# Synthesis and Characterization of Magnetorheological Fluids

**Anil Kumar, Neeraj Kumar, M. S. Niranjan**

***Abstract:*** ***Magnetorheological fluids (MRF) are mixture of ferromagnetic micron sized particles in silicon or hydraulic oil carrier fluid. By application of external varying strength magnetic field various physical properties of these fluids can be controlled and they becomes semi-solids depending on magnetic field strength application.MR fluids fulfill the desired performance requirements i.e. on application of magnetic field exhibits high shear and low initial viscosity, quick response , low hysteresis, low power consumption and temperature stability These special properties of MR fluids made them suitable for many type of industrial applications including machining. Hence fluids can be very effectively used in magnetorheological finishing process (MRF) which has unique feature of finishing truncated and complicated geometrical shapes and surfaces and capable of producing surface in nanometers. As surface finish is an important parameter in precision fits, product quality, and high-strength applications. The three dimensional surfaces finishing works such as different angled deep pockets or projections. Many industries have this type of i.e. mould & dies manufacturing, automobiles manufacturing, aerospace industry, semiconductor machining and optics machining etc. Such application leads to enhanced demand of nano-finishing of 3D surfaces without damaging surfaces/sub-surfaces. As due to change in properties because of change in composition the MR effect is also influenced. Therefore the composition of MR fluids is very important to achieve desired MR effect. The composition of magnetorheological fluids can be evaluated with the help of characterizations and desire MR fluid can be synthesized according to requirements of the process. This paper will explain in detail how we can synthesize and characterize the Magnetorheological fluids using state of the art equipments and can optimize their performance.***

***Keywords: Magnetorheological, Nano-Particles, M R fluids, Carbonyl Iron Powder, Rheological Properties, SEM, VSM, Rheometer etc.***

## I. INTRODUCTION

The materials having nano-scale size of particles in the range of 1 to 100 nm are generally referred as nano-materials. The properties of these materials are very much depends on their size of particles, with change in their particle size and physical properties also get changed significantly. For example the binding force in magnetorheological materials also gets changed when their catalytic capabilities and surface reactivity gets changed. These properties can be enhanced or reduced according to the requirements of the process. The surface chemistry of nano-scale particles differs from micro-particles. As more than 50 % ions or atoms present on the surface in nano-scale materials, hence it allows variation and control of bulk properties based on surface effects. Further due to controlled surface structure it leads to improvement in behavior of nano-particles as most of the time material failure occurs on material surfaces [3].

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### A. Magnetorheological Fluid and M R Effect Mechanism

Magnetorheology is the branch of science which study the flow behavior and deformation of material on application of magnetic field. MR fluid was invented in 1949 by Jacob Rabinow [10], whose rheological conduct can be controlled by external application of magnetic field. Magnetorheological Fluids (MR fluids) are mixture of magnetic particles, abrasive particles, carrier fluid and stabilizing chemicals which act as main element in MR finishing process. MR fluids are a special category of intelligent materials whose rheological conduct such as evidential viscosity and shear stress varies with variation in applied strength of magnetic field. The evidential viscosity changes very fast ($10^5$-$10^6$ times) with application of magnetic field and these changes gets reversed completely on removal of applied magnetic field. The Magnetic particles and abrasives particles are unevenly spread when the magnetic field is not present. These particles form a columnar structure like stable chain with application of external magnetic field as shown in fig 1. The magnetic forces between abrasives encompassing iron particles provide bonding strength. The magnitude of this bonding strength is a function of concentration of iron, intensity of magnetic field, particle size and particle's magnetic permeability. The magnetic field strength directly influences the dipole moment acquired by the particles. When the kinetic energy of particles is less than their inter-particle dipolar interaction, particles starts making multiple dipoles chains which are line-up with magnetic field direction. [11].

### B. Magnetorheological Finishing

Magnetorheological (MR) finishing is a cutting-edge machining process to machine without damaging work-piece surface or sub-layers.

The cutting forces in this process, are accurately controlled by external application of magnetic field and preset desired removal of material can be achieved which also help to obtain precise tolerances during machining which is an essential criteria for nano level finishing of work-piece.

On abrasives the cutting forces present in this cutting process (approximately $1 \times 10^{-7}$ N) are comparatively very less as compared to traditional polishing methods

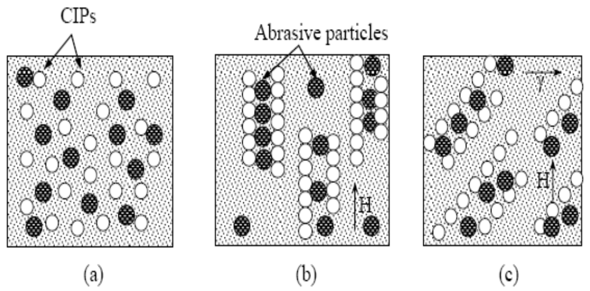


**Fig 1.Magneto Rheological Fluid particles layout when**
**(a) Magnetic field is absent**
**(b) H strength of magnetic field applied**
**(c) H magnetic field & shear strain applied**

($5–200 \times 10^{-3}$ N) **[3]**. The process is used for finishing variety of surfaces such as flat, concave, convex and aspherical optical components [3**].** Magnetorheological fluid (MRF) develops non-permanent finishing layer , whose rigidness can be controlled and influenced instantly by varying strength of magnetic field applied. The work-piece is attached at fixed distance from moving wheel and magnetic field is produced by electromagnet which is placed below the wheel surface. When MRP fluid is supplied to the wheel, and the magnetic field pull the fluid towards the wheel and it starts working as a polishing tool. The preset computer program is used to change position of work-piece as it sweeps through polishing zone. Machining takes place on the surface and tips of surface asperities are abraded due to plastic deformation caused by stress concentration. There are many advantages of MRF as it is a well-controlled finishing process, Surface finish can be obtained in nano-meters, the location of abrasion & intensity control is possible, can generate uniform, predictable and repeatable results on large range of finishing operations, give job flexibility and jobs can be finished in few minutes otherwise which requires hours of highly skilled hand polishing, it is very suitable for highly precision hard material components used in various industries. The improvement in surface finish of moving components helps in reduction of friction and increase the lifespan of such components.

## II. M R FLUID SYNTHESIS

The formation of M R fluids depends on the application requirements but M R fluids generally contain the following basic components:-

a) **Liquid Carrier** : - Mineral Oil, Silicone Oil, Synthetic Hydrocarbon Oil, Water, Glycol Thiophosphate etc.

b) **Magnetic Particles** : - Carbonyl Iron Powder, Electrolytic Iron Powder, Cobalt Alloys, Nickel Alloys etc.

c) **Additives** : - Grease, Lithium Stearate, Ferrous Oleate, Aerosil 200 and297, Arsil 1100, Arabic gum etc.

d) **Surfactants** : - Oleic Acid, Ammonium Hydroxide, Tetra methyl, Citric Acid etc.

### (A) M R Fluid Component Selection Criteria

As due to change in properties because of change in composition the MR effect is also influenced. Therefore the composition of MR fluids is very important to achieve desired MR effect. Some desirable base fluid properties of Magnetorheological fluids are as detailed below:

(1) With abrasive particles and Magnetic materials base fluids should be non-reactive and non-corrosive.

(2) It is desirable that fluid should have high boiling point ( B.P.) and high temperature stability.

(3) Base fluid should be easily available and should be inexpensive.

(4) Due to change in temperature the viscosity should not vary beyond pre-determined range.

Following factors may be kept in mind while selecting constituents of MR fluids:

### i. M R Fluid Carrier Liquids

In composition of Magneto rheological fluids (MR Fluids) carrier / base liquid is the main component (50-80 per cent by volume). The carrier fluid viscosity should be least dependent on temperature so that high MRF achieved [9]. The commonly used carrier liquids are:

*a) Synthetic And Mineral Oil*

In mineral oils the rate at which viscosity changes with change in temperature is more. Hence for low temperature applications, a mineral oil as a carrier fluid is limited. Synthetic oil posses some important properties like higher flash point, lower friction, do not thicken at high temperatures, high viscosity index and high shear strength [9].

*b) Silicone Oil*

Silicone oil has good heat-transfer characteristics, oxidation resistance, high flash points, very low vapour pressure and good temperature-stability. But sealing of Silicone oil is very difficult. Over a wide temperature span there is little change in physical properties and from -40 to 204°C temperature range it gives a relative flat viscosity temperature slope and serviceability [9].

### ii. M R Fluid Magnetic Particles

The attainable force increases as the size of magnetic particle increases, but due this off state viscosity of MR fluid also increases. Usually the dimension of magnetic particles is about 1μm to 10μm [15]. The mass presence of magnetic particles may be up to fifty percentage in base fluid [9]. The other desirable properties required in a MR fluid are high saturation magnetization, high Permeability, Low coercivity, small reminance and small hysteresis loop. [9]. Carbonyl iron particles (CIP) must be chemically pure, meso-scale and aspherical in shape in order to eliminate the shape distortions. The relation between induced magnetization in a magnetic material (M) & applied magnetic field (H) can be ascertained using a hysteresis loop as shown in fig.2.

The amount of residual magnetic field retained by any magnetic material after magnetic field is removed after arriving at saturation is called as the retentivity of that material [15].

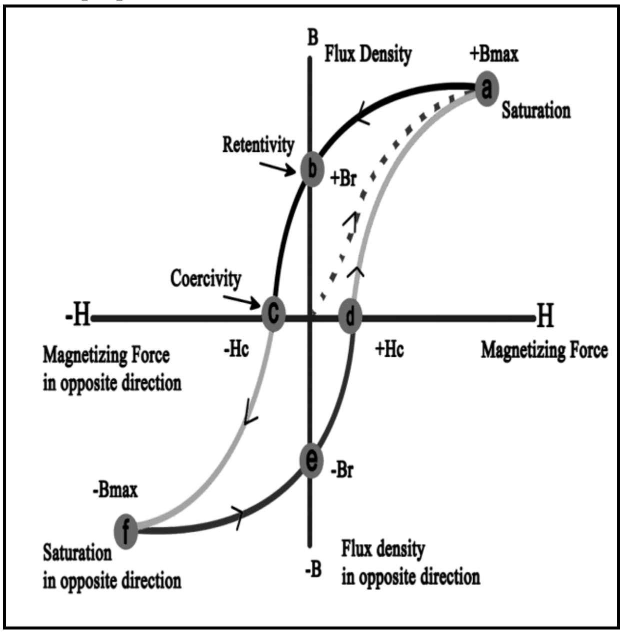


**Fig.2 M-H Curve**

In order to reduce the magnetic field to zero the amount of reverse magnetic field needs be applied to a magnetic material is also called the coercive Force. How easily magnetic flux can be induced in a material is called as Permeability. Whereas it's reciprocal that is opposition of a ferromagnetic material for setting up of induced magnetic field in it is called reluctance. Low coercivity and retentivity, high permeability, high saturation magnetization, high electrical resistivity and small remnance are the desired magnetic properties of M R fluids [15].

### iii. M R Fluid Additives

High stability in MR fluids can be achieved by using suitable additives. Grease, ferrous napthanate, ferrous oleate etc can be used as dispersants as their viscosity is very high, sodium stearate, Lithium stearate etc are used as thixotropic additives. In order to avoid the contact between CI particles, they are coated with materials such as Gaur-gum, polystyrene etc which will reduce the density of CI particles and enhance stability against the sedimentation [9].

### iv. Bidisperse Fluids

The Conventional M R fluids are mixture of ferromagnetic micron sized particles in silicon or hydraulic oil carrier fluid. In Bidisperse fluids are prepared while adding two different sizes of M R suspension particles in carrier fluid. Here the M R fluid may be containing micron-sized and nanometer-sized suspension particles in carrier fluid. The advantage of such nanometer sized particle bidisperse fluids is that it reduces the settling rate of M R fluids, as pores in between the large sizes particles are filled by the small nanometer sized particles which results during sluggish flow reduction in fluid transport. While the adverse effect of adding nanometer sized particles in bi-disperse M R fluids is that the high yield stress production capacity at its magnetic saturation point is also gets reduced. Hence too much quantity of nanometer sized particles addition in MR fluids is not recommended.

## III. CHARACTERIZATION OF M R FLUID COMPONENTS

The commonly used devices for characterization of MRF samples are Rheometer, Scanning Electron Microscope (SEM) & Vibrating Sample Magnetometer (VSM). Rheological measurements is carried out using Parallel Plate Rheometer the measurements includes determination of viscosity, yield stress and shear rates. Scanning Electron Microscope (SEM) is used to determine the morphological state of the samples. Vibrating Sample Magnetometer (VSM) is used to determine magnetic saturation (Ms), permeability, coercivity (Hci) and retentivity (Mr) etc magnetic properties of samples. The results so obtained then can be discussed in context of the surface finishing application. It should also include correlating the different MR fluid component's suitability according to desired surface finishing requirements [14].

### A.Measurement Of M R Fluid Magnetic Properties

The magnetic properties of CI powders are determined by using Vibrating Sample Magnetometer (VSM) as shown in Fig. 3.

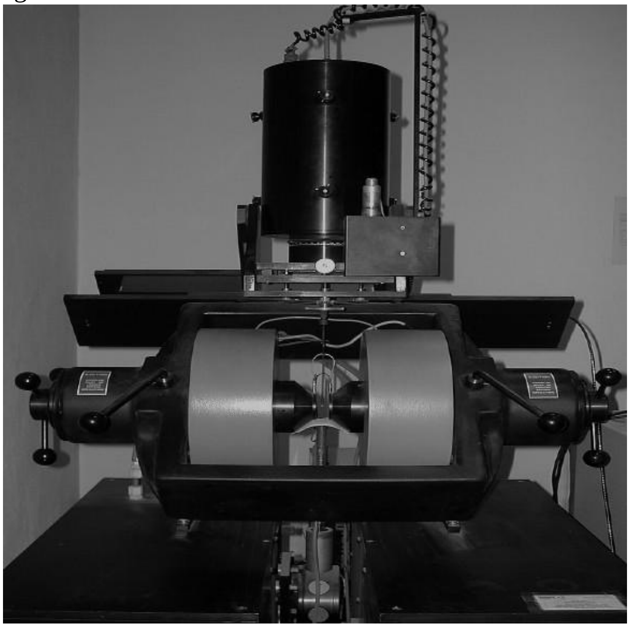

**Fig.3 (a) Vibrating Sample Magnetometer (VSM)**

A magnetic particle's cylindrical sample is prepared and placed between strong magnetic coils of VSM. When this sample is subjected to mechanical vibrations under a constant magnetic field, then as a result of this voltage is induced in the pickup coils, the induced voltage is directly proportional to the material's magnetic moment [14]. Thus by knowing different magnetic properties i.e. coercivity, saturation magnetization, retentivity, etc. we can draw hysteresis (M H) curve for the sample material.

*i. Measurements Using Rheometer*

A Rheometer is a very useful device to determine various important properties of MR

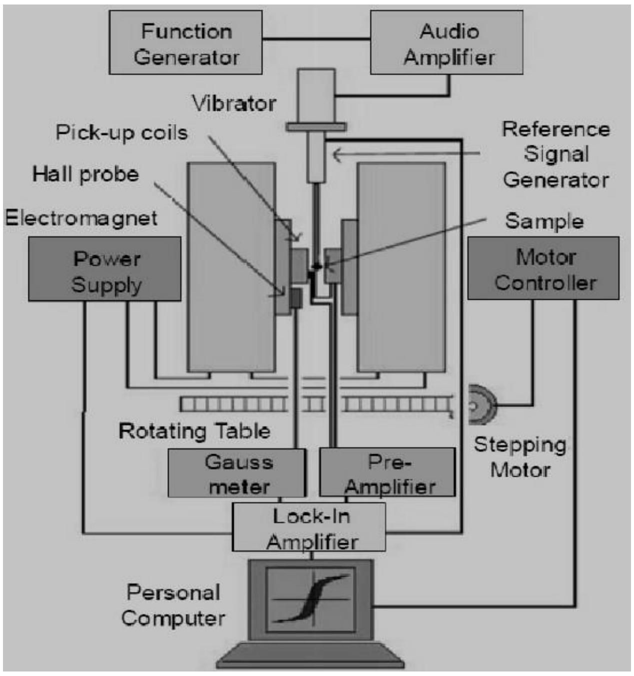


**Fig.3 (b) Schematic Diagram of the phenomenon used by (VSM)**

fluids. A schematic diagram and picture of an actual Rheometer is given in fig.4. As shown in figure this device has five main parts: MR fluid sample fixture, Circuit for electromagnet, compression load cell, a mechanical system for inputs and data accession. The MR fluid sample fixture consisted of two plates placed parallel to each other. By movement of lower plate which is connected to a motor which provides movement linearly to the lower plate, the size of the gap between these two plates can be increased or decreased with the help of this motor. Further in order to observe the lower plate movement an optical laser sensor is used so that a preset gap can be maintained during the test. The D.C. servo motor produces the shear actions. The speed of motor is measure using an optical encoder. An electromagnet of about 10 mT to 1 T capacity is produced using a 3500 turns coil when the radius of magnetic pole is 20 mm. Magnetic field (B-field) strength is determined using a magneto-meter. The probe of this magneto-meter is pushed in the gap between the upper plate and upper pole directly to determine the actual strength of magnetic field. The normal force generated in MR fluid due to excitation is determined with the help of compression load cell which is fitted below the lower plate shaft. The signals generated by load cell and motor encoder are received by the data accession units and the same is stored in a computer for further use [1].

*ii. Measurements Using SEM*

A scanning Electron Microscope popularly known as SEM is a very useful device used to study the surface details of a sample material [14]. In this device the material sample is subjected to a beam of heavy energy electrons and the electrons out-put produced after striking the sample material surface is used for analysis to draw the conclusions about the surface features of the sample material which includes material composition, surface topography, direction and layout of grains, morphology, crystal size, shape and layout information etc. The topography shows the surface features of material i.e. its texture, roughness or smoothness. The Morphology indicates the size and shape of crystals of material. Similarly composition means compound and elements which constitute the material. The crystallography is details about the atom's arrangement in the materials. A detailed particles visual image with spatial resolution of 1 nm can be obtained using SEM and its can be used to magnify the particle size up to 3 X $10^5$ times.

**Fig. 4 (a) Rheometer with Magnetorheological device (MRD)**

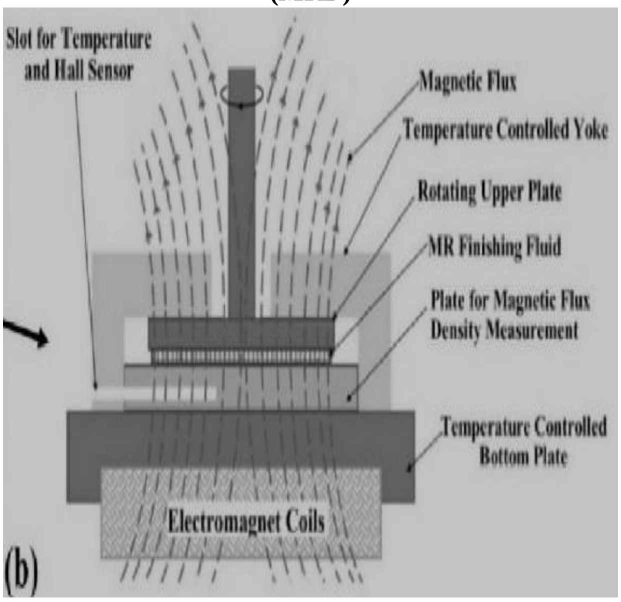


**Fig. 4 (b) the working principle of Rheometer**

The Scanning Electron Microscope is used only to observe images of sample's surface and no internal features of sample material can be obtained using this device.

This device is also widely used in determining that after modifying the sample surface, if any morphological particle changes have occurred. This device has following main Parts:-
(i) Electron emission gun
(ii) System for Vacuum generation
(iii) The Column which consists of scanning coil, condenser lenses, signal detector, objective lens, stag-motor etc.
The generation of beam of electrons is executed by the gun, this beam of electrons then travels in a vertical trajectory through vacuum and also passes through various lenses and pre-set electro-magnetic fields as detailed in Fig.5. The sample is subjected to a beam of electrons which is focused on sample with the help of objective lens. Over a specific sample the focused beam scans and with help of deflector coils the beam is manipulated by magnification in such a way that it covers full surface of the sample. The scan generator performs the function of controlling the deflector coil.

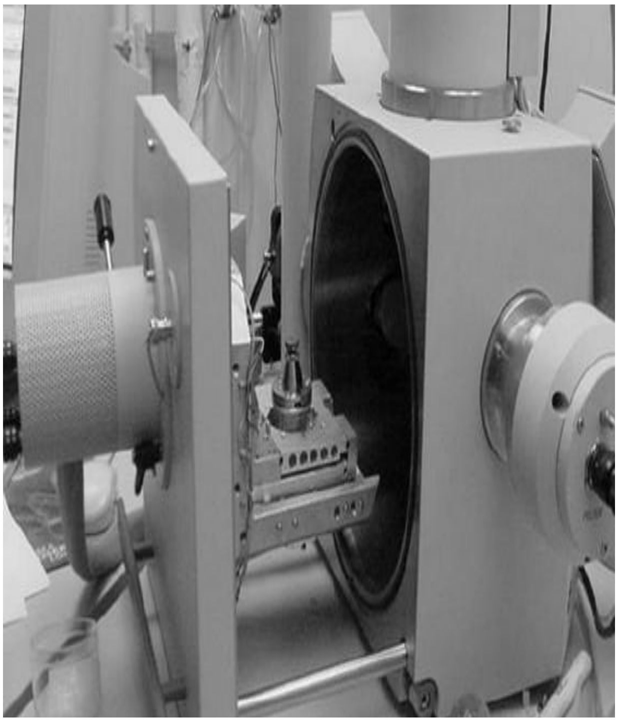

**Fig. 5 (a) Scanning Electron Microscope (SEM)**

Hence change in manipulation of pattern takes place as the magnification changes. Due to strike of electron beam on sample surface, it results in production of a number of signals. The detector detects these signals and converted these signals in such a way to enable them to produce an image of the sample's surface. Hence the signals produced by the sample provide information about the sample surface as texture, crystalline structure, chemical composition and material orientation of the sample. The SCM has a big advantage which allows focusing at a time more on more than one sample. The SEM also has better resolution which makes it possible that specimens placed very close to each other can be visualized by magnification at different levels. SEM is an instrument which is preferred in research activities due to ease of sample surveillance, enhanced magnification, superior resolution and bigger depth of focus.

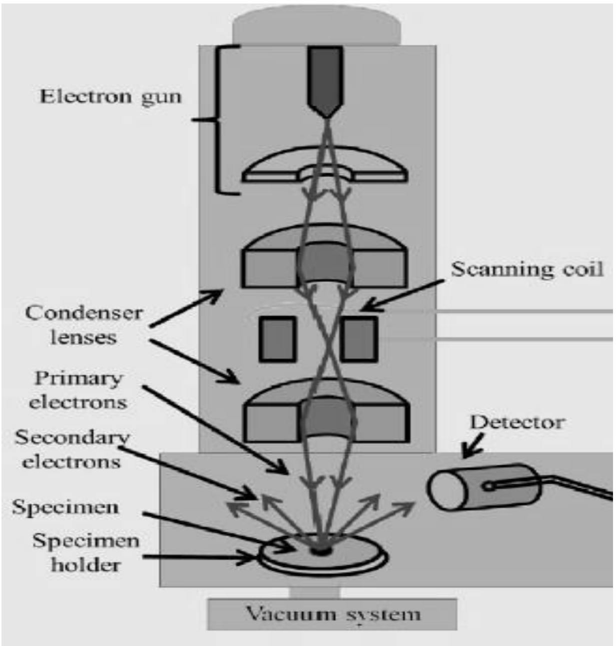


**Fig. 5(b) Working principle of SEM.**

*iii. Sedimentation Ratio calculation of M R fluids*

Desired Magnetorheological fluid composition can be achieved by wisely selection of its various components i.e. CI particles and the carrier fluid. In MRF sedimentation is un-wanted property .The measurement of sedimentation is done by the changing the boundary position between turbid and clear components of carrier fluid by observing the process visually. The MRF samples are kept for three days in test tube of glass which is cylindrical in shape (dia. 40 mm & length 0.5 m). After three days the length of turbid and clear part is measured with the help of measuring instrument to find out the sedimentation ratio ($S_R$). Sedimentation ratio can be expressed by the equation given below:
Sedimentation ratio (($S_R$) [%]
= [length of the clear part / length of the turbid part] *100

## IV. RESULTS AND DISCUSSION

1. The composition of Magneto rheological fluids (MR Fluids) carrier / base liquid is the main component (50-80 per cent by volume). The carrier fluid viscosity should be least dependent on temperature so that high MRF achieved. A carrier fluid should possess some desirable properties like good heat-transfer characteristics, oxidation resistance, higher flash point, lower friction, does not thicken at high temperatures, high viscosity index and high shear strength.
2. The advantage of such nanometer sized particle bi-disperse fluids is that it reduces the settling rate of M R fluids, as pores in between the large sizes particles are filled by the small nanometer sized particles which results during sluggish flow reduction in fluid transport. While the adverse effect of adding nanometer sized particles in bi-disperse M R fluids is that the high yield stress production capacity at its magnetic saturation point is also gets reduced. Hence too much quantity of nanometer sized particles addition in MR fluids is not recommended.

3. The commonly used devices for characterization of MRF samples are Rheometer, Scanning Electron Microscope (SEM) & Vibrating Sample Magnetometer (VSM). Rheological measurements is carried out using Parallel Plate Rheometer the measurement includes determination of viscosity, yield stress and shear rates. Scanning Electron Microscope (SEM) is used to determine the morphological state of the samples.

## V. CONCLUSIONS

1. Magneto rheological fluid (MRF) develops non-permanent finishing layer, whose rigidness can be controlled and influenced in instantly by varying strength of magnetic field applied. There are many advantages of MRF as it is a well-controlled finishing process, Surface finish can be obtained in nano-meters, the location of abrasion & intensity control is possible, can generate uniform, predictable and repeatable results on large range of finishing operations, give job flexibility and jobs can be finished very fast.
2. The quality of machined surface is depending on composition of MR Fluids. As the due to change in properties because of change in composition the MR effect is also influenced. Therefore the composition of MR fluids is very important to achieve desired MR effect.
3. The testing of MRF rheological properties is very important as it help us to know its flow behavior for which the most significant parameter is volume percentage of iron particles in MRF which contribute about 91 % to affect the viscosity & yield stress of MRF.
4. Rheological measurements is carried out using Parallel Plate Rheometer the measurement includes determination of viscosity, yield stress and shear rates. Scanning Electron Microscope (SEM) is used to determine the the morphological state of the samples. Vibrating Sample Magnetometer (VSM) is used to determine magnetic saturation (Ms), permeability, coercivity (Hci) and retentivity (Mr) etc magnetic properties of samples.
5. After evaluation of all these important properties an optimized combination can be then synthesized to confirm the theoretical findings to achieve highest surface finish, without severe damage to work-piece surface and with minimum induced stress in work-piece due to machining.

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