Chapter 1

INTRODUCTION

There has been a booming interest recently in this work smart material of their astonishing behavior and their broad application in the area of mechanical engineering. Belonging to this category MR fluid exhibit the peculiar rheological properties that is controlled by magnetic field.MR fluid are highly colloidal suspension of highly polarizable magnetic particle in the non magnetic fluid.

The finishing action in Magnetorheological abrasive flow finishing (MRAFF) process relies mainly on bonding strength around abrasive particles in Magnetorheological polishing (MRP) fluid due to cross-linked columnar structure of carbonyl iron particles. The fluid flow behaviour of MRP fluid exhibits a transition from weak Bingham liquid like structure to a strong gel-like structure on the application of magnetic field. Depending on the size and volume concentration of abrasives and carbonyl iron particles (CIPs) in the base medium. The powders are extracted from the base fluid. Their morphology, size distribution, chemical composition and magnetic characteristics are analysed and compared to that of unused powder. The chemical composition of used base fluids are analysed and compared to that of an unused base fluid. Results indicate that the iron particles tend to fracture and the surface tends to spall. To perform the finishing efficiently, a thorough knowledge of material removal mechanism and behaviour of magnetic fluids in presence of magnetic field is required. In the present study, an attempt has been made to understand the material removal and surface finishing mechanism in BEMRF process by magneto-static simulation of machining process

1.1. MR Fluid

Magnetorheological (MR) fluids comprise of soft ferro-/ferromagnetic particles suspended in nonmagnetic fluids such as hydrocarbon, silicone oil, or aqueous carrier fluid [1-6]. The MR fluids show the characteristic of

Newtonian fluid when no magnetic fields are exerted. However, in the presence of magnetic field, they exhibit a continuous, rapid, and reversible change from a fluid-like state to a solid-like state within milliseconds [7,8]. This is because dispersed magnetic particles can form chains which align in the direction of the magnetic field due to the magnetic–polarization interaction, and then returns to its free flowing liquid state upon removal of the external magnetic field. Magnetorheological (MR) fluids are suspensions of non-colloidal (~0.05-10μm), multi-domain, and magnetically soft particles in organic or aqueous liquids. The characteristics of the mr fluid allow their engineering application in sealing, civil damping, shock absorbers, and polishing.

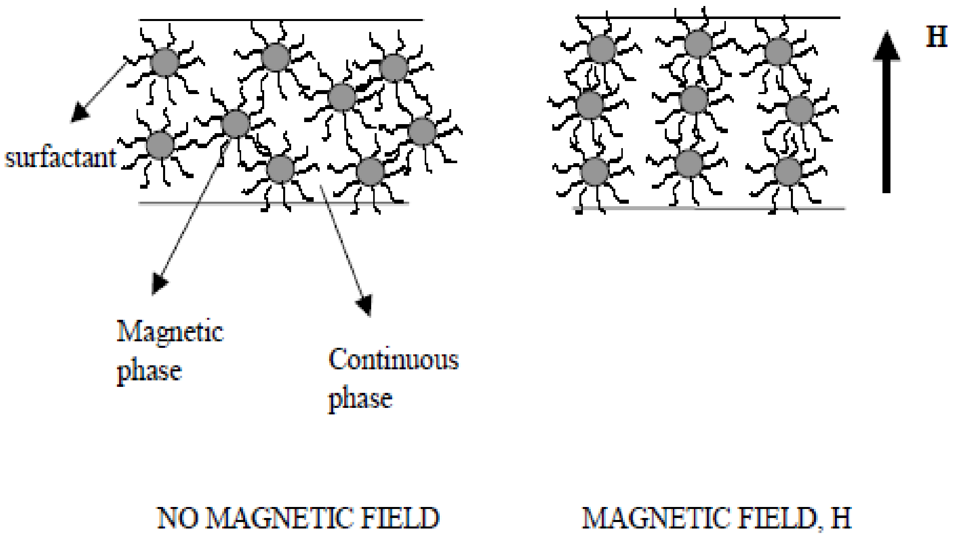


Fig.1.1. Schematic of the formation of chain-like formation of magnetic particles in MR fluids in the direction of an applied magnetic field [8]

Magnetorheological fluid is a fascinating smart fluid with the ability to switch back and forth from a liquid to a near-solid under the influence of a Magnetic field. It is usually used for applications in braking. The term "Magnetorheological fluid" comes from a combination of magneto, meaning magnetic, and rheo, the prefix for the study of deformation of matter under applied stress. Magnetorheological fluids are not currently in wide use but are considered a futuristic type of material. Magnetorheological fluid (MR fluid) is a type of smart fluid in a carrier fluid, usually a type of oil. When subjected to a magnetic field, the fluid greatly increases its apparent viscosity, to the point of becoming a visco-elastic solid. Importantly, the yield stress of the fluid when in its active ("on") state can be controlled very accurately by varying the magnetic field intensity. The upshot of which is that the fluid's ability to transmit force can be controlled with an electromagnet, which gives rise to its many possible control-based applications. The MR fluid is supplied to the gap between a work-piece and a moving wall to polish the work-piece. When a proper magnetic field is applied to the MR fluid, the viscosity and stiffness of the fluid increase by more than several tens of times within milliseconds. Thus, the MR fluid can rotate continuously as long as it adheres to the wheel surface resulting from the applied magnetic field

1.2. Rheology of Magnetorheological (MR) Fluids

It has been previously pointed out that, the magnetic properties such as saturation magnetization, permeability, susceptibility of the dispersed phase, as well as the applied magnetic field are important parameters in obtaining high magnetorheological (MR) effect which is defined as the shear stress increase $\Delta\tau$ due to the magnetic field [9]. Many of the models, developed for ER fluids can be adopted for MR fluids in low magnetic fields. However, at high magnetic fields, due to the non-linearity and magnetic saturation of the particles, the linear used to treat ER fluids are no longer valid for MR fluids. The importance of the “off-state” viscosity of MR fluids comes from the figure of merit for MR fluids which is given by the “turn up” ratio defined as the ratio of “on-state” yield stress to the “off-state” viscosity. “On-state” refers to the state of the MR fluid under an applied magnetic field and the on-state yield stress behavior depends on the magnetic properties and the volume fraction of the magnetic phase [10]. The off-state viscosity, which is a function of carrier liquid, additives, surfactants [11], particle loading and particle size distribution (PSD) [12], is the value when no magnetic field is applied. Due to the addition of additives and surfactants and changes in magnetic particle microstructure during shear, most MR fluids exhibit thixotropic behavior and shear thinning [13]. The break up of weak agglomerates or bonds in the shear field is a major cause of a shear thinning behavior of MR fluids.

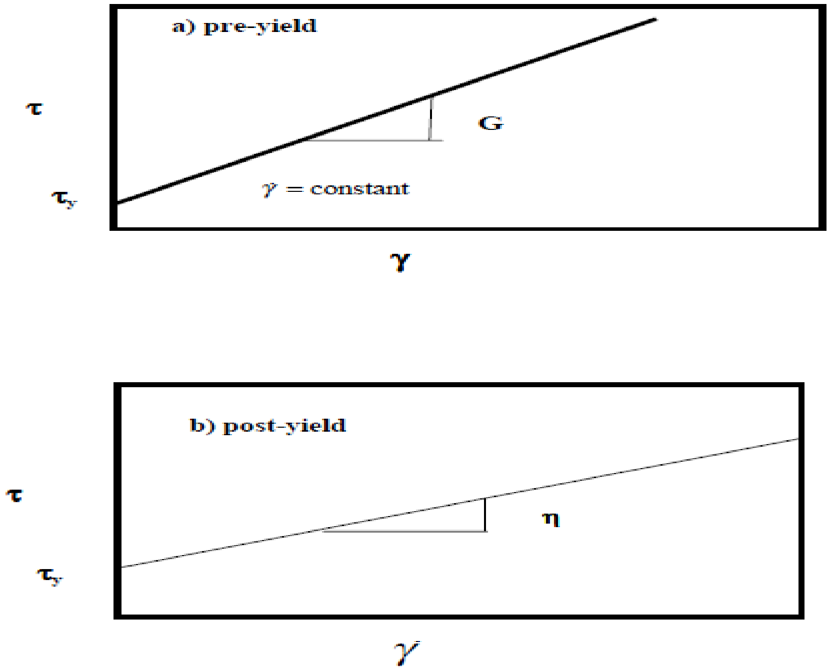
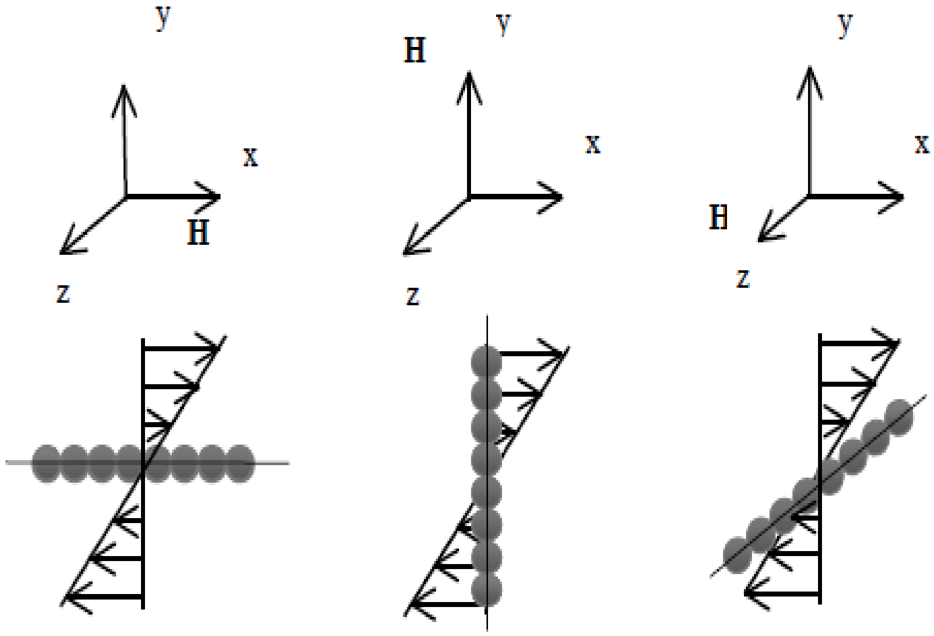


Fig. 1.2. Bingham Plastic Models [13]

The yield stress of the MR fluids mainly depends on the saturation magnetization and volume fraction of the magnetic particles. In the analytical models developed by Ginder and co-workers, the yield stress increases linearly with increasing volume fraction [14,15]. However, at high volume fractions, the exponential increase of yield stress with increasing volume fraction was reported by Volkova and Chin [16,17]. This can be attributed to the higher packing of particles where the affine deformation can be restricted leading to higher stress [17].



(a) (b) (c)

Fig.1.3. Anisotropy of MR fluids:The value of the yield stress depends on the direction of the applied magnetic field and the shear direction[14]

1.3. Magnetorheological Finishing

The MRF 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. In the absence of a magnetic field, an ideal MR-fluid exhibits Newtonian behaviour. On the application of an external magnetic field to a MR-suspension, a phenomenon known as Magnetorheological effect, shown in Fig.1.3.(a), is observed. In Fig.1.3(a), particles magnetize and form columns when external magnetic field is applied. The particles acquire dipole moments proportional to magnetic field strength and when the dipolar interaction between particles exceeds their thermal energy, the particles aggregate into chains of dipoles aligned in the field direction. Because energy is required to deform and rupture the chains, this micro-structural transition is responsible for the onset of a large "controllable" finite yield stress [18]. When the field is removed, the particles return to their random state and the fluid again exhibits its original Newtonian behaviour

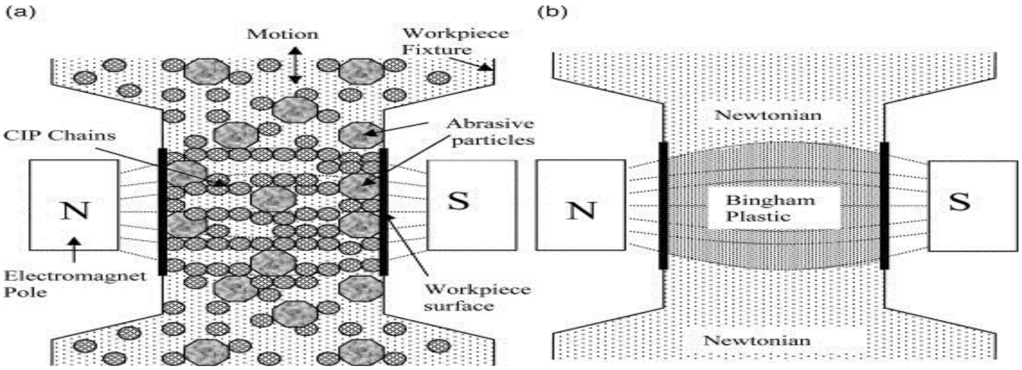


Fig. 1.4: Magnetorheological Effect (a) MRP-fluid under magnetic field (b) State of MRP- fluid [18]

The computer controlled Magnetorheological finishing process has demonstrated the ability to produce the surface accuracy of order 10-100 nm peak to valley by overcoming many fundamental limitations inherent to traditional finishing techniques [19].These unique characteristics made Magnetorheological Finishing as the most efficient and able process for high precision finishing of optics.

1.4. MRP Fluid behaviour

The behaviour of a MR fluid can thus be considered similar to a Bingham plastic, a material model which has been well-investigated. However, a MR fluid does not exactly follow the characteristics of a Bingham plastic. For example, below the yield stress (in the activated or "on" state), the fluid behaves as a visco-elastic material, with a complex modulus.

Thus MR fluid behaviour becomes:

$$\tau = \tau_y(H) + \eta \frac{dv}{dz}, \tau > \tau_y$$

Where,

τ = Shear stress

τ_y = Yield stress

H = Magnetic field intensity

H = Newtonian viscosity

$\frac{dv}{dz}$ is the velocity gradient in the z-direction.

1.5. Common MR fluid Surfactants

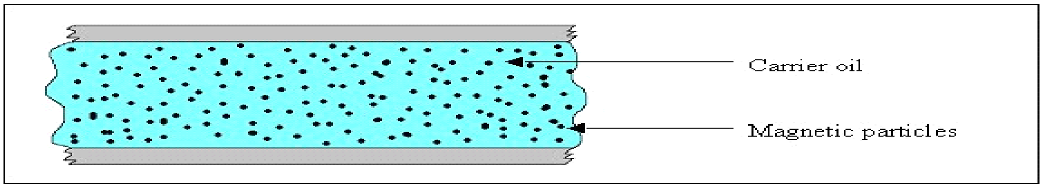
MR fluids often contain surfactants including, but not limited to:

- oleic acid
- tetra methyl ammonium hydroxide
- citric acid
- soy lecithin

These surfactants serve to decrease the rate of ferro particle settling, of which a high rate is an unfavourable characteristic of MR fluids. The ideal MR fluid would never settle, but developing this ideal fluid is as highly improbable as developing a perpetual motion machine according to our current understanding of the laws of physics. Surfactant-aided prolonged settling is typically achieved in one of two ways: by addition of surfactants, and by addition of spherical ferromagnetic nanoparticles. Addition of the nanoparticles results in the larger particles staying suspended longer since to the non-settling nanoparticles interfere with the settling of the larger micrometre-scale particles due to Brownian motion. Addition of a surfactant allows micelles. to form around the ferroparticles. A surfactant has a polar head and non-polar tail (or vice versa), one of which adsorbs to a nanoparticles, while the non-polar tail (or polar head) sticks out into the carrier medium, forming an inverse or regular micelle, respectively, around the particle. This increases the effective particle diameter. Steric repulsion then prevents heavy agglomeration of the particles in their settled state, which makes fluid remixing (particle redispersion) occur far faster and with less effort. For example, Magnetorheological fluids will remix within one cycle with a surfactant additive, but are nearly impossible to remix without them. While surfactants are useful in prolonging the settling rate in MR fluids, they also prove detrimental to the fluid's magnetic properties (specifically, the magnetic saturation), which is commonly a parameter which users wish to maximize in order to increase the maximum apparent yield stress. Whether the anti-settling additive is nanosphere based or surfactant based, their addition decreases the packing density of the ferroparticles while in its activated state, thus decreasing the fluids on-state/activated viscosity, resulting in a "softer" activated fluid with a lower maximum apparent yield stress. While the on-state viscosity (the "hardness" of the activated fluid) is also a primary concern for many MR fluid applications, it is a primary fluid property for the majority of their commercial and industrial applications and therefore a compromise must be met when considering on-state viscosity, maximum apparent yields stress, and settling rate of an MR fluid.

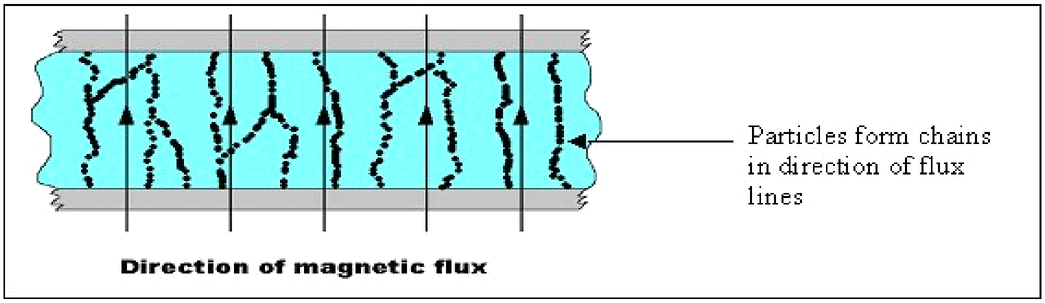
1.6. How it Works?

The magnetic particles, which are typically micrometer or nanometer scale spheres or ellipsoids, are suspended within the carrier oil are distributed randomly and in suspension under normal circumstances, as below



When a magnetic field is applied, however, the microscopic particles (usually in the 0.1–10 μm range) align themselves along the lines of magnetic flux, see below. When the fluid is contained between two poles (typically of separation

0.5–2 mm in the majority of devices), the resulting chains of particles restrict the movement of the fluid, perpendicular to the direction of flux, effectively increasing its viscosity Thus in designing a Magnetorheological (or MR) device, it is crucial to ensure that the lines of flux are perpendicular to the direction of the motion to be restricted. Importantly, mechanical properties of the fluid in its “on” state are anisotropic.

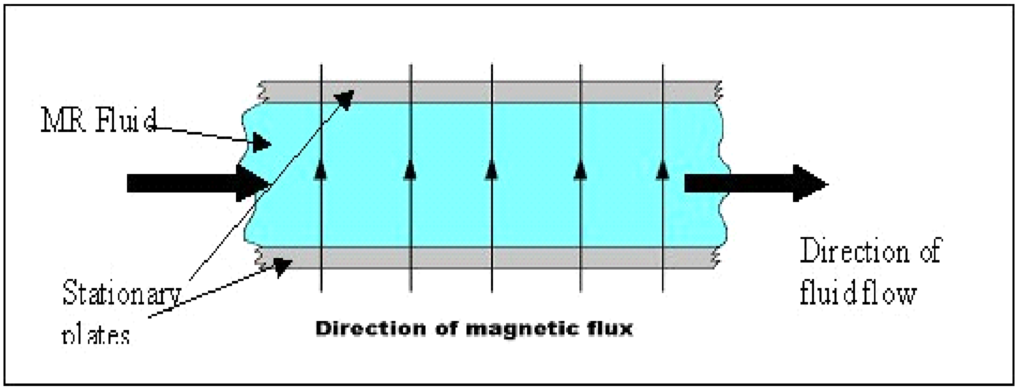


1.7. Modes of Operation and its Applications

An MR fluid is used in one of three main modes of operation, these being flow mode, shear mode and squeeze-flow mode. These modes involve, respectively, fluid flowing as a result of pressure gradient between two stationary plates; fluid between two plates moving relative to one another; and fluid between two plates moving in the direction perpendicular to their planes. In all cases the magnetic field is perpendicular to the planes of the plates, so as to restrict fluid in the direction parallel to the plates.

1.7.1. Flow Mode

The applications of Flow mode can be used in dampers and shock absorbers, by using the movement to be controlled to force the fluid through channels, across which a magnetic field is applied



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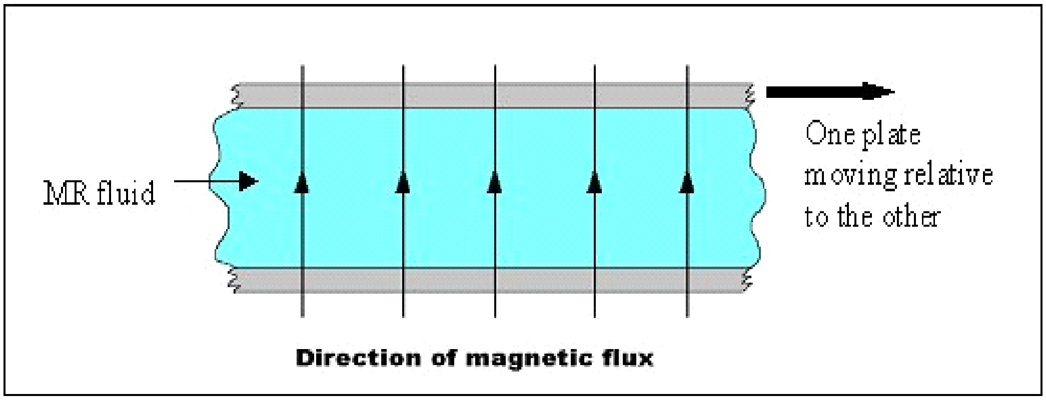
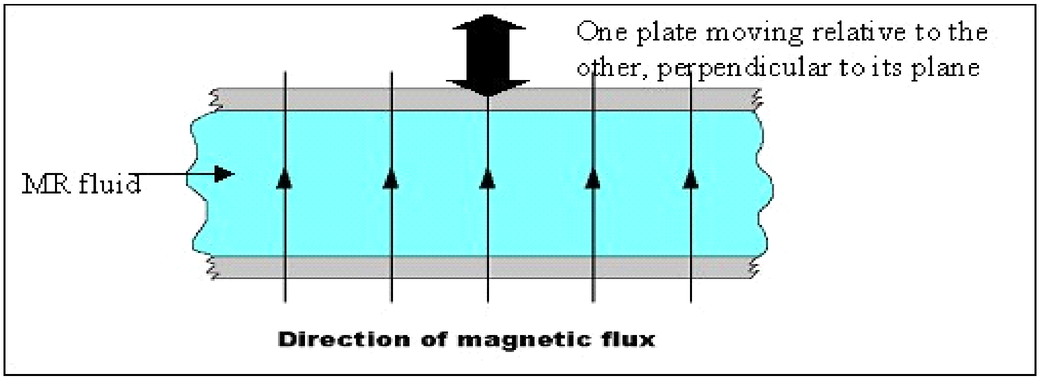
1.7.2. Shear Mode

Shear mode is particularly useful in clutches and brakes in places where rotational motion must be controlled.



1.7.3. Squeeze-Flow Mode

Squeeze-flow mode, on the other hand, is most suitable for applications controlling small, millimetre-order movements but involving large forces.



This particular flow mode has seen the least investigation so far. Overall, between these three modes of operation, MR fluids can be applied successfully to a wide range of applications. The method of operation of a Magnetorheological fluid is simple. A Magnetorheological fluid is made up of micrometer-sized ferroparticles, particles like iron that respond to a magnetic field, suspended in an oil-based medium. When outside the influence of a magnetic field, the particles float freely, causing the material to behave like any colloidal mixture, such as milk. When a magnetic field is turned on, however, the ferroparticles align in vertical chains along the field's flux lines, restricting the fluid flow and increasing the viscosity up to around that of a weak plastic.

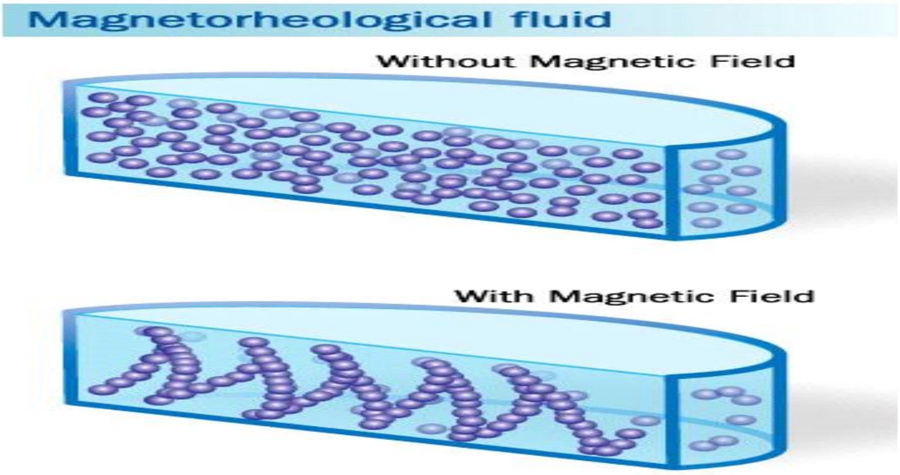


Fig.1.5. Behavior of MR fluid (i) Without Magnetic Field (ii) With Magnetic Field

1.8. Applications

The application set for MR fluids is vast, and it expands with each advance in the dynamics of the fluid.

1.8.1. Mechanical Engineering

Magnetorheological dampers of various applications have been and continue to be developed. These dampers are mainly used in heavy industry with applications such as heavy motor damping, operator seat/cab damping in construction vehicles, and more.

1.8.2. Military and Defence

The U.S. Army Research Office is currently funding research into using MR fluid to enhance body armour.

1.8.3. Optics

Magnetorheological Finishing a Magnetorheological fluid-based optical polishing method, has proven to be highly precise. It was used in the construction of the Hubble Space Telescope's corrective lens.

1.8.4. Automotive and Aerospace

If the shock absorbers of a vehicle's suspension are filled with MR fluid instead of plain oil, and the whole device surrounded with an electromagnet, the viscosity of the fluid (and hence the amount of damping provided by the shock absorber) can be varied depending on driver preference or the weight being carried by the vehicle - or it may be dynamically varied in order to provide stability control. This is in effect a Magnetorheological damper.

1.9. Recent Advances

Recent studies which explore the effect of varying the aspect ratio of the ferromagnetic particles have shown several improvements over conventional MR fluids. Nano-wire-based fluids show no sedimentation after qualitative observation over a period of three months. Conventional commercial fluids exhibit a typical loading of 30 to 90 wt%, while Nano-wire-based fluids show a percolation threshold of ~0.5 wt% (depending on the aspect ratio). They also show a maximum loading of ~35 wt%, since high aspect ratio particles exhibit a larger per particle excluded volume as well as inter-particle tangling as they attempt to rotate end-over-end, resulting in a limit imposed by high off-state apparent viscosity of the fluids. This new range of loadings suggests a new set of applications are possible which may have not been possible with conventional sphere-based fluids.

1.10. Limitations

Although smart fluids are rightly seen as having many potential applications, they are limited in commercial feasibility for the following reasons:

- High density, due to presence of iron, makes them heavy. However, operating volumes are small, so while this is a problem, it is not insurmountable.
- High-quality fluids are expensive.
- Fluids are subject to thickening after prolonged use and need replacing.
- Settling of ferro-particles can be a problem for some applications.

Commercial applications do exist, as mentioned, but will continue to be few until these problems (particularly cost) are overcome.

Chapter 2

LITERATURE REVIEW

In this chapter descriptions of research papers sstudied for the present work is given, some researchers have done remarkable work in the field of MRF, BEMRF. They investigate the effects of process parameters like working gap, Current; speed of rotation, magnetic field, concentration of CIP particles and Abrasive particles on output responses namely, surface finish and material removal, below is the details of the literature review available.

A. Kumar et.al [20] studied the mechanism of BEMRF process. Ball end Magnetorheological finishing (BEMRF) process was developed for finishing flat and 3D work-piece surfaces. They used a finishing tool to flow pressurized Magnetorheological polishing fluid through the centre of the rotating tool core and gets stiffened in the form of a magnetically controlled ball end shape at the tip surface of the tool. This forms a polishing spot of controlled size and shape which is used as a finishing medium by guiding it to follow the surface to be finished through computer controlled 3-axes motion. Attempt were made to understand the material removal and surface finishing mechanism in BEMRF process on a ferromagnetic work-pieces, a mathematical model was developed for modelling of magnetic field-induced normal force during finishing by BEMRF process. A mathematical model was developed for magnetic-field induced normal force which was identified as an important process parameter for the desired surface finishing and material removal in the newly developed BEMRF process.

Goncalves et al. [21] review the state of the art in magnetorheological technology, and examine various models used to describe the MR fluid behavior. Two models have been particularly well documented in the literature, namely the Bingham Plastic and the Herschel–Bulkley models. The focus of the present article was to develop and validate a rheological model able to capture both pre- and post-yield behavior of MRF, and in the same time be easy to implement I commercially available CFD codes in order to simulate the flow in practical devices.

V.K. Jain et.al [22] studied the mechanism of MRF. Magnetorheological finishing (MRF) utilizes Magnetorheological (MR) fluid, which consists of magnetic particles, nonmagnetic abrasives, and some additives in water or other carrier to polish the materials. They conducted an experimental study to predict the effect of process parameters (concentration of magnetic particles and abrasive particles, carrier wheel speed, and initial surface roughness) on surface finish and material removal rate in MRF of single crystal silicon blank. They performed an optimization study within the selected range of the independent parameters. It was found that 39.58% CIPs, 5.07% abrasive, and 298.36 RPM carrier wheel speed are the optimum values to minimize final Ra and maximize MRR.

Gandhi and Bullough [23] review the behavioral attributes o various models for magnetorheological and electrorheological fluid in the preyield regime, and conclude that the Kelvin–Voigt model is most convenient to represent this solid-like, not fluid-like, behavior. When examining the implications of using a fluid model for representation of preyield behavior, conclude that the preyield viscosity has a large variation with frequency, with large values at very low frequency and decreasing at higher frequencies when the preyield behavior is effectively represented as a Maxwell fluid. As a result, they argue that the solid model in the preyield regime is more suitable for broadband excitation problems than a fluid model, which has frequency dependent parameters.

Bitman et al. [24] replace the Bingham model by an Eyring constitutive model to investigate the behavior of electrorhelogical dampers. Because the two-parameter (yield stress and postyield viscosity) Bingham model has a zero shear rate discontinuity, it has been replaced by the Eyring model, which has a smooth transition through the zero shear rate condition and also has two rheological constants for a constant field (magnitude of the shear stress and steepness of the shear rate gradient in the preyield region). This is a more convenient alternative to the biviscous model, which has two distinct viscosities and governing equations within the preyield (low shear rate) and postyield (high shear rate) regions

Choi et al. [25] investigate the rheological characteristics of ER/MR fluids with respect to both cylinder and parallel disk rotational viscosimeters, and derive the governing equations based on Binghamplastic, biviscous, and Herschel–Bulkley constitutive models. It has been found that flow curves (shear stress vs. shear rate) for the rotational coaxial cylinder viscosimeter are sensitive to the calculation methods since two or three distinct flow conditions occur in the gap. However, in the case of rotational parallel disk viscosimeter the flow curve can be obtained directly from fundamental equations without any approximation strategies. This is the viscosimeter also used for the experimental investigations presented in this article. In an attempt to model the yield behavior of magnetorheological suspensions,

Lange et al. [26] consider that the behavior of MRF flow under the influence of a magnetic field is consistent with the Bingham model. They derived the yield shear stress and the Bingham viscosity from the pressure drop versus the volumetric flow rate in a capillary rheometer at high-flow velocity, arguing that such high velocities are relevant for new industrial applications such as shock and vibration dampers.

Li et al. [27] investigated the creep and recovery behaviors of the same MR fluid under constant shear stress, using the same experimental equipment. They conclude that

(i) at low stresses the MR fluid behaves as a linear viscoelastic body;

(ii) when the applied stress gets close to the yield stress the suspension is almost instantaneously strained without viscous flow, thus the MR fluid behaves as a plastic solid;

(iii) When the stress is larger than the yield stress the MR fluid behaves as a plastic fluid

Li et al. [28] investigate the viscoelastic properties of MR suspension within the pre-yield region, since these properties are considered especially relevant for vibration damping applications. They used a German Paar Physica rheometer with plate-plate configuration in strain-controlled mode, and a MRF-132LD suspension produced by Lord Corporation, both the equipment and MR fluid being quite similar to the ones used in the present investigations. Both strain-amplitude sweep (frequency 10 Hz and amplitude 10_4 . . . 10_3) and frequency sweep (amplitude 10_3 and frequency from 1 to 100 Hz) tests were performed in order to determine the storage modulus and loss modulus as functions of frequency, strain amplitude, applied coil current (which is proportional to the magnetic flux density) and volume fraction of iron powder dispersed in silicone oil.

Bongsu Jung et.al [29] use the magneto rheological fluids for finishing is one of the most promising smart processes for the fabrication of ultra-fine surfaces, particularly three-dimensional millimetre or micrometer structures. Non-traditional manufacturing processes like ion-milling [11] and electro-discharge machining (EDM) [12,13] are frequently used as the primary process for shaping and/or manufacturing these components. Thus, the middle products obtained frequently require ultra-fine surface quality (a few to tens of nanometers in surface and/or shape accuracy), thereby creating a critical demand for efficient surface finishing processes.

A. Dorfmann et.al [30] described the magnetorheological fluids, undergoing steady motion in the presence of a magnetic field. A general three-dimensional non-linear constitutive law for such a fluid is given for the case in which the magnetic induction vector is used as the independent magnetic variable. The material is characterized by a specific magnetic-field dependent yield stress and by a field independent viscosity for the yielded fluid. In particular, an increase in the magnitude of the magnetic field changes the shape of the velocity profile significantly. In all three cases a region develops where the fluid moves as an elastic solid. For a sufficiently large magnitude of the magnetic field fluid flow is no longer possible.

Bhau K. Kumbhar et.al [31] discussed about MR fluid whose rheological characteristics change rapidly and can be controlled easily in presence of an applied magnetic field. MR brake is a device to transmit torque by the shear stress of MR fluid. However, MR fluids exhibit yield stress of 50-90 kPa. In this research, an effort has been made to synthesize MR fluid sample/s which will typically meet the requirements of MR brake applications. In this study, various electrolytic and carbonyl iron powder based MR fluids have been synthesized by mixing grease as a stabilizer, oleic acid as an antifriction additive and gaur gum powder as a surface coating to reduce agglomeration of the MR fluid. MR fluid samples with different compositions preferably to suit braking application have been synthesized. Based on this synthesis and characterization

Rahul S. Mulik, et.al [32] Use of ultrasonic vibrations and magnetic abrasive finishing (MAF) process to finish surfaces to nanometer order in a relatively short time. Percentage change in surface roughness (%ΔRa) for AISI 52100 steel workpiece has been considered as response and unbonded SiC abrasives are used in the work The surface roughness value obtained by UAMAF was as low as 22 nm on hardened AISI 52100 steel workpiece using unbonded SiC.

2.1. Research Gap

After a comprehensive study of the existing literature, it has been observed that existing MR finishing processes can be run at some what low tool rotational speed. It is due to the fact that the non magnetic abrasive particles encompassed by magnetic iron particles are thrown away from the working area and reduces the finishing efficiency of the MR finishing process. The material is removed from the work-piece surface on the principle of three body wear mechanism in the existing MR finishing processes. To improve the material removal rate and finishing efficiency of the process, an attempt has been made to developed magnetic abrasive particles and synthesized the MRP fluid in the present research work.

2.2. Research Objectives

Objective I: To developed the magnetic abrasive particles (MAPs) and synthesized the smart MRP fluids by adding the base fluid (Paraffin oil heavy and AP3 grease) in appropriate vol% of the constituent.

Objective II: To study the flow behavior of synthesized MRP fluid at different magnetic field and compare the result with unbonded magnetic abrasive particles based MRP fluid.

Objective III: To conduct the experiments on mild steel work-piece surface with MAPs based MRP fluid sample as well as unbonded magnetic abrasives based MRP fluid on ball end magnetorheological finishing (BEMRF) tool.

Objective IV: To compare the percentage reduction in surface roughness (%ΔR_a) obtained by finishing the mild steel surface with MAPs based synthesized MRP fluid sample with finishing by unbonded magnetic abrasives based MRP fluid.

Chapter 3

RHEOLOGICAL CHARACTERIZATION

Magnetorheological (MR) fluids are the suspensions of micron-sized dispersed magnetic phase in a non-magnetic carrier continuous phase along with additives. Magnetic abrasive particles (MAPs) based MR polishing (MRP) fluid sample has been synthesized in the present re work. These MAPs are developed at 1000^0C with appropriate sintering cycle using solid phase sintering method. Then MRP fluid sample has been synthesized with 45 volume% magnetic abrasive particles and 55 volume% base fluid. After synthesis of MRP fluid, magnetorheological characterization has been done at different magnetic field on MCR-301 magnetorheometer and steady state rheograms have been drawn. The flow behavior of magnetic abrasive particles (MAPs) based MRP fluid sample has been compared with flow behavior of unbonded magnetic abrasives based MRP fluid. The result shows better yield behavior and viscosity of MAPs based MRP fluid sample as compared to unbonded magnetic abrasives based MRP fluid.

3.1. Preparation of Sample

Magnetic abrasive particles (MAPs) are developed at 1000^0C with appropriate sintering cycle using solid phase sintering method. The MRP fluid sample has been synthesized with 45 volume% magnetic abrasive particles (MAPs) and 55 volume% base fluid (S_2). Another MRP fluid sample has been prepared with 20 volume% carbonyl iron powder, 25 volume% silicon carbide abrasives of 3000 mesh size, and 55 volume% base fluid (S_1) as shown in table 3.1. After synthesis of MRP fluid, magnetorheological characterization has been done at different magnetic field on MCR-301 magnetorheometer and steady state rheograms have been drawn.

Table 3.1: Composition of MRP fluid

S.No.	Composition	Sample No.
1.	20 vol% CIP CS grade , 25 vol% SiC of 3000 mesh size, 55vol% of base fluid	Unbonded magnetic abrasives based (S_1)
2.	45 vol% of magnetic abrasive particles (MAPs), 55vol% of base fluid	Bonded magnetic abrasive particles based (S_2)

Density of CIP (CS Grade) =7.78gm/cm^3

Density of SiC (3000mesh Size) =3.22gm/cm^3

3.2. Rheological Characterization

After synthesis of both types of MRP fluidsamples, the magnetorheological characterization has been done at different magnetic field on ANTON PAAR MCR-301 magnetorheometer and steady state rheograms have been drawn.

3.2.1. Rheometry

In MR fluid applications, most devices operate using pressure driven flow mode, direct shear mode or squeeze mode. Examples of pressure drive flow mode devices include servo valves, dampers and shock absorbers. In case of direct shear mode, clutches, brakes, chucking and locking devices can be given as examples. The squeeze mode has been used in low motion, high force applications [33,34].

The design and realization of an actuator with MR fluid requires exact description of the rheological and magnetic properties of the MR fluids. Basic classes of rheometry are considered as stress driven and strain rate driven.

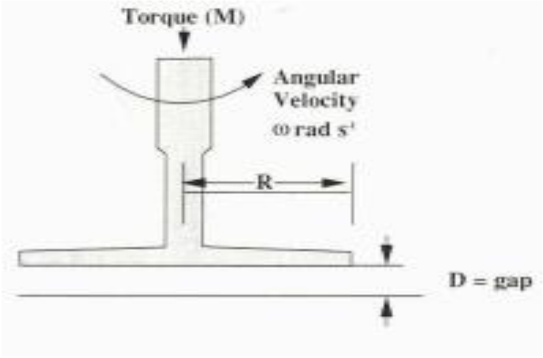


Figure 3.1 Rheometer Geometries of Parallel Plate[35]

Table 3.2: Equations of Rheological Properties for Parallel Plate Geometries [35,36]

	Shear stress	Shear rate	strain	viscosity
Parallel plate	$\frac{M}{2\pi R^3}$	$\frac{\Omega R}{h}$	$\frac{R\theta}{h}$	$\frac{\pi\Omega M R^4}{2h}$

Where,

M is the torque,

h is the height,

R, is the radius

Ω is the angular velocity

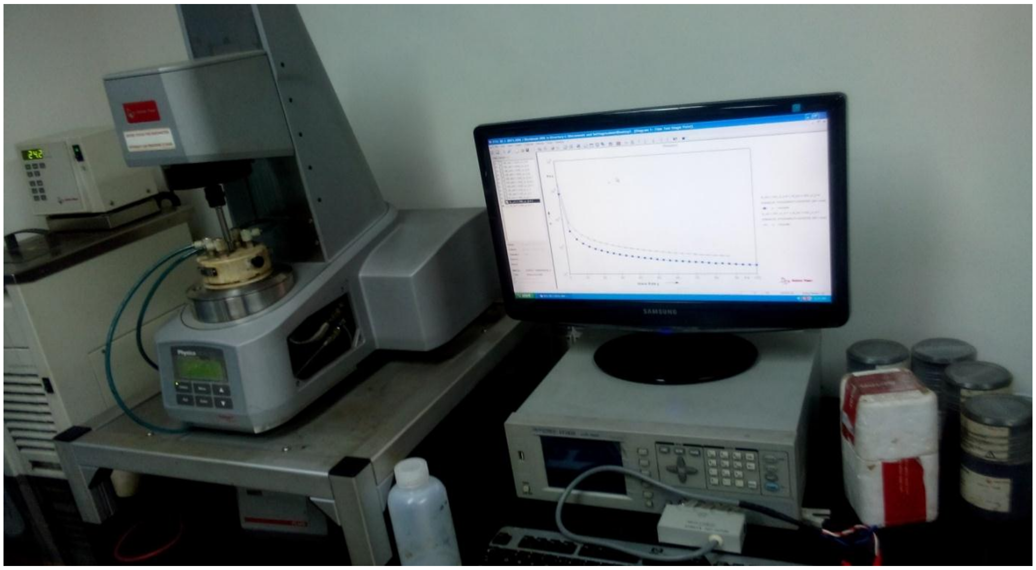
Θ is the angular displacement

3.2.2. Experimental Setup

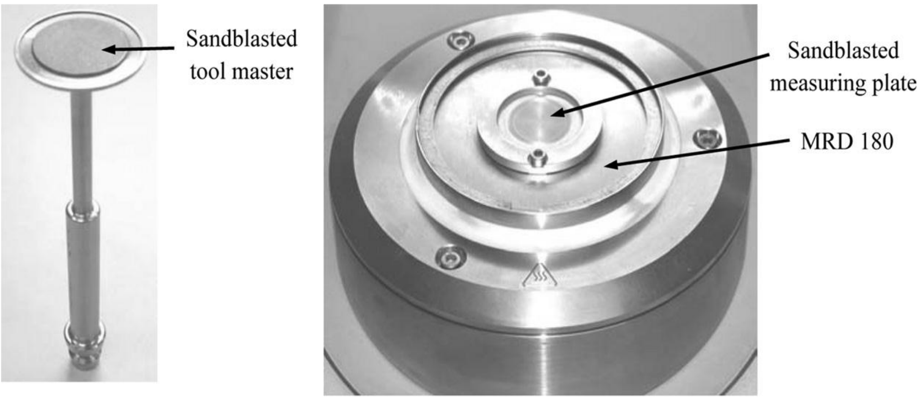
The rheological properties of all fluid samples are tested using a stress-controlled rheometer (Anton Paar MCR301 with MRD 180 attachment), using parallel plate geometry and a gap of 1mm between parallel plates. The measuring plates are sand blasted to avoid the slippage of MR fluid with plate geometry due to rotation of the shaft of the measuring system, and it also prevents wearing out of the plate geometry due to the abrasive action of constituent particles in the MR fluid during experimentation.

MR fluid is filled in a constant gap between parallel plates during the experiment as shown in Fig.3.3 the top disc rotates while the bottom disk remains stationary. A coil is placed below the bottom disk while flux returns are mounted above and around the upper disk, to close the magnetic circuit. After putting the sample between the upper rotating plate and the stationary bottom plate, the magnetic circuit is closed using the flux returns. Homogeneous magnetic field was set perpendicular to the shear flow direction of MR fluid.

(a) **(b)**



(c)



(a) (b)

Fig.3.3. Schematic View of Magnetorheometer (ANTON PAAR MCR-301 MODEL)

3.3. Observations

Rheological properties of MRP fluid samples are tested on parallel plate magnetorheometer at 1 mm gap and at different current levels.

3.3.1.Observation Table

Table 3.3: Shear Stress and viscosity at Current 0A

	Unbonded 20vol% CIP CS, 25vol% SiC, 55vol% Base fluid	**45vol% sintered MAPs, 55vol% Base fluid**	**Unbonded 20vol% CIP CS, 25vol% SiC, 55vol% Base fluid**	**45vol% sintered MAPs, 55vol% Base fluid**
Shear Rate	**Shear Stress**	**Shear Stress**	**Viscosity**	**Viscosity**
0.0999	0.302	52.8	3.02	529
3.43	0.552	119	0.161	34.7
6.76	0.659	124	0.0975	18.3
10.1	0.722	134	0.0715	13.3
13.4	0.79	148	0.0588	11
16.7	0.861	161	0.0514	9.63
20.1	0.911	174	0.0454	8.64
23.4	0.961	185	0.041	7.91
26.7	1.03	197	0.0384	7.36
30.1	1.13	208	0.0375	6.93
33.4	1.17	220	0.0349	6.57
36.7	1.14	230	0.0311	6.27
40.1	1.24	241	0.0308	6.01
43.4	1.3	249	0.0299	5.75
46.7	1.32	253	0.0283	5.42
50	1.46	246	0.0292	4.92
53.4	1.53	230	0.0287	4.31
56.7	1.45	297	0.0256	5.23
60	1.59	260	0.0265	4.33
63.4	1.59	286	0.0251	4.51
66.7	1.69	181	0.0253	2.71
70	1.62	126	0.0231	1.8
73.4	1.68	118	0.0229	1.61
76.7	1.72	112	0.0225	1.47
80	1.88	102	0.0234	1.27
83.3	1.91	92.3	0.0229	1.11
86.7	1.91	155	0.022	1.79
90	1.61	206	0.0179	2.29
93.3	1.35	73.1	0.0144	0.783
96.7	0.918	64.8	0.00949	0.67
100	0.695	59.2	0.00695	0.592

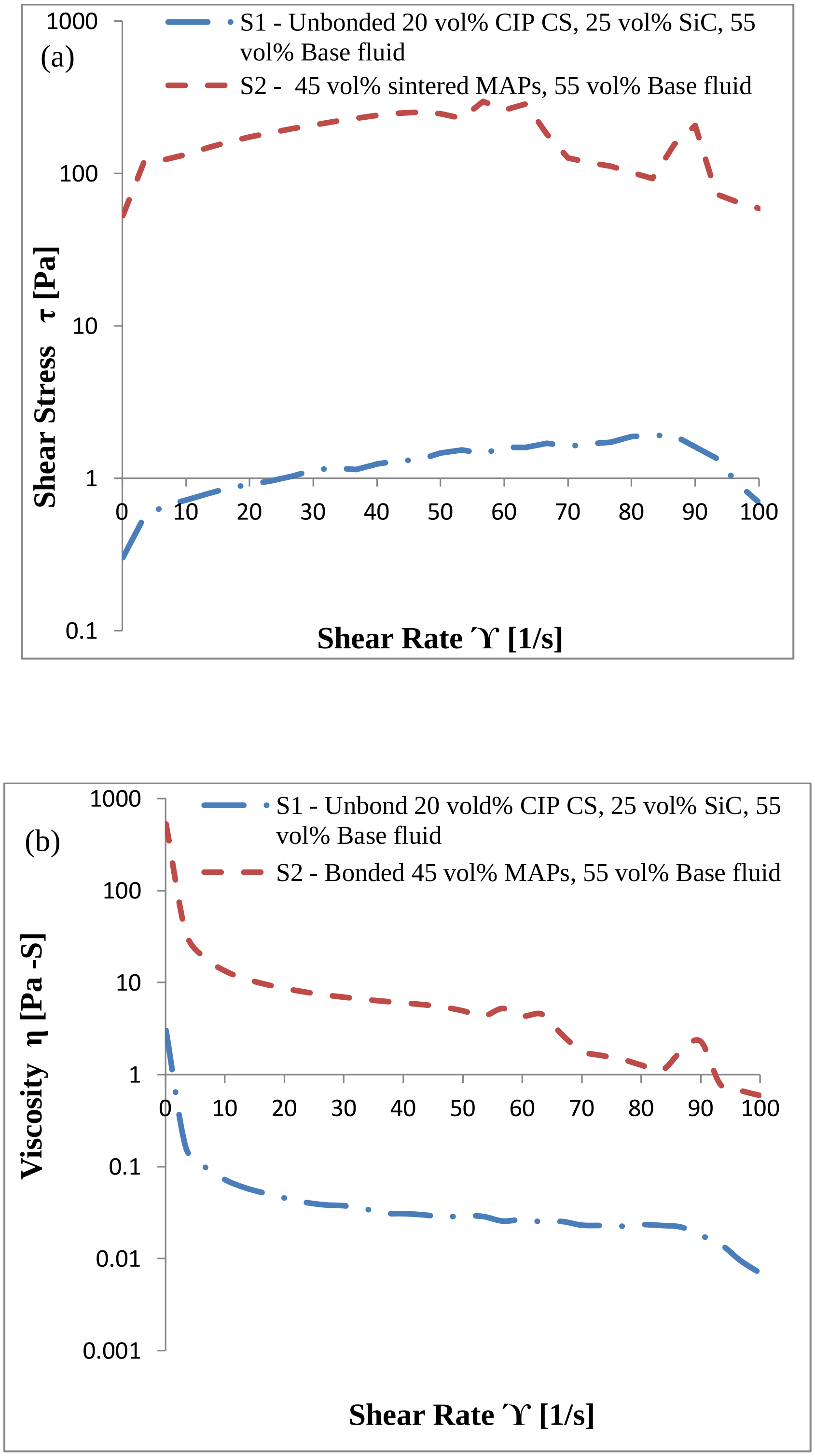
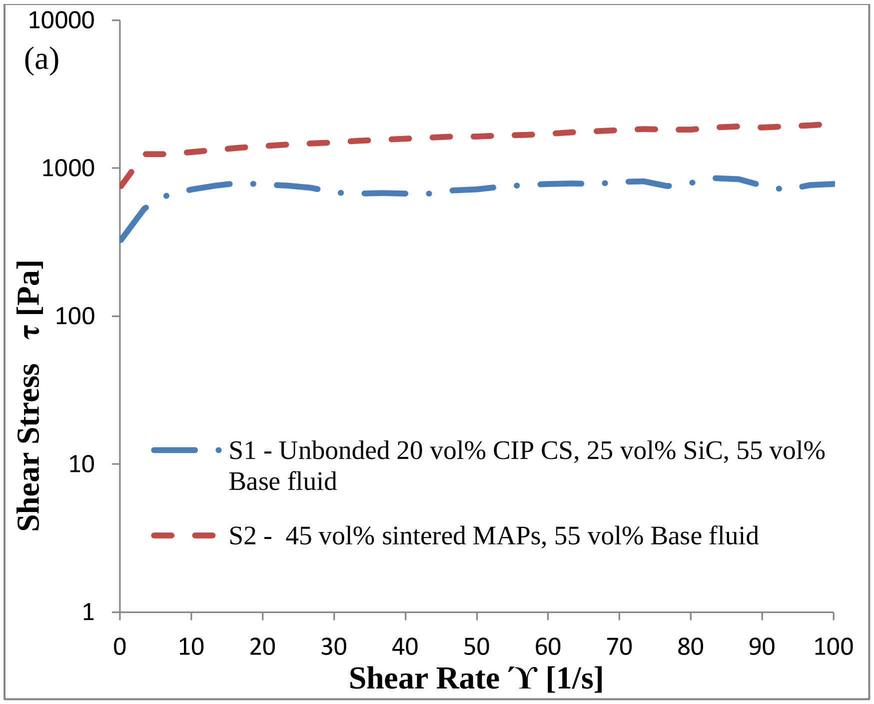


Fig. 3.4. (a) Shows Shear Stress (b) Viscosity at 0A

3.3.2.Observation Table

Table 3.4: Shear Stress and viscosity at Current 0.4A

	Unbonded 20vol% CIP CS, 25vol% SiC, 55vol% Base fluid	**45vol% sintered MAPs, 55vol% Base fluid**	**Unbonded 20vol% CIP CS, 25vol% SiC, 55vol% Base fluid**	**45vol% sintered MAPs, 55vol% Base fluid**
Shear Rate	**Shear Stress**	**Shear Stress**	**Viscosity**	**Viscosity**
0.1	326	757	3,260	7,570
3.43	533	1,240	155	361
6.76	662	1,250	98	185
10.1	719	1,290	71.3	128
13.4	763	1,330	56.9	98.9
16.7	792	1,370	47.3	82
20.1	777	1,410	38.7	70.3
23.4	766	1,450	32.7	61.8
26.7	735	1,470	27.5	55.1
30.1	686	1,500	22.8	49.8
33.4	672	1,530	20.1	45.9
36.7	681	1,560	18.5	42.5
40.1	673	1,590	16.8	39.6
43.4	676	1,610	15.6	37.2
46.7	706	1,640	15.1	35
50	717	1,640	14.3	32.8
53.4	750	1,660	14.1	31.1
56.7	768	1,680	13.5	29.6
60	783	1,710	13	28.4
63.4	789	1,750	12.4	27.6
66.7	781	1,780	11.7	26.7
70	806	1,810	11.5	25.9
73.4	812	1,840	11.1	25.1
76.7	757	1,830	9.87	23.8
80	796	1,830	9.95	22.8
83.3	860	1,890	10.3	22.7
86.7	845	1,920	9.75	22.1
90	765	1,890	8.5	21
93.3	711	1,920	7.62	20.6
96.7	769	1,950	7.95	20.2
100	785	1,990	7.85	19.9



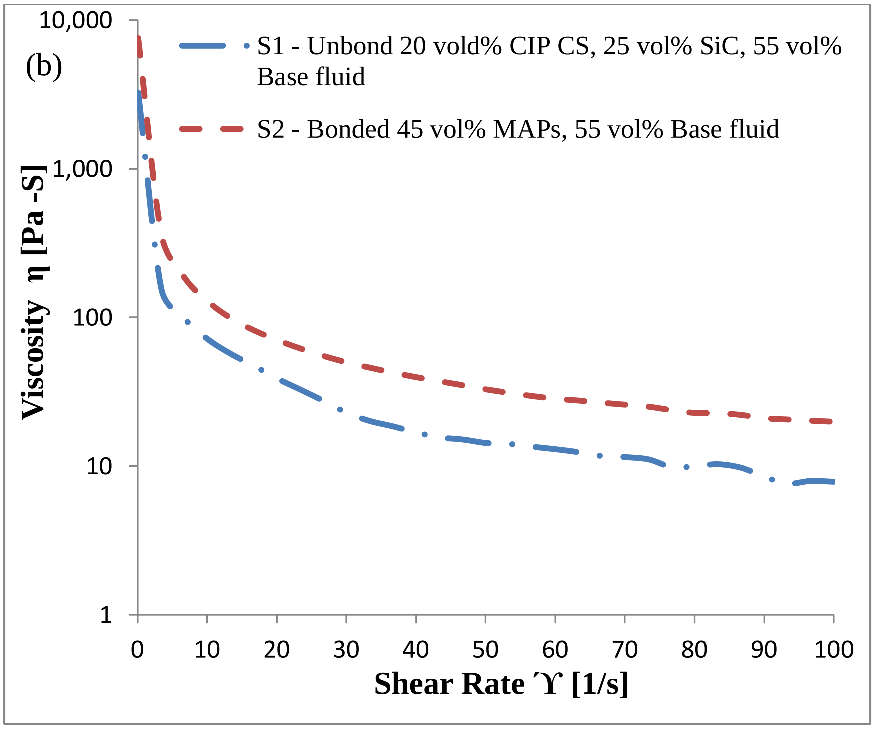


Fig.3.5. (a) Shows Shear Stress (b) Viscosity at 0.4 A

3.3.3.Observation Table

Table 3.5: Shear Stress and viscosity at Current 0.7A

	Unbonded 20vol% CIP CS, 25vol% SiC, 55vol% Base fluid	**45vol% sintered MAPs, 55vol% Base fluid**	**Unbonded 20vol% CIP CS, 25vol% SiC, 55vol% Base fluid**	**45vol% sintered MAPs, 55vol% Base fluid**
Shear Rate	**Shear Stress**	**Shear Stress**	**Viscosity**	**Viscosity**
0.1	902	1,580	9,020	15,800
3.43	1,100	2,510	322	730
6.76	1,340	2,620	198	388
10.1	1,740	2,650	172	263
13.4	1,860	2,680	139	200
16.7	1,930	2,720	115	163
20.1	1,970	2,770	98	138
23.4	2,020	2,830	86.1	121
26.7	2,060	2,870	77.2	108
30.1	2,120	2,930	70.6	97.4
33.4	2,190	2,970	65.5	89
36.7	2,140	3,020	58.4	82.1
40.1	2,130	3,050	53.3	76.1
43.4	2,170	3,080	50	70.9
46.7	2,210	3,110	47.3	66.6
50.1	2,270	3,150	45.3	62.9
53.4	2,300	3,170	43.1	59.5
56.7	2,350	3,210	41.5	56.5
60	2,370	3,240	39.5	53.9
63.4	2,370	3,280	37.5	51.7
66.7	2,400	3,310	36	49.6
70	2,320	3,330	33.1	47.5
73.4	2,310	3,370	31.5	45.9
76.7	2,220	3,410	28.9	44.5
80	2,220	3,430	27.8	42.9
83.4	2,050	3,460	24.6	41.6
86.7	2,070	3,490	23.8	40.3
90	2,090	3,520	23.2	39.1
93.3	2,270	3,550	24.4	38
96.7	2,290	3,580	23.7	37
100	2,270	3,610	22.7	36.1

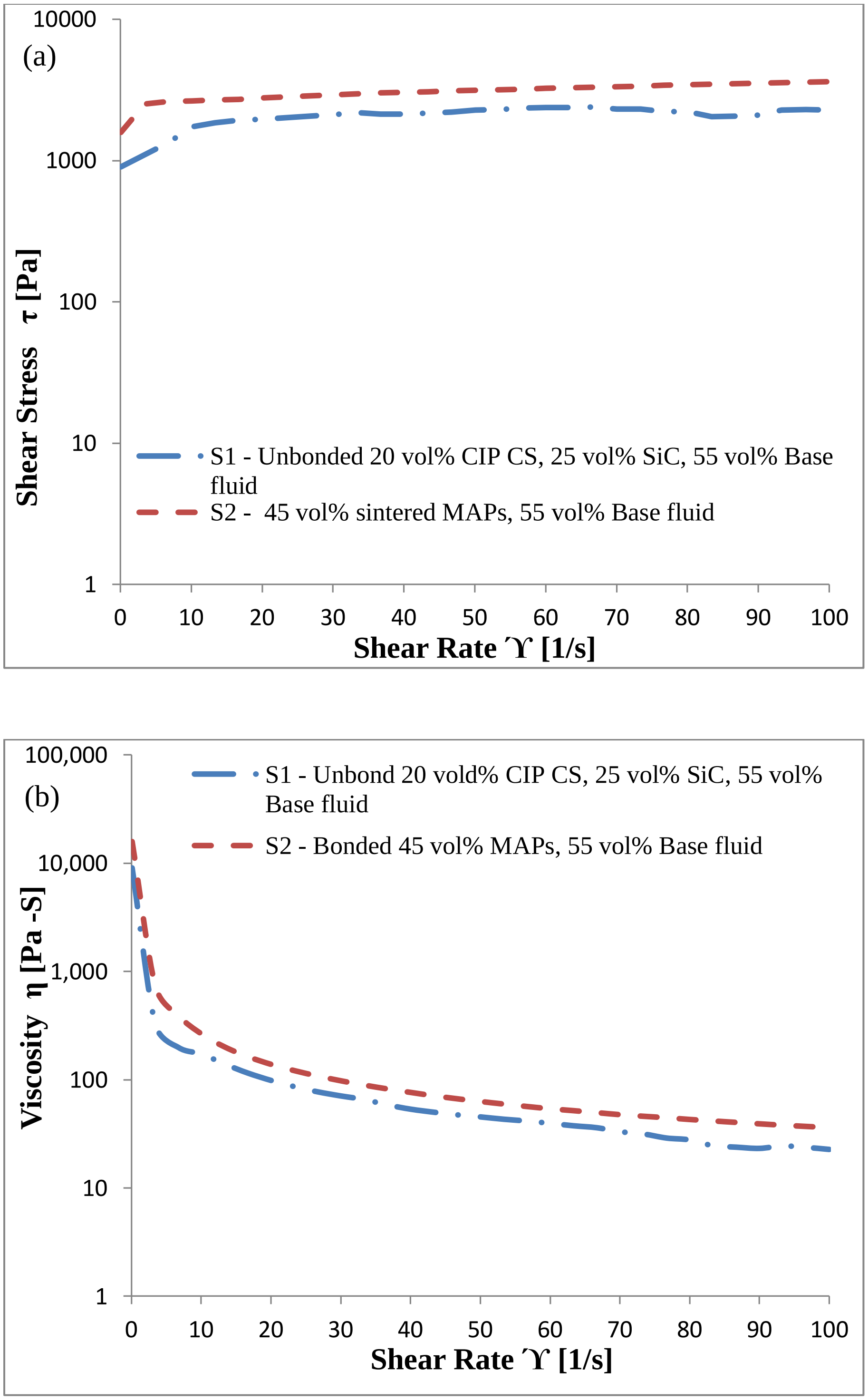


Fig. 3.6. (a) Shows Shear Stress (b) Viscosity at 0.7 A

3.3.4.Observation Table

Table 3.6: Shear Stress and viscosity at Current 1A

	Unbonded 20vol% CIP CS, 25vol% SiC, 55vol% Base fluid	**45vol% sintered MAPs, 55vol% Base fluid**	**Unbonded 20vol% CIP CS, 25vol% SiC, 55vol% Base fluid**	**45vol% sintered MAPs, 55vol% Base fluid**
Shear Rate	**Shear Stress**	**Shear Stress**	**Viscosity**	**Viscosity**
0.1	1,750	2,690	17,900	24,500
3.43	2,600	3,000	5,050	13100
6.76	2,805	4,150	630	9013
10.1	3,150	4,430	341	719
13.4	3,320	4,420	276	417
16.8	3,400	4,750	242	355
20.1	3,510	5,890	215	315
23.4	3,770	5,270	187	325
26.7	3,860	6,540	167	245
30.1	4,540	5,960	151	258
33.4	4,590	6,280	137	238
36.7	4,640	6,050	126	248
40	4,690	6,460	117	198
43.3	4,750	6,670	110	154
46.7	4,770	8,730	102	187
50.1	4,850	9,180	96.9	183
53.4	4,880	8,590	91.5	161
56.7	4,930	8,520	86.9	150
60.1	4,970	8,300	82.8	138
63.4	5,060	8,500	79.8	128
66.7	6,060	7,970	90.9	159
70	6,210	8,380	88.6	145
73.4	6,310	8,400	86.1	149
76.7	6,500	8,610	84.8	128.3
80	6,640	8,730	82.9	118.8
83.4	6,700	8,920	80.3	109.7
86.7	6,740	9,110	77.7	104.1
90	6,770	9,230	75.2	101.2
93.3	6,810	9,470	72.9	99.3
96.6	6,830	9,310	70.6	95
100	6,870	9,570	68.7	83.7

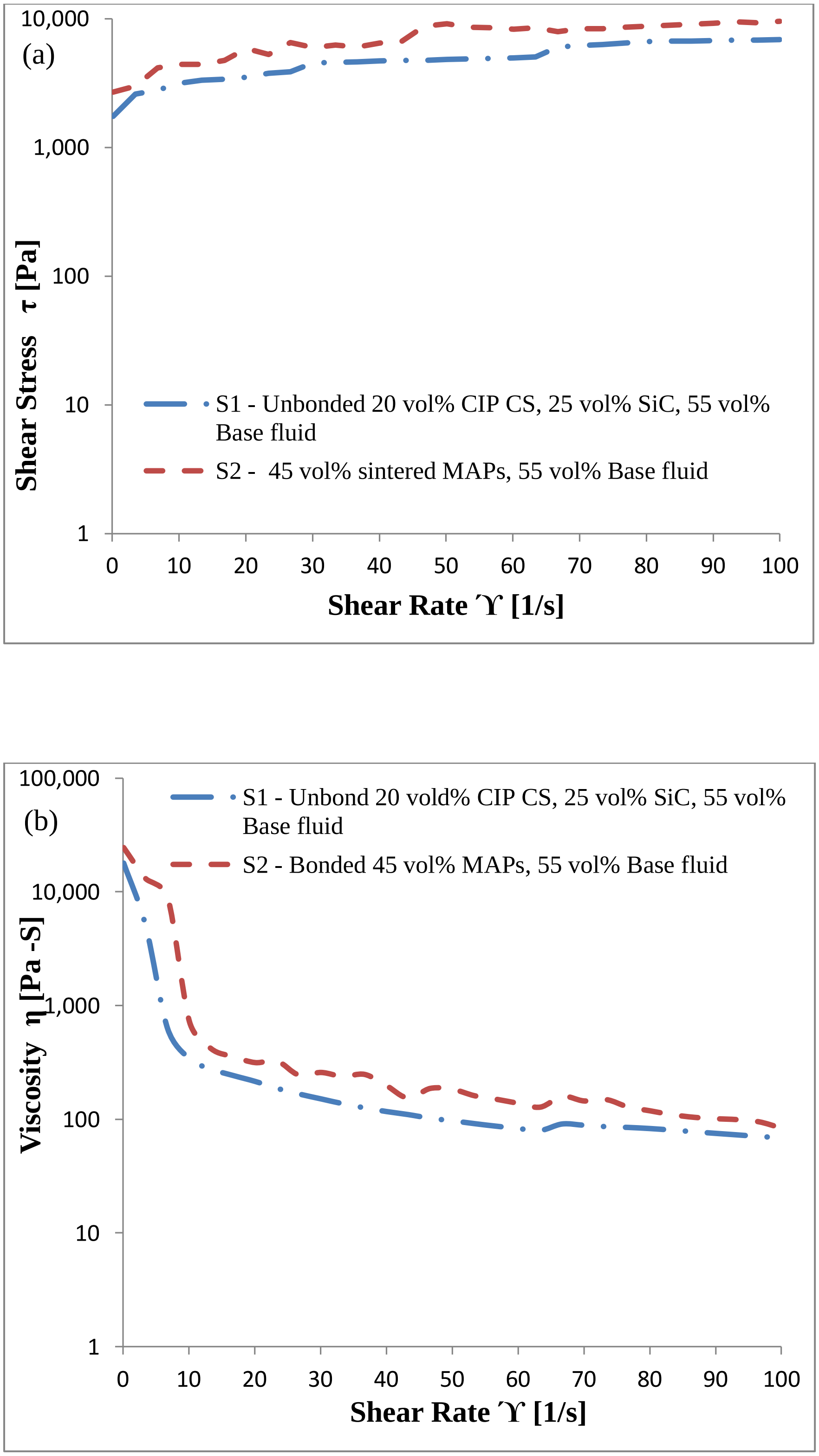
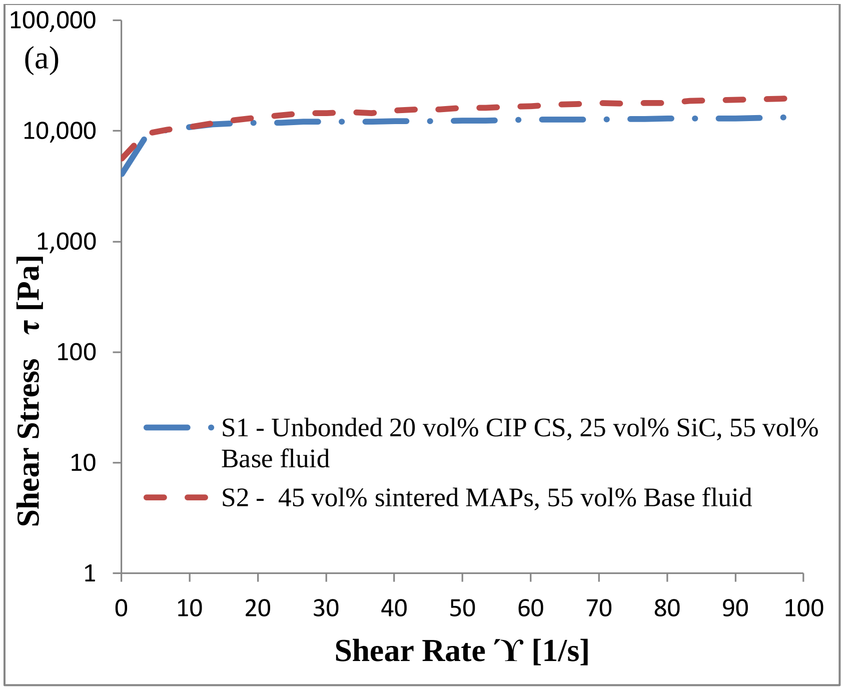


Fig.3.7. (a) Shows Shear Stress (b) Viscosity at 1A

3.3.5.Observation Table

Table 3.7: Shear Stress and viscosity at Current 2A

	Unbonded 20vol% CIP CS, 25vol% SiC, 55vol% Base fluid	**45vol% sintered MAPs, 55vol% Base fluid**	**Unbonded 20vol% CIP CS, 25vol% SiC, 55vol% Base fluid**	**45vol% sintered MAPs, 55vol% Base fluid**
Shear Rate	**Shear Stress**	**Shear Stress**	**Viscosity**	**Viscosity**
0.0999	4,060	5,650	40,600	46,700
3.43	8,620	9,350	2,510	2,730
6.76	10,300	10,300	1,520	1,530
10.1	10,900	10,900	1,080	1,080
13.4	11,400	11,700	846	873
16.7	11,700	12,500	701	744
20.1	11,800	13,200	587	657
23.4	11,900	13,900	508	593
26.7	12,100	14,400	454	537
30.1	12,100	14,400	403	478
33.4	12,100	14,800	362	443
36.7	12,100	14,500	331	395
40.1	12,200	15,300	304	381
43.4	12,300	15,700	282	362
46.7	12,300	15,700	264	336
50	12,400	16,200	248	324
53.4	12,400	16,100	233	302
56.7	12,500	16,500	221	291
60.1	12,600	16,700	211	279
63.4	12,700	17,300	201	273
66.7	12,700	17,500	191	262
70.1	12,700	17,900	182	255
73.3	12,800	17,700	174	241
76.7	12,800	17,900	167	233
80.1	12,900	17,900	161	224
83.3	12,900	18,700	154	224
86.7	12,900	18,900	149	218
90	13,000	19,100	144	212
93.3	13,100	19,400	140	208
96.7	13,200	19,500	136	201
100	13,200	20,000	132	200



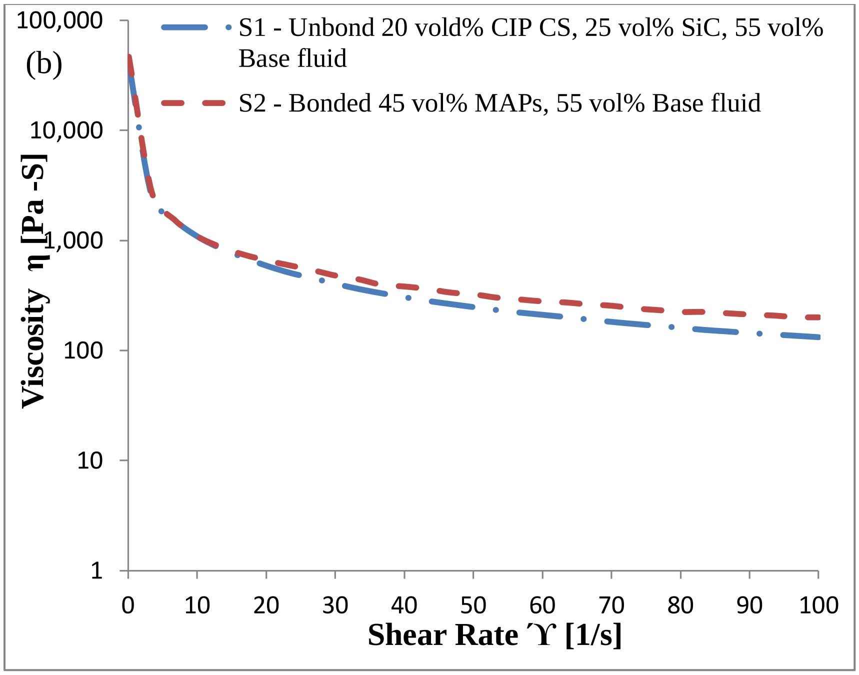


Fig.3.8. (a) Shows Shear Stress (b) Viscosity at 2 A

Chapter 4

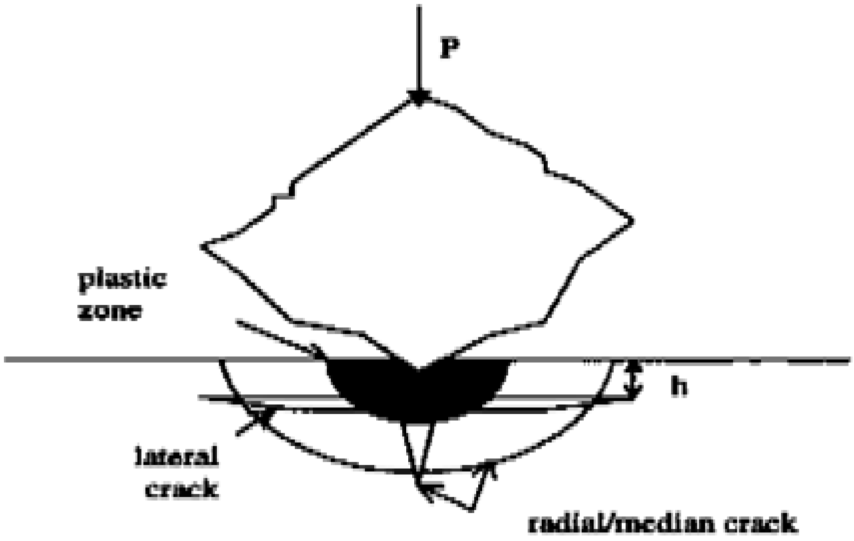
EXPERIMENTAL WORK ON BERMF TOOL

In Magnetorheological fluid finishing (MRFF), indentation of abrasive particles into the work-piece surface is due to normal force applied on it by the surrounding magnetic particles. The magnetic field induced normal force is responsible for the materials removal and final surface roughness. In this chapter, it has been attempted to understand the material removal mechanism with the help of abrasives present in the MRP fluid.

4.1. Mechanism of Material Removal

Material removal and surface finishing in BEMRF process is due to the abrasion action which mainly depends on how long the abrasives are in constant interaction with the work-piece surface. When MR polishing (MRP)-fluid reached at the tip surface of the tool, the electromagnet is switched ON to make it stiff whose physical shape was found like a ball end at the tip surface of tool. The nonmagnetic abrasive particles are closely surrounded by the carbonyl iron particles (CIPs) chains. Inside the nonmagnetic abrasive particles, the flux density is very small for any external magnetic field intensity. Therefore, the majority of abrasive particles are repelled from the higher gradient of magnetized tool tip surface towards the lower gradient of magnetic flux density (work- piece surface) [20]. These abrasives which are in contact with the work-piece surface are called as active abrasives and are responsible for the material removal during the rotation of a finishing spot of MRP-fluid on work-piece surface. The active abrasives are tightly gripped by CIPs chains structure towards the outer periphery of the finishing spot of MRP-fluid. When gripped active abrasive particles have relative motion on work-piece surface during the rotation of finishing spot of MRP-fluid, the peaks of the work-piece surface wear out. The gripping of nonmagnetic abrasive particles in CIPs chains structure depends on the rheological properties of MRP-fluid under magnetic field [10]. The higher yield strength of MRP-fluid can be found at higher magnetized tool tip surface. The carbonyl iron particles (CIPs) chains will be able to hold abrasive particles more firmly and strongly like a single body for longer period under high shear strength. This is necessary for efficient removal of material from the workpiece surface during finishing operation.

When high yield strength of finishing spot of MRP-fluid rotates on the work-piece surface, the high shear strength of gripped active abrasives able to cut the peaks of the surface in the form of micro chips due to abrasion by two- body wear mechanism. When continuous feed rate is given to the work-piece surface with respect to rotation of finishing spot of MRP-fluid, the final surface finish can be achieved after wear out almost all layers of roughness peaks by abrasion.



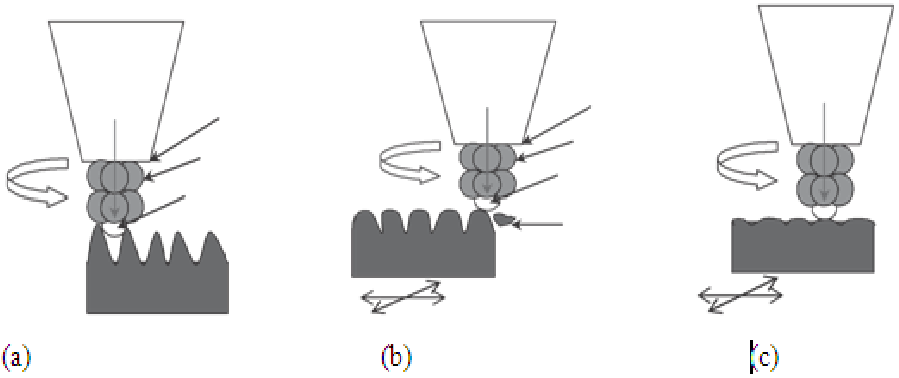


Fig.4.1.Mechanism of material removal in BEMRF process **(a)** Gripped active abrasive particle with CIPs chains approaching initial roughness peaks of theworkpiece surface **(b)** Updated roughness peaks after removing the first layer in the form of microchips **(c)** Final roughness peaks after removing the almost all its layers in the form of micro-chips

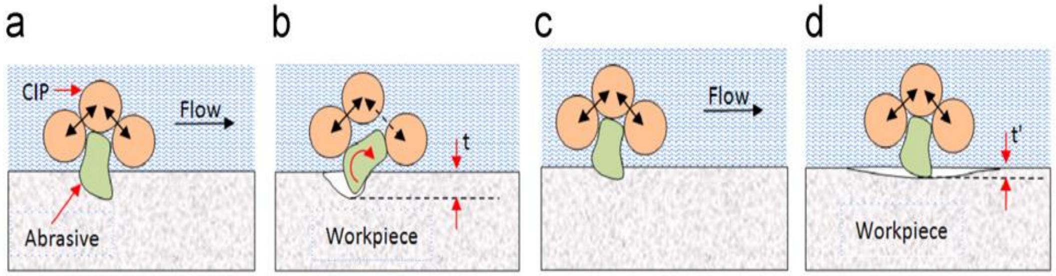


Fig 4.2. Mechanism of material removal in the case of (a) Big indentation, (b) Roll over the abrasive particle, (c) Small indentation, and (d) Continuous material removal

4.2. Experiment Conducted on BEMRF Tool

A novel Ball End Magnetorheological Finishing (BEMRF) process can be used for finishing of flat as well as 3D surfaces of ferromagnetic and non ferromagnetic work pieces. In this process a magnetically controlled ball end shape of MR polishing fluid is formed at the tip of the tool which is used for finishing the work-piece surface and a computer controlled program guides it to follow the surface to be finished. The smart behaviour of MRP- fluid precisely controls the finishing forces and hence the final surface finish.

The design requirements in BEMRF process like a ball end shape of MR polishing fluid is required to form at the tip surface of the tool for finishing of flat surfaces. This was used as a finishing segment and 3-axis computer controlled program guides it to follow the surface to be finished. This tool was named as magnetorheological (MR) finishing tool. The schematic diagram of MR finishing tool is shown in Fig.4.3.

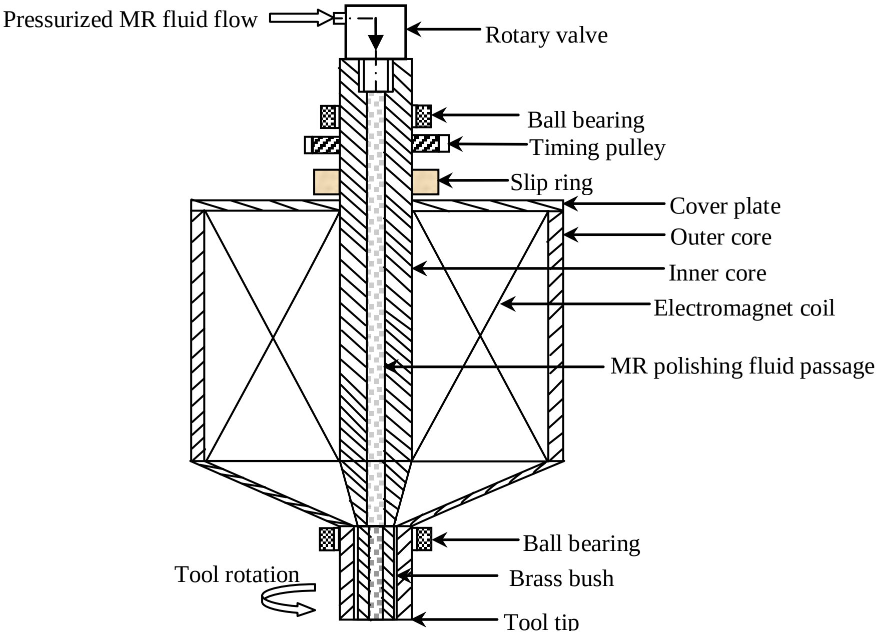


Fig.4.3. Schematic diagram of MR finishing tool [37]

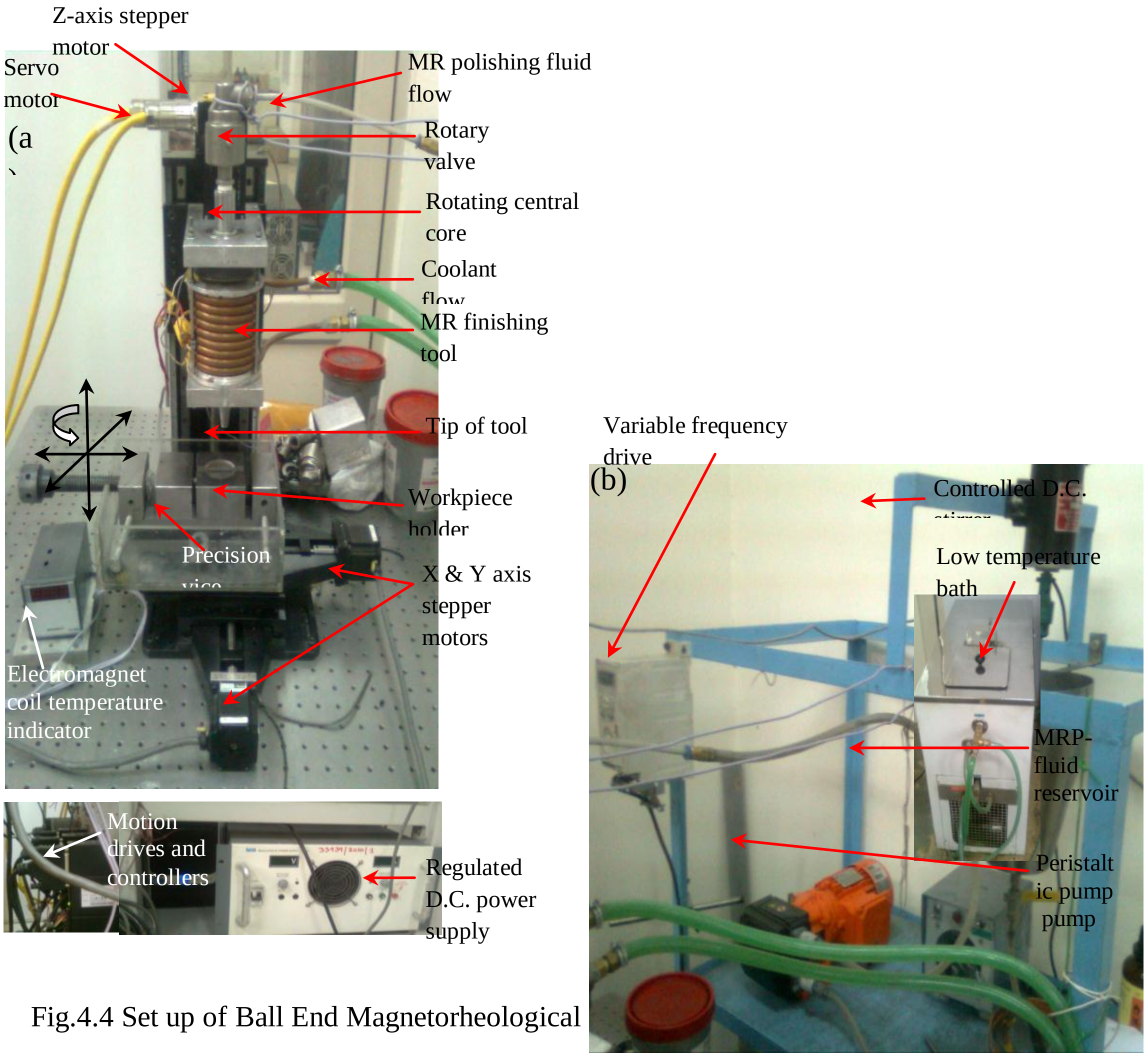


Fig.4.4 Set up of Ball End Magnetorheological

Now, the experiments has been conducted with unbounded magnetic abrasives based MRP fluid (S_1) and bonded magnetic abrasive particles based MRP fluid (Sample2) at current of 5.7A,0.7 mm working gap and 10 mm/min feed rate of the work-piece. Initial surface roughness before the experiments and final surface roughness after conducting the experiments has been measured with the help of Talysurf at 4 mm data length and 0.25 mm cut off length.

Chapter 5

RESULT ANALYSIS AND DISCUSSION

The magnetorheological characterization results show that the yield shear stress as well as ultimate shear stress and viscosity of synthesized bonded magnetic abrasive particles based MRP fluid sample (S_2) have been found more as compared to unbounded magnetic abrasives based MRP fluid sample (S_1) at all current level in the entire range of shear rate. It is due to the reason that the magnetic abrasive particles obtained by sintering process held firmly with each other in the presence of magnetic field because magnetic abrasive particles and surrounding particles are magnetic in nature.

The experiments have been conducted on BEMRF tool with both types of MRP fluid samples at same machining conditions. The percentage reduction in surface roughness ($\%\Delta R_a$) has been calculated after conducting the experiments as shown in table 5.1.

Table 5.1- Initial and final roughness value and $\%\Delta R_a$

Sample No.	Initial surface roughness	Final surface roughness	$\%\Delta R_a$
Unbonded magnetic abrasives based (S_1)	$R_a = 0.172$ µm $R_q = 0.235$ µm $R_z = 1.84$ µm	$R_a = 0.0963$ µm $R_q = 0.131$ µm $R_z = 1.43$ µm	44.01 44.26 22.28
Bonded magnetic abrasive particles based (S_2)	$R_a = 0.138$ µm $R_q = 0.18$ µm $R_z = 0.96$ µm	$R_a = 0.0605$ µm $R_q = 0.079$ µm $R_z = 0.76$ µm	56.15 56.11 20.83

The profile of surface roughness before and after finishing with both samples has been shown below in fig. 5.1 and fig. 5.2 respectively.

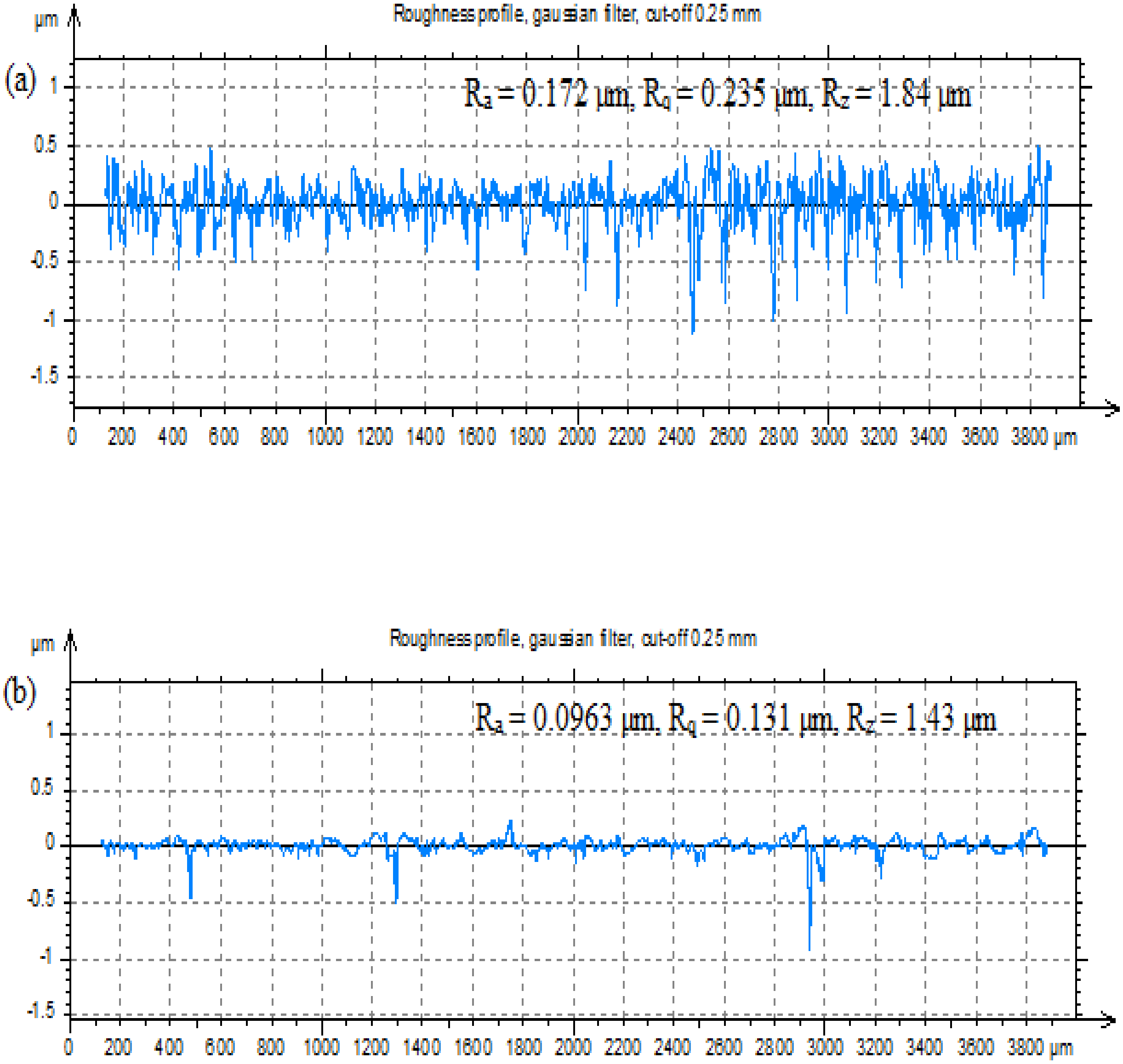


Fig. 5.1: (a) Initial surface roughness (b) final surface roughness after finishing with sample S_1.

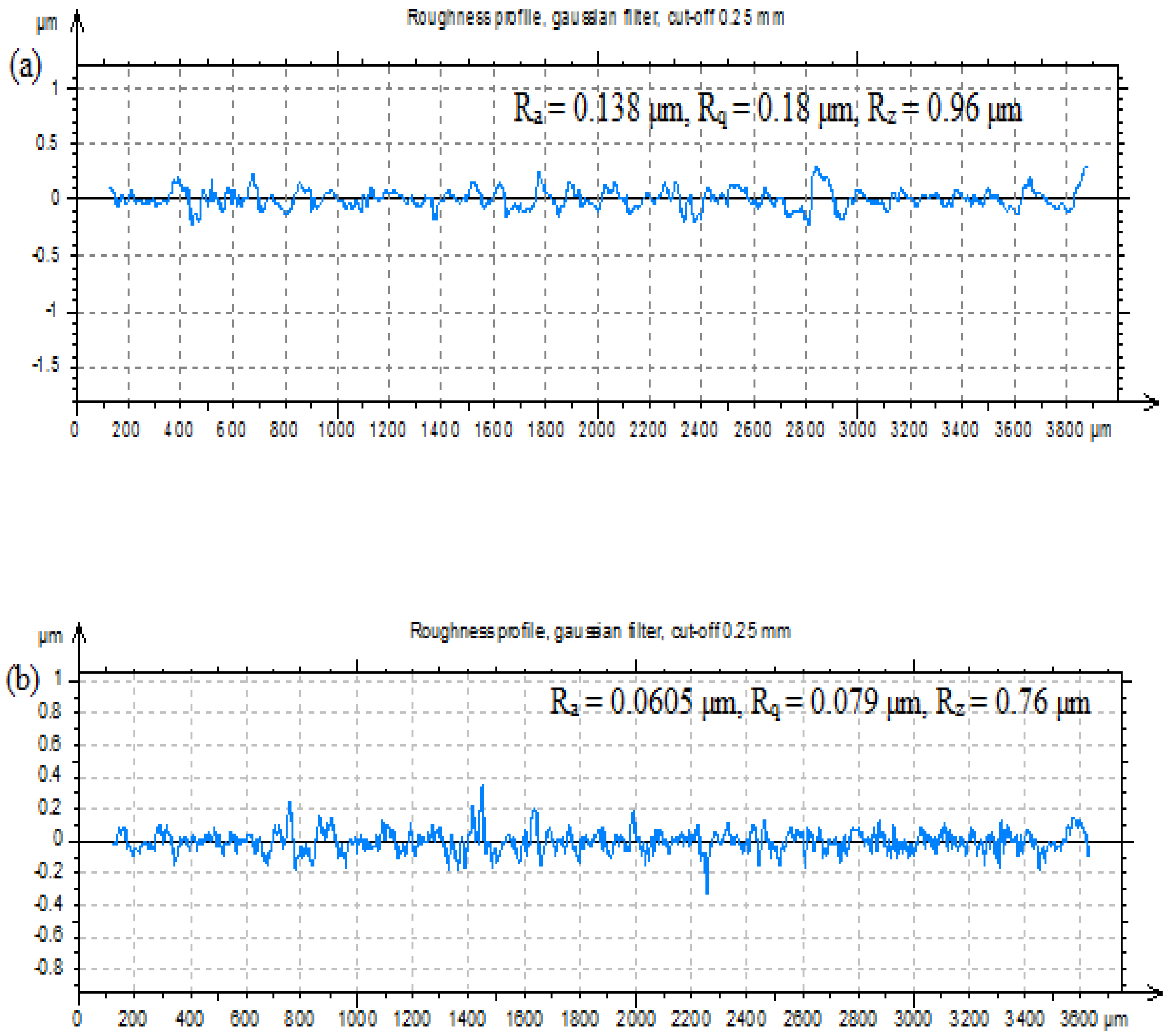


Fig. 5.2: (a) Initial surface roughness (b) Final surface roughness after finishing with sample S_2.

The results show that the percentage reduction in surface roughness ($\%\Delta R_a$) was found better by finishing the work-piece surface with synthesized bonded magnetic abrasive particles (MAPs) based MRP fluid (S_2) as compare to finishing with unbounded magnetic abrasives based MRP fluid (S_1) at same machining conditions. This shows that bonded magnetic abrasive particles impart more shear stresss on the work-piece surface and shear off work-piece material more quickly as compared to unbonded magnetic abrasives during MR finishing. It is due to the fact that the magnetic abrasive particles obtained by sintering process are held more firmly with respect to unbounded magnetic abrasives because bonded abrasives are surrounded in the magnetic particles environment. Secondly, bonded magnetic abrasive particles wear out the material from work-piece surface on the principle based on two body wear mechanism in which one body is magnetic abrasive particle and another body is work-piece surface.

CONCLUSION AND FUTURE SCOPE

The following conclusions are drawn after the magnetorheological characterization of both types of MRP fluid and experimental analysis on BEMRF tool.

1. The magnetorheological characterization results show that the yield shear stress as well as ultimate shear stress and viscosity of synthesized bonded magnetic abrasive particles (MAPs) based MRP fluid sample (S_2) have been found more as compared to unbounded magnetic abrasives based MRP fluid sample (S_1) at all current level.
2. The results show that the percentage reduction in surface roughness ($\%\Delta R_a$) was found better by finishing the work-piece surface with synthesized bonded magnetic abrasive particles (MAPs) based MRP fluid sample(S_2) as compare to finishing with unbounded magnetic abrasives based MRP fluid sample (S_1). This shows that bonded magnetic abrasive particles impart more shear stresss on the work-piece surface during finishing and shear off work-piece material more quickly as compared to unbonded magnetic abrasives based MR finishing.

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