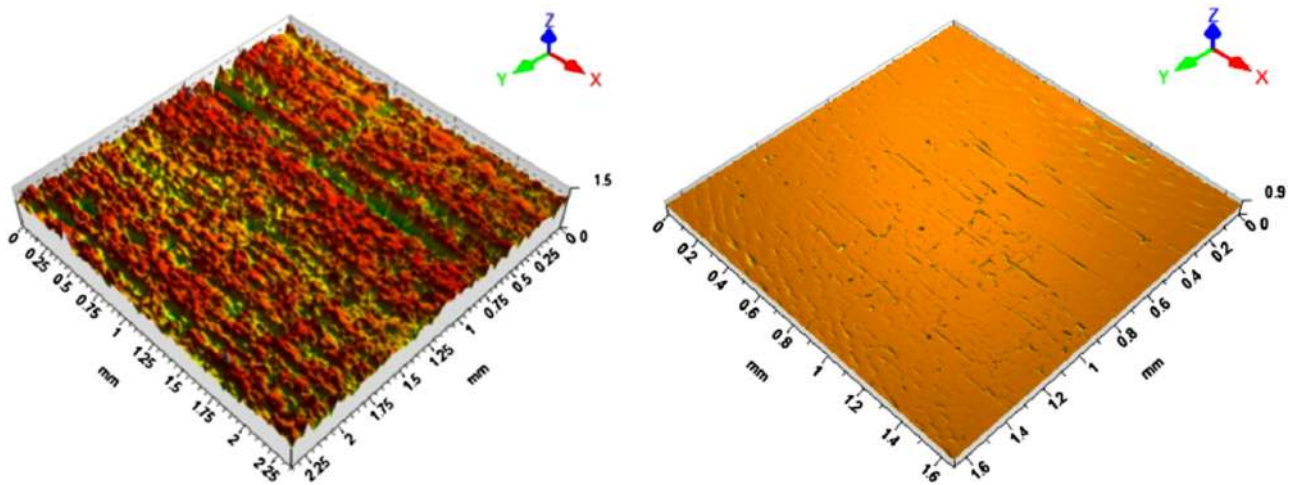


Fig. 8. Surface roughness value (a) before and (b) after CMMRF process [65].

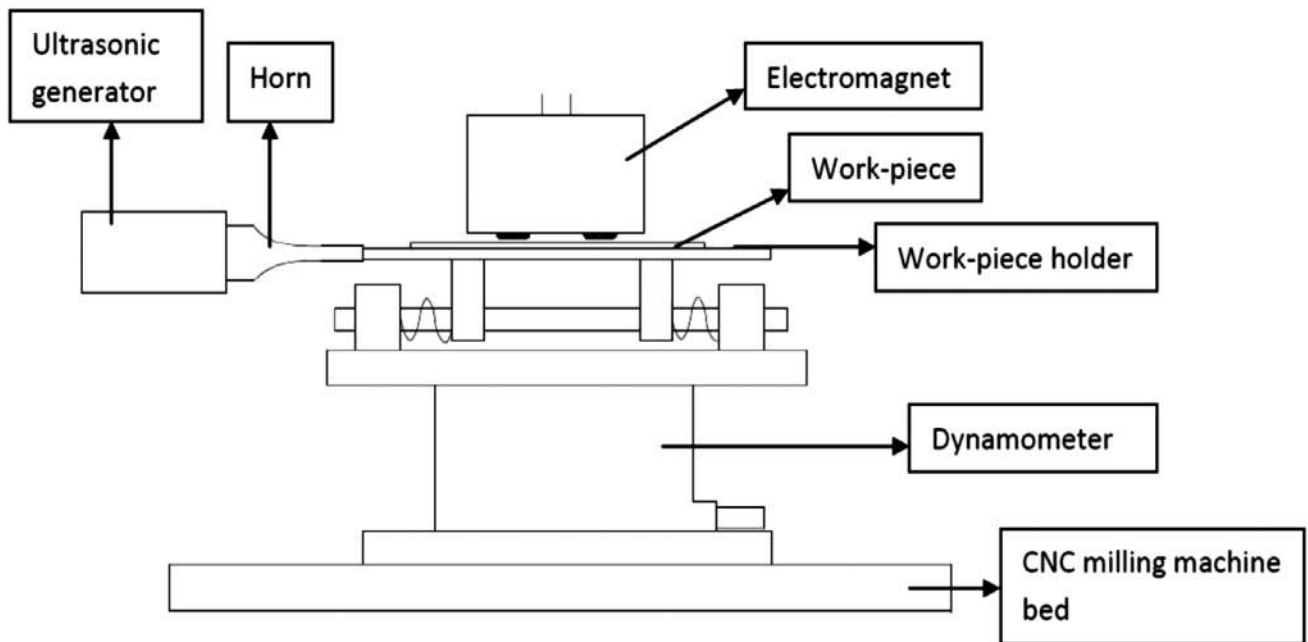


Fig. 9. Schematic of ultrasonic machining set-up [66].

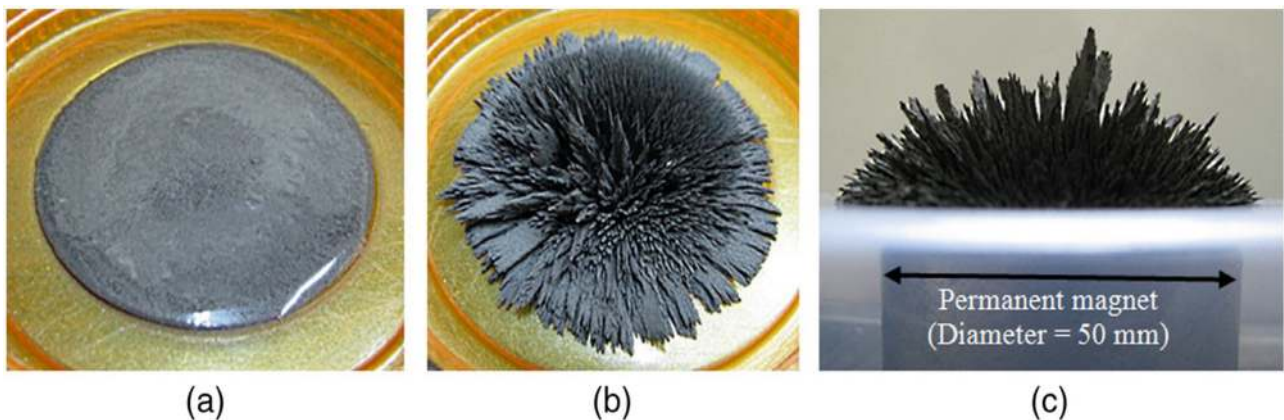


Fig. 10. Condition of MR fluid (a) without magnetic field (b) with magnetic field (c) side view [76].

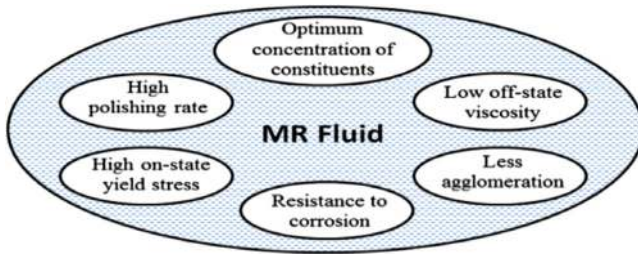


Fig. 11. Essential requirements of MR fluid [77].

magnetic field [77,78]. MR fluid is the prime concern for achieving desired output. Figure 11 shows the extensive requirements of MR fluid.

3.1 Composition of MR fluid

MR fluid consists of CIP, nonmagnetic abrasives and carrier fluids. These CIPs and abrasives are randomly oriented without the magnetic field as shown in Figure 12a. Under the effect of magnetic field, these particles align themselves along the lines of magnetic flux. These CIPs acquire dipole proportional to field strength and when dipole interaction exceeds their thermal energy these particles are aligned in the form of a chain as shown in Figure 12b. Energy is required to deform and rupture these chains. This microstructural transition is responsible for the onset of a large controllable yield stress as shown in Figure 12c. Their concentration should be kept optimum for getting best results. From the available literature, there are some examples of different concentration used by the researchers for experiments. For MRAFF process, used concentration was 20% CI powder (Grade CS from BASF, avg. particle size 18 μm), 20 vol% silicon carbide abrasive powder of 400 mesh size and 60 vol% of viscoplastic base medium (20 wt.% AP3 grease and 80 wt.% paraffin liquid heavy) was prepared [15]. The yield shear stress and viscosity of bi-disperse MRP fluid for all experiments were found maximum at 16 vol% CIPs of CS grade, 4 vol% CIPs of HS grade, 25 vol% abrasives and 55 vol% base fluid [33]. The yield shear stress and viscosity of bi-disperse MRP fluid were maximum as compare to monodisperse MRP fluid.

3.2 Stability against sedimentation

Researchers [25,27] have added submicron-sized particles (fumed silica FS) into CI based MR fluid. These spherical particles not only reduced sedimentation but also improved flocculation stability of the CI-based MR fluid without any noticeable change in the MR behavior.

3.3 Additives

Additives are suspending agents and anti-corrosion/anti-wear components. Grease or other thixotropic additives are highly viscous fluid used to improve settling stability [26]. MR fluid contains a stabilizer such as glycerol to add viscosity to the MR fluid and to create conditions that help to keep the magnetic particles and abrasive particles in suspension.

4 Magnetorheological abrasive flow finishing (MRAFF)

In this chapter finishing methods like AFM and honing combined with MRF technology are explained and this newly developed hybrid process is termed as MRAFF [15] as shown in Figure 13. It takes advantages of both AFM and MRF.

This process has the capability of finishing complex internal and external geometries up to nano-level surface roughness value. It imparts better control on the process performance as compared to AFM process due to in-process control over abrading medium's rheological behavior through magnetic field. In MRAFF process, back and forth motion of magnetically stiffed MR fluid across the passage formed by workpiece and fixture is shown in Figure 14. MRAFF process and its variants with process parameters are explained in Table 3 below. MRAH and rotational-magnetorheological abrasive flow finishing (R-MRAFF) are the two new processes which are discussed. The R-MRAFF is the one of the variant of MRAFF in which rotational motion is given to workpiece for more uniform and fast finishing the freeform surface. In other process named MRAH in which conventional honing is modify by magnetorheological effect of finishing fluid. The parameters come under machine are pressure during machining, time taken by the process, rotational speed of workpiece, reciprocating velocity of the MR fluid, working gap between electromagnet poles etc. The medium used during these processes is MR fluid and its concentration and size of abrasive particles and CIPs are used according to the requirement. The workpiece property either it is magnetic or nonmagnetic influence the response. Two output responses; material removal rate and surface finish are described here.

The knee joint in the past is finished by MAFF process. But this process has limitations in terms of larger finishing time and non-uniformity in the finished surface. To overcome these problems, Satish et al. [80], developed a new process known as R-MRAFF for finishing the complex surface with high finishing rate. With this process smooth mirror like surface finish is achieved by giving combined motion (axial and rotational) to the workpiece. For the complex surface, there are many inclination angles of the abrasives to indent on the workpiece surface. The final roughness value increases and finishing rate decreases with increase in the angle of inclination of surface. Because at higher angle of inclination the magnetic lines of forces are spread over the surface hence, flux density will get reduced. There is face-wise study of knee joint implant by the researchers for complete observation of the surface.

Large variation in the magnetic flux density is observed due to non-uniform gaps at different locations and different curvature on the surfaces. Because of non-uniformity in the freeform surface the surface near the magnet feel more magnetic field as compare to farthest surface. The average finishing rate in case of R-MRAFF is as high as 2 times as compared to the MAFF. The BEMRF process shows good results with magnetic materials hence a new process new process MRAH [79] is developed to finish any complex

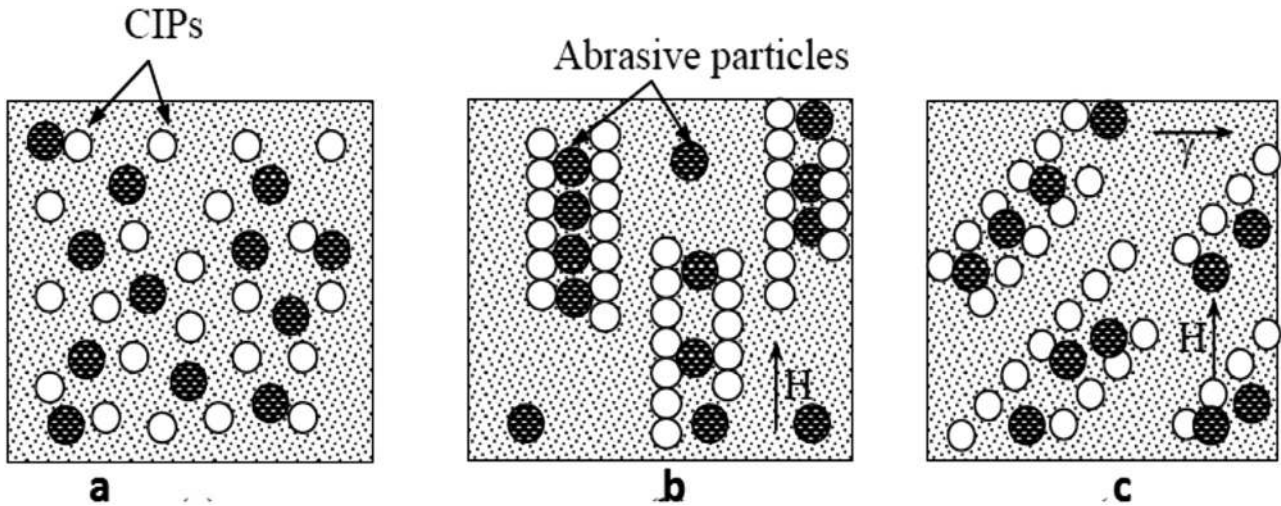


Fig. 12. Magnetorheological effect, (a) MRP-fluid at no magnetic field, (b) at magnetic field strength H and (c) at magnetic field H & applied shear strain γ . [15].

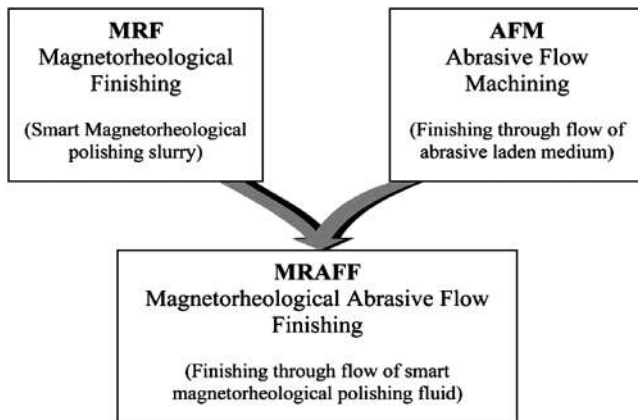


Fig. 13. Relation between the three process MRF, AFM and MRAFF [15].

shape non-magnetic workpiece with improved finishing rate. In MRAH, workpiece rotates and reciprocating motion is provided to the MR fluid. Schematic diagram of MRAH is shown in Figure 15 below. In MRAH [79] the workpiece rotates and reciprocating motion is provided to the MR fluid. Schematic diagram of MRAH is shown in Figure 14 below. When field density is increased the finishing fluid becomes stiff due to the formation of CIP chains. Due to this the roughness is decreased and material removal is increased. After a value of 0.6 T, there is a meager improvement in roughness. There is no sufficient bonding between CIP and abrasive. The CIPs are attracted towards the pole faces of magnet after a threshold value. The experiment is performed on two types of material; one is magnetic and another one is nonmagnetic. There is only 6.7% improvement in roughness value for magnetic material because the CIP trapped all the abrasive near the workpiece. This phenomenon reduced the relative movement of abrasives on the workpiece surface. But for nonmagnetic, it shows better results and the improvement in roughness is 24%.

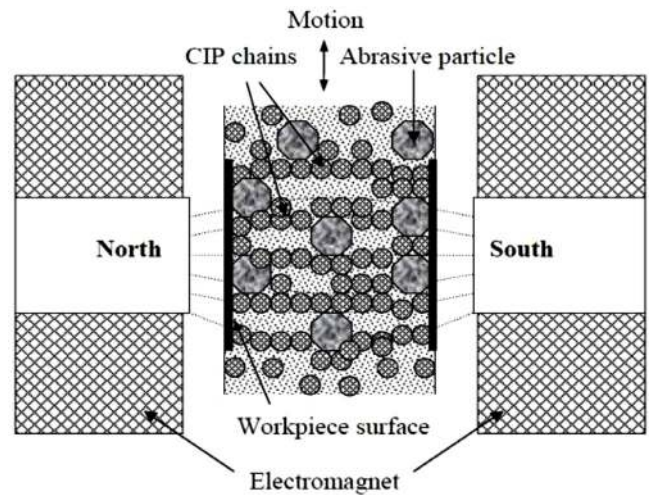


Fig. 14. Mechanism of magnetorheological abrasive flow finishing process [50].

5 Modelling and optimization

To understand the complexity of the process, it is necessary to construct a model either mathematical or theoretically to study the effect of various process parameters on the output responses; surface finish, MRR and finishing force. The model in general provides the information, which gives an insight into the nature of the phenomenon occurring in the real life situation. Through the MR fluid in MRF and MRAFF process, the normal and tangential forces are acting on the work pieces due to MR fluid pass through the magnetic field. Normal force is responsible for indenting the work piece surface and tangential force is responsible for removal of material from the work piece surface.

Ginder et al. [81] calculated the inter-particle forces and resulting shear stresses in magnetorheological fluid. The field due to a linear chain of particles in a fixed average magnetic induction is determined from finite element

Table 3. MRAFF and its variants with process parameters.

Process	Machine	Magnetorheological fluid	Electromagnet	Workpiece	Prominent results	References
MRAFF	No. – 200 cycles, τ -50–90 kPa, P- 3.75 MPa, z- 30 mm, I- 6A	20 vol% CIP (18 μ m), 20 vol% SiC(# 400) and 60 vol% of viscoplastic base medium	B-0.574 T, H-150– 250 kA/m	Stainless steel (35 \times 5 \times 2 mm)	R_a changes from 0.6 μ m to 0.34 μ m	[15]
MRAH	t- 20 min, N_{holder} -310 rpm, V_{Punger} -15 cycles/min	30 vol% CIP (size 8 μ m), 25 vol% SiC (size 15 μ m)	B-0.65 T	Mild steel (AISI 1020), Stainless steel (SS 316L)	$\% \Delta R_a$ for 41.7% (mild steel) and 43.5% (stainless steel)	[79]
R-MRAFF	No.-1600 cycles, N-150 rpm, P- 15- 35 bar, t-24.7 hr, z-1 mm	30 vol% CIP, 15 vol % SiC (#500-2000), 43 vol% of viscoplastic base medium and 12 vol % Surfactant	Permanent magnet (Nd-Fe-B), B- 0.37 T, Hc (836 kA/ m)	Knee joint implant (stainless steel)	(1) At small angle magnetic line concentrated (2) $\% \Delta R_a$ -17.5 (Final)	[90]

τ – shear stress, P_{Punger} – reciprocating velocity, Hc – coercive field force, N – rotational speed, No – no of cycles, P – pressure, z – working gap, I – current, B-magnetic flux density, # – mesh size, MRAH – magnetorheological abrasive honing, R-MRAFF – rotational magnetorheological abrasive flow finishing.

Table 4. Key capabilities of various MAAF process.

Process	Aim	Benefits
BEMRF	To create a flexible bush at the end of magnetorheological polishing tool	Any freeform surface can be finished by maintaining proper gap
MRFF	Use of different types of MR fluid like chemical based, water based and oil based	Very hard material like titanium can be finished upto nanometric level
PMT	Use of permanent magnet instead of electromagnet	Heating effect due to electromagnet coils can be avoided and soft diamagnetic copper alloy can be finished
MFAF	A magnetic fixture for permanent magnet was created for titanium workpiece	It can be made possible to concentrate all the magnetic lines on the workpiece
MRAH	Combination of conventional honing process with MR effect of MRF technology	Finishing time can be reduced by rotating the job with MR effect
R-MRAFF	Rotation of permanent magnet fixture along with reciprocating motion of MR fluid	High finishing rate and uniform finishing of all faces

analysis. They concluded that the maximum shear strength of MR fluids varies as the square of the saturation magnetization M_s of the particle. It means that the larger M_s is possessed by the new particles in MR fluid which have higher yield strength.

Kordonski et al. [82], observed that the concentration of magnetic particles may change due to evaporation or leakage of carrier fluid, as well as particle sedimentation and the magnetic properties may change due to temperature, corrosion of particles or irreversible aggregation. They designed two types of sensors for in line measurements of magnetic particle's concentration in MR fluids; one is flow type sensor & another is flash type sensor. The flow-type sensor is based on the principle of mutual inductance and is intended for measurements in pipes and channels. The flash-type sensor reacts to changes in the reluctance of the MR fluid and can be used for measurements in gaps, tanks, containers layer adjacent to the wall.

Yarmand [83] investigated numerically the thermal characteristics of turbulent Nano fluid flow in a rectangular pipe. CFD software (ANSYS-FLUENT) has been employed to simulate the results. From the variety of Nano fluids used by the author, the SiO_2 generates the highest Nusselt number followed by Al_2O_3 , ZnO , CuO and the pure water. SiO_2 has the least heat transfer coefficient but because of the lowest thermal conductivity it has highest Nusselt no. among the tested Nano fluids.

Sidpara et al. [84], designed a theoretical model of forces (normal and tangential) acting on the work piece to improve the in-depth understanding of the mechanism of material removal during MR fluid based finishing process. The normal forces are experienced by compression due to squeezing of MR fluid between the working gaps and tangential force due to rotation of carrier wheel. The magnets are used around the workpiece in these MAAF process. Due to magnetic field, magnetic levitation force acts on the MR fluid. In it, majority of abrasive particles move away from the magnet or towards the outer periphery of the ribbon and the workpiece surface [36]. Hence, material removal takes place by interaction of abrasive particles, which are gripped by stiffened MR fluid and

workpiece. The levitation force (F_m) is proportional to the gradient in the magnetic field and it is calculated by

$$F_m = -V\mu_0 M \nabla H$$

where V is the volume of the non-magnetic body (abrasive particles), M is the magnetization of the magnetic fluid, μ_0 is the permeability of free space and ∇H is the gradient of a magnetic field. Four parameters were selected for this study; volume concentration of CIPs, volume concentration of abrasive particles, working gap and wheel speed. They concluded that the normal and tangential force decrease with increase in working gap, however it will increase with increase in abrasive particles concentration but after a value of 3.5%, forces starts to decrease because of more abrasives particles decrease the stiffness of MR fluid and break its chains with CIP. Firstly, the normal and tangential forces increase with increase in wheel speed but after the value of 300rpm the tangential force start decreasing due to flattening of the MR fluid ribbon. It is also observed that the theoretical normal force and tangential force model including squeeze force showed better agreement with experimental results as compared to the model without considering of squeeze force. Squeezing force is based on the theory of rolling. The concept is similar to the squeezing the metal in rolling as MR fluid in MRF.

Das et al. [85], designed and fabricated a capillary viscometer to study the effect of magnetic field on the rheological properties of the medium and finite difference method to evaluate the stresses developed during the process. Normal force on the abrasive particles is calculated from the applied magnetic field. it is concluded that the viscosity of the fluid increases in a third-order logarithmic function of magnetic field and also yield stress of the fluid increases with magnetic field as shown in the equation mentioned below

$$\begin{aligned} \mu_p &= 5918.57 + 10191.33\ln(B) + 6110.52(\ln(B))^2 \\ &\quad + 1222.70(\ln(B))^3 \\ \tau_y &= -33.10 + 67.09\ln(B)/B + \frac{51.54}{B^{1.5}} \end{aligned}$$

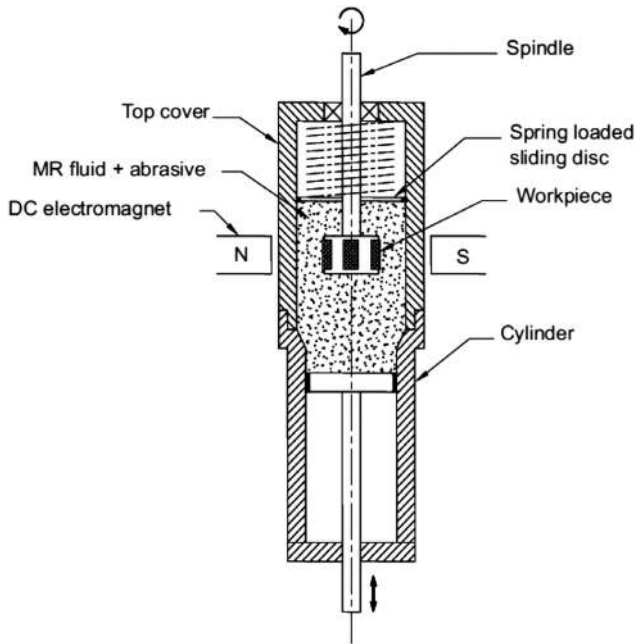


Fig. 15. Schematic diagram of the MRAH [79].

μ_p is the plastic viscosity (Pas), B is the density of magnetic field (T) and τ_y is shear yield stress of the fluid (N/m^2). At higher normal force the larger plug flow region of the flowing fluid is obtained with higher magnetic field due to the formation of strong structure of CIP chains with increased magnetic field. It is also concluded that the shearing takes place only when the shear force is more than the reaction of the workpiece. Singh et al. [86], studied the mechanism of material removal and magnetic field induced normal force during BEMRF process. It was explained that due to the induced normal force material removal and percentage change in roughness was increased. Also this magnetic field induced normal force decreased with increase in working gap. For more improvement in BEMRF process [87], it was required to plan a theoretical model for this process. In this model, theoretical understanding of surface roughness and mechanism of material removal associated with ferromagnetic workpiece is involved. There are two forces acting; one is magnetically induced normal force and another one is shear forces acting on the abrasive. This normal force is mainly responsible for penetration of abrasive into the workpiece surface and shear force model aids in the understanding of three body wear mechanism between the abrasive and the workpiece surface as shown in Figure 16.

6 Applications of magnetic assisted abrasive flow machining

Various researchers have used magnetic assisted abrasive finishing (MAAF) technique for finishing various components used in electronics, optical and biomedical fields to the required level of accuracy as explained in Table 3. The various applications of MAAF process are discussed below.

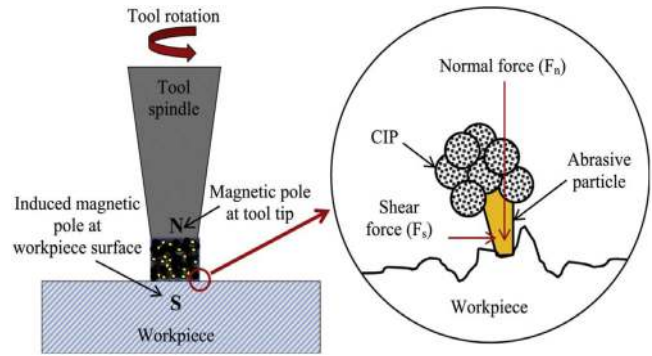


Fig. 16. Forces associated with BEMRF process [87].

6.1 Machining of electronics and industrial components

Silicon crystal with nano-level surface finish has many applications. It is used as IC chip in semiconductor, silicon strip mirror for cryogenic applications and synchrotron beam line and substrate material for X-ray mirrors. Single point diamond turning is commonly used to finish silicon crystal but this process imparts turning marks on the final finished silicon surface. Therefore, MRF is more suitable for silicon finishing as compared to other processes.

Sidpara et al. [35] attained a final roughness value of silicon crystal as low as 8 nm from the initial value of 1300 nm. Yin et al. [36] developed abrasive assisted technology to polish micro bores in metal- 400 and 500 μm bores in steel S45C, 500 μm bores in stainless steel and ceramics – 304 and 260 μm bores in zirconia material. Gears have many diverse applications in the field of automobile, rotorcraft drive system, locomotives, marine applications, railway track etc. The gears are commonly produced by conventional gear cutting methods or casting process. After manufacturing of gears, finishing of gears is a challenging task in many machining shops. It is finished by MAAF process with great accuracy [75]. The convergent and divergent nozzles made up of nitro-alloy and brass is finished by MAAF process used in hydraulic units [33]. The diesel engine fuel injector nozzles can also be finished by MAAF process. Improved quality of the nozzle characteristics is found in MAAF processed injectors resulting in enhancement of engine performance and improved emission.

6.2 Machining of optical components

Lenses are usually made of brittle material such as glass, which tends to fail by cracks when it is machined. Even a single micro-crack can drastically affect a lens' performance, making it completely ineffective for its intended application. Traditional methods like grinding make the process very expensive and labour intensive. To overcome these problems, MRF is developed which makes revolution in the field of optics by automate the lens finishing techniques. Highly precise lenses are used in medical equipment such as endoscopes, collision-avoidance devices for transportation industry, scientific testing devices and military's night vision equipment such as infrared binoculars.



Fig. 17. Knee joint implant before and after finishing [80].

6.3 Machining of biomedical component

Freeform surfaces are widely used in biomedical, aerospace, turbine blades, automobile and optical components. These surfaces are commonly manufactured by rapid prototyping, casting and advanced CNC machines. After machining, finishing of these surfaces to higher level is a difficult task and many researchers have developed different types of finishing process. Sidpara et al. [66] finished knee joint implant by using magnetorheological fluid-based finishing tool and the best possible surface finish obtained through this process is 28 nm.

Kumar et al. [80] developed R-MRAFF for finishing of freeform component similar to knee joint implant to nanometer level with uniform finishing of all faces. Figure 17 shows the knee joint implant before and after finishing through flexible brush created at the tip of polishing tool process.

7 Research challenges of MAAF

The MAAF is an advanced nanofinishing process but there are still some unsettled challenges exist which are explained below:

- BEMRF process is very slow process, takes large time during finishing of hard material [55];
- with MAFF [64], uniform finishing of freeform surfaces can't be achieved because of variation in the working gap between the tool and workpiece;
- in each MAAF process, owing to sedimentation problem, it is mandatory to change the MR fluid after some period of time. To avoid this problem some additives are added in MR fluid which makes these processes costly [77]. Hence, search for economical, environmental friendly and efficient process is still on;
- MRAFF process can't finish surfaces which have sharp edges because up and down motion of the MR fluid take away sharp edges first and destroy the shape of workpiece [15]. Finishing of spherical surfaces is also not possible by MAAF process;
- these MAAF processes are good for finishing the ferrous material, their rate of finishing decreases when we finish the non-ferrous materials [12]. Owing to low relative

permeability of non ferrous materials as compared to ferrous materials, it is still a difficult job. Al alloy and Copper was finished through MAAF but significant finishing could not be performed due to low magnetic permeability.

8 Research potentials

The review presented in this article reveals an insight into a broad area of MRF and MRAFF and its process variants. However, magnificent possibilities still exist for further improvement in process efficiency of MAAF. The significant measures of MAAF process efficiency can be in terms of machining time, surface quality and economics [29]. The set-up time for MAAF depends on the design of fixtures and tooling for guiding the media. A change in workpiece geometry, in general, implies development of a new fixture. This increases the overall cost of the design and manufacture in MAAF [47]. It would be imperative to develop adjustable fixtures for different geometries so as to increase productivity of MAAF. It was revealed from the literature review that major focus was laid on glasses with simple geometry. A possible research avenue is open for finishing the materials other than optics, such as metallic, composites metallic and ceramic components used in aerospace, medical, nuclear reactor automobiles, etc., require stringent control over surface roughness. MRF and allied processes have been efficiently used for finishing of prosthesis implants, such as knee joint [64] and hip joint [49]. MRF is very efficient for finishing of nonmagnetic materials, but it is also necessary to explore the application of MRF for magnetic materials. Only a few reports are available where MRF and allied processes are used for finishing of magnetic materials [37]. Further development in this regard will provide an alternate and efficient way of Nano finishing of the components made of magnetic materials finishing of metals or hard materials by standard MR fluid is not appropriate because of low volumetric MRR, which may result in high processing time. Therefore, it is necessary to increase the aggressiveness of MR fluid by addition of suitable chemicals, which soften the metallic surface and assist the abrasive particles in mechanical abrasion.

It is observed that the working gap does not remain constant when the MRFF tool moves over the freeform surface. As a result, the stiffness (yield stress) of the MR fluid is also different at different working gap so there is large variation in final surface roughness [25]. Thus fixture and special tooling should be designed for getting uniform results. Mostly the results available in the literature are for flat, cylindrical surfaces. Limited research literature is available on finishing of freeform surfaces and for sphere surfaces by MAAF. The use of electromagnet in these MAAF process for generating magnetic field may cause heating problem. Hence the viscosity at the end phase of polishing tool is decreased and the use of electromagnet makes the setup complicated and costly. So there is demand of the process to overcome this heating problem or the use of permanent magnet instead of electromagnet. There is also need to monitor the MAAF process online for optimization of the whole process. The experimental results should be optimized by the theoretical model.

9 Conclusion

This paper presented an overview of recent developments in MAAF process and their critical parameters. The major conclusions of the study are as follows:

- the MAAF is a nano-finishing technique for surface finishing. It can finish both internal and external surface with great control over forces;
- media act as a self-deformable multiple cutting tools. It changes its shape according to the complexity of the workpiece; many attempts have been made to develop efficient, environmental friendly, cost effective media;
- the BEMRF process shows better results for magnetic material as compared to non-magnetic material. This process can finish any shape of workpiece. But time taken by the process is very high;
- the permanent magnet was used in place of electromagnet coil to avoid heating problem and to finish diamagnetic copper material in less time;
- for getting better result with hard stainless steel material the motion is given to MR fluid;
- in R-MRAFF process rotational motion is provided to freeform workpiece for getting uniform roughness value of all faces;
- the MRFF was tried with three different types of MR fluid to decrease the finishing time. Chemical reactions are performed on the workpiece surface to soften it before finishing.

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Cite this article as: Chinu Kumari, Sanjay Kumar Chak, A review on magnetically assisted abrasive finishing and their critical process parameters, *Manufacturing Rev.* **5**, 13 (2018)