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ORIGINAL ARTICLE

Rheological characterization of magnetorheological polishing fluid for MRAFF

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Abstract 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 rheological properties hence, bonding strength gained by abrasives through surrounding CIP chains varies. To study the effect of particle size on rheological properties of MRP fluid, a hydraulically driven specially designed capillary magnetorheometer was fabricated. The rheological properties of MRP fluids in the homogeneous magnetic field perpendicular to the shear flow direction are evaluated. The three constitutive models, viz. Bingham plastic, Herschel–Bulkley and Casson's fluid, are used to characterise the rheological behaviour of MRP fluid by fitting the rheological data obtained from capillary magnetorheometer and evaluating respective constants in their constitutive equations.

Keywords MRAFF · Magnetorheology · Bingham fluid · Hershel–Bulkley fluid · Casson's fluid · Capillary magnetorheometer

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Abbreviations

- τ fluid shear stress (Pa)
- τ_o magnetic-field-induced dynamic yield shear stress (Pa)
- η plastic viscosity of MR fluid (Pa^{-s})
- $\dot{\gamma}$ shear rate (s^{-1})

1 Introduction

In magnetorheological abrasive flow finishing (MRAFF), the magnetic-field-dependent yield stress and viscosity of magnetorheological polishing (MRP) fluid are controlled by controlling magnetising current in the electromagnet coils producing magnetic field across the finishing zone [1]. The MRP fluid comprises of carbonyl iron particles (CIPs) and very fine abrasives dispersed in viscoplastic base medium of mineral oil and grease, which exhibits unique reversible change in its rheological properties on the application and removal of external magnetic field. The carbonyl iron particles acquire magnetic dipole moment proportional to field strength and aggregate into interconnected chain-like columnar structure aligned in the field direction, embedding non-magnetic abrasive particles in between or within. The rheological characteristics and bonding strength gained by abrasive particles in presence of CIPs and magnetic field play an important role in MRAFF action. Therefore, to understand MRAFF mechanism, it is important to understand the rheological properties of synthesised MRP fluid compositions with different particle sizes at varying magnetic field strengths. This paper discusses the design and fabrication of capillary magnetorheometer, experimentation procedure and results of evaluation of the rheological properties of MRP fluid with different particle size of silicon carbide with CS grade CIPs at different magnetic flux density. It also deals with characterisation of MRP fluid using Bingham, Hershel–Bulkley and Casson's fluid models.

2 Magnetorheological polishing fluid

Magnetorheological (MR) fluids belong to a class of smart controllable materials invented in late 1940s by Rabinow [2] that respond to an applied magnetic field with a change in rheological behaviour. MR fluids are suspensions of micron-sized dispersed magnetic phase in a non-magnetic carrier continuous phase along with additives. MRP fluids used as finishing medium in MRAFF process are synthesised by mixing non-magnetic abrasive particles in specially prepared weak Bingham plastic MR fluid. The presence of non-magnetic abrasive particles in MRP fluid make its rheological behaviour different from pure MR fluid. In MRP fluid, the magnetic CIPs and abrasive particles are dispersed into viscoplastic base medium under low shear conditions. In the absence of a magnetic field, an ideal MRP fluid exhibits weak Bingham behaviour. On the application of an external magnetic field to a MR suspension, a phenomenon known as magnetorheological effect is observed [3]. The popular choice for magnetic disperse phase in MRP fluid is iron because it is the element with highest saturation magnetization ($\mu_o M_s$=2.1 T) [4]. High purity (>99.9%) iron powder prepared using decomposition of iron pentacarbonyl known as CIP are magnetically softer and are relatively inexpensive to suit for the synthesis of MRP fluids. Organic liquids are the preferred continuous phases for most MR fluid applications, except in MR fluids for optical polishing where water was used as the base fluid due to adsorption of organic liquids on optical surfaces. The desired properties of base fluid for MR fluid are as follows:

(a) The fluid should be temperature-stable and should have higher boiling point.
(b) It should be non-corrosive and non-reactive with magnetic and abrasive particles.
(c) The viscosity of base fluid should be temperature stable in a pre defined range.
(d) It should be less expensive and easily available.

The base fluids described in literature for preparation of MR fluids are silicone oils, kerosene, mineral oils, glycols and water. MR fluid should be stable and redispersible for any practical application. During storage or inactivity, the magnetic and abrasive particles in MRP fluid settle down and form very tight-knit sediment. Once formed, it is very difficult to redisperse them. To overcome this problem, researchers have used various additives such as fibrous carbon, silica, oleic acid and various polymers to achieve stability against settling and enhance redispersibility. Rankin et al. [5] made an attempt to prevent sedimentation of particles by experimentation with viscoplastic base prepared from mineral oil and grease. After their study, the viscoplastic medium could be used in MR suspensions to prevent sedimentation of particles without significantly affecting the MR response. One of the requirements is that the viscoplastic medium should have a large enough yield stress to prevent sedimentation, and at the same time, it should be small enough to ensure that medium does not hinder field-induced particle migration.

3 Rheological behaviour of MRP fluid

The rheological properties of smart controllable fluids such as electrorheological and MR fluids depend on concentration and density of particles, particle size and shape distribution, properties of the carrier fluid, additional additives, applied field, temperature and other factors [6]. The interdependency of all these factors is very complex yet important in establishing methodologies to optimise the performance of these fluids for finishing applications. In the 'off' state when there is no magnetic field, the MR fluids appear similar to liquid paints and exhibit comparable levels of apparent viscosity 0.1 to 1 Pa s^{-1} at low shear rates [7]. On the application of magnetic field, MR fluid undergoes considerable increase in static yield stress due to alignment of CIPs along the direction of magnetic field which results in rheological transition to Bingham plastic fluid. A shear stress or a pressure difference perpendicular to magnetic field direction is required to break this structure formed in MR fluids. The response time of this transition is about 10–20 ms depending on the magnetic circuit design of the system [8]. The experimental evidences have confirmed that MR fluids in the presence of a magnetic field exhibit both a pre-yield regime characterised by an elastic response and a post-yield regime characterised by a viscous response [9]. Since MR fluids typically operate in a continuous yield regime, they are usually characterised by their field-dependent yield stress. The steady shear rheological response of a MR fluid is typically described as a Bingham plastic fluid with a yield shear stress [10] as

$$\begin{aligned} &\tau = \tau_0 + \eta\dot{\gamma} \text{ for } \tau > \tau_0 \\ &\tau = 0 \text{ for } \tau \leq \tau_0 \end{aligned} \quad (1)$$

where τ is the fluid shear stress, τ_o is magnetic field induced dynamic yield shear stress, η is plastic viscosity of MR fluid and $\dot{\gamma}$ is shear rate (s^{-1}). The plastic viscosity of the medium is mostly governed by the base fluid. The field-induced shear stress τ_o depends on the magnetic field strength, H. The strength of the fluid (i.e. the value of static yield shear stress) increases as the applied magnetic field increases. However, this increase is nonlinear since the particles are ferromagnetic and magnetisations in different parts of the particles occur non-uniformly [11]. MR fluids exhibit dynamic field strength of 50–100 kPa for applied magnetic fields of 150–250 kA/m (~2–3 kOe) [12]. The ultimate strength of MR fluid is limited by magnetic saturation. MR fluids are inherently anisotropic; the yield stress will depend on relative orientation of the magnetic field and the direction of deformation.

Rheologically, the MR fluid exhibit viscoplastic behaviour which shows little or no deformation up to a certain level of stress, and it flows readily above this yield stress. Concentrated suspensions of solid particles in Newtonian liquids often shows yield stress followed by nearly Newtonian flow. These suspensions are called viscoplastic or Bingham plastic after E. C. Bingham. Ginder [13] reported that the MR fluids also exhibit shear thinning, i.e. possessing a decreasing apparent viscosity with increasing strain rate in all applied fields. The Herschel–Bulkley constitutive shear flow relationship (Eq. 2) accounts for this post-yield shear thinning behaviour. The pre-yield behaviour is rigid as in Bingham plastic model.

$$\tau = \tau_0 + K\dot{\gamma}^n \text{ for } \tau > \tau_0 \quad (2)$$

where the exponent, n, is called the flow behaviour index and K as consistency parameter. The Herschel–Bulkley model is found more suitable for MR fluids [14]. Casson [15] proposed an alternate model to describe the flow of viscoplastic fluids. A Casson fluid is defined as a shear thinning fluid which is assumed to have an infinite viscosity at zero rate of shear, a yield stress below which no flow occurs and a zero viscosity at an infinite rate of shear [16]. Casson's constitutive equation in time-independent shear flow is a nonlinear relation between shear stress and rate of strain [17], given by

$$\sqrt{\tau} = \sqrt{\tau_c} + \sqrt{\eta_c\dot{\gamma}} \text{ for } \tau > \tau_c \quad (3)$$

where τ_c denotes the yield stress and η_c denotes Casson's viscosity (viscosity at high shear rates). The nonlinear Casson's constitutive equation has been found to describe accurately the flow curves of the suspensions of pigments in lithographic varnishes used for preparation of printing inks and silicon suspensions. Jdayil et al. [18] accurately modelled plastic flow behaviour of electrorheological fluids using Casson's constitutive equations.

4 Rheological measurements of MRP fluid

Rheometer is an instrument that measures both stress and deformation history of the material for which constitutive relation is not known [19]. Researchers have developed a variety of apparatuses or customised available commercial rheometers with special magnetic field inductor and metrology attachments for measurement of yield stress and viscosity of MR fluids. To quote a few are parallel plate geometry by Lemaire and Bossis [20], concentric cylinder rheometer by Laun et al. [21], modified rotating cylinder type by Shorey et al. [22], modified cone plate type by Odenbach et al. [23], pressure-driven capillary by Dang et. al [24] and parallel plate rheometer by Chin et al. [25]. A good review and comparison was discussed by Laun et al. [21]. To use MRP fluid in MRAFF process, it is required to characterise the fluid properties quickly and easily. In particular, the determination of magnetic-field-induced yield stress and dynamic viscosity is important to study the flow behaviour and bonding strength imparted to abrasive particles by CIP chains during finishing. Despite the expanding interest and research in MR fluids, there is currently no commercial rheometer available for determining rheological properties of the MRP fluid. Researchers have modified the existing commercial rheometers or viscometers to allow incorporation of electromagnets in

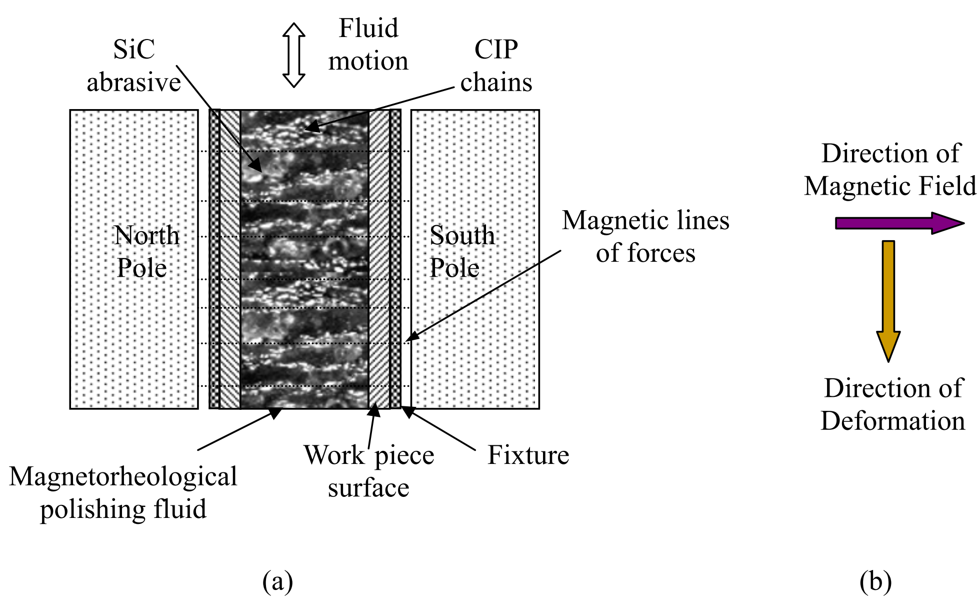
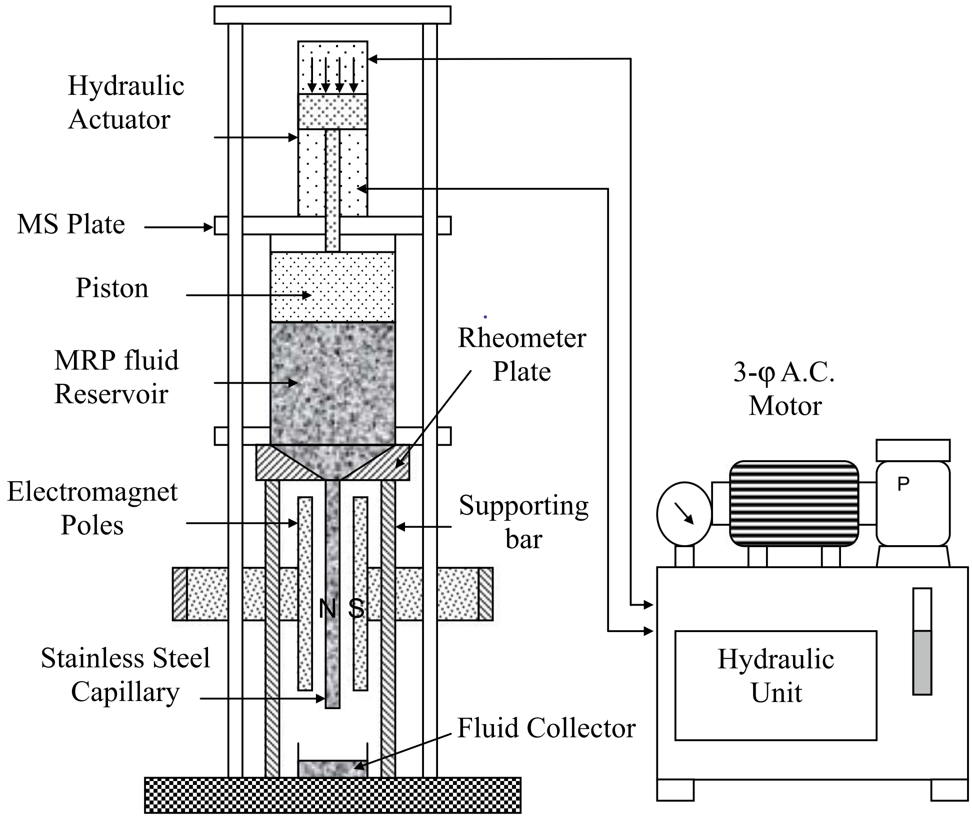
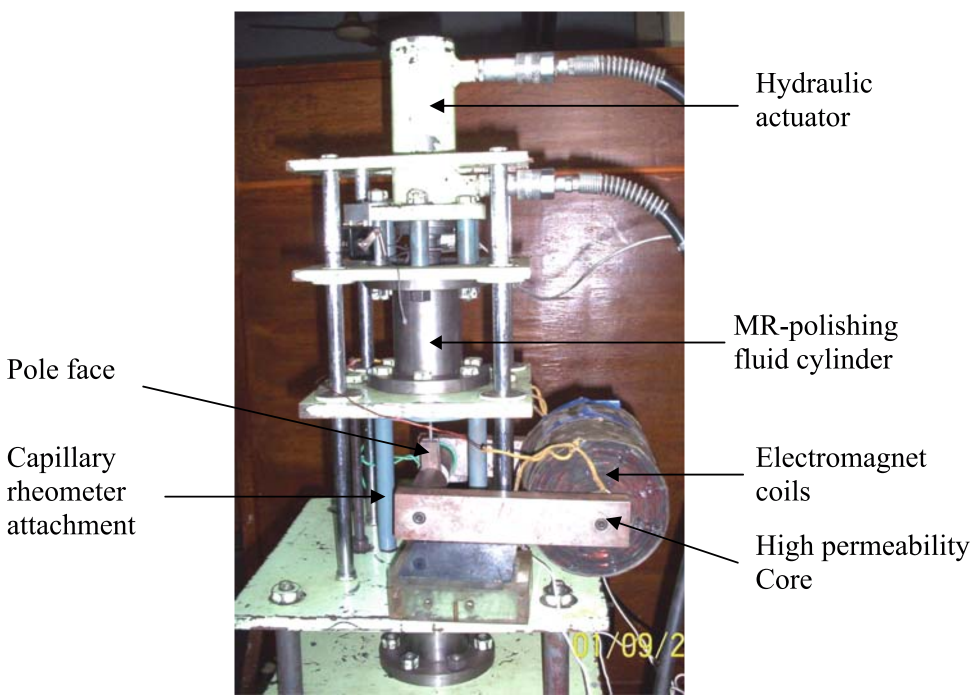


Fig. 1 Flow and field direction in MRAFF process showing actual photograph of MRP fluid (**a**) and capillary rheometer (**b**)

Fig. 2 Capillary magnetorheometer attachment mounted on MRAFF setup: **a** Schematic, **b** photograph



(a)



(b)

Table 1 Properties of carbonyl iron powder (BASF)

Grade	Physical	Composition (%)		Particle size distribution		
				d_{10} (μm)	d_{50} (μm)	d_{90} (μm)
CS	Mechanically soft	Iron	>99.5	3.5	6.0	18.0
		Carbon	<0.05			
		Oxygen	0.2			
		Nitrogen	<0.01			

sample shearing zone. The modifications typically involve constructing fixtures of low carbon steel and adding a wire coil or electromagnet to deliver a variable magnetic field to the sample. Unfortunately, many modifications reported in literature are complex and time-consuming. At the same time, presence of abrasives in MRP fluid poses a high risk for the rheometer's life. Keeping in view all these constraints, a pressure-driven capillary magnetorheometer was designed and fabricated with the following advantages as discussed in the following section:

(a) Similarity with MRP fluid flow in MRAFF. As shown in Fig. 1, the direction of fluid deformation is perpendicular to magnetic field in MRAFF setup and capillary rheometer.
(b) Presence of abrasives in polishing fluid damage the surface of commercially available rheometer.
(c) High yield stress of MRP fluid in magnetic field.
(d) Simple in construction and accurate for steady viscosity measurements.

5 Design of a capillary magnetorheometer

Rheometer design involves measurement of the quantities like force, torque, pressure and angular velocity depending on the type and then conversion of these quantities to stress and strain on the sample. The stress and strain data on fluid allow determination of rheological material functions which are needed to evaluate the parameters in the constitutive equation. Van Wazer et. al. [26] reviewed many rheometer designs and explained their working principle. Capillary

Table 2 Silicon carbide abrasives particle size

S. no.	Mesh size	Avg. particle diameter (μm)
1	800	19.0
2	1,000	15.2
3	1,200	12.67
4	1,500	10.13

Table 3 Magnetorheological polishing fluid: compositions

Constituent	% Volume concentration
Carbonyl iron powder	20
Silicon carbide	20
Base medium	60

rheometer is a pressure-driven type which has two basic designs:

1. controlled drive pressure and measurement of flow rate and
2. controlled flow rate and measurement of pressure drop.

Pressure can be controlled by a hydrostatic head, external compressed gas, dead weight or hydraulic pressure. Flow rate can be controlled by motion of a driving piston. A typical design of a capillary rheometer for high yield stress fluids consists of a piston controlled by a ball screw drive or by gas or hydraulic pressure. There is wall slip with concentrated dispersions. The aspect ratio L/R, where L is the length of capillary under influence of magnetic field and R is the radius of capillary tube, should be approximately 60 for capillary rheometer [19]. The rheometer design for magnetorheological polishing fluid needs special attention due to application of magnetic field across capillary and presence of abrasive particles in the fluid. First design of capillary magnetorheometer was based on the design by Dang et al. [24] using compressed air. As the yield stress of MRP fluid is high enough to initiate the flow under gravity, it was planned to use the compressed air for the same. All the materials used in the construction of rheometer were nonmagnetic. Base and rheometer body were made from aluminium, and stainless steel capillaries were used for flow during measurement. To improve accuracy of the instrument, a digital pressure gauge with accuracy of 0.01 MPa was used to measure the pressure in the cylindrical rheometer fluid reservoir. The maximum pressure of the compressed air available and safe for use was 1.0 MPa. This rheometer design worked for MRP fluid with very low volume concentration of CIPs. The actual MRP fluid used for finishing had 20 vol.% each CIP and abrasives and need very high pressure to extrude through capillary in the presence of

Table 4 Magnetorheological polishing fluid: compositions: types

S. no.	Name	CIP Grade	SiC mesh size
1	MRPF-20CS-20SiC800	CS	800
2	MRPF-20CS-20SiC1000	CS	1000
3	MRPF-20CS-20SiC1200	CS	1200
4	MRPF-20CS-20SiC1500	CS	1500

magnetic field. Such high pressure cannot be obtained from compressed air. Therefore, to measure rheological properties of actual MRP fluid, a modified design was made using hydraulically driven piston in fluid reservoir. Second design which was used to conduct rheological experiments consists of the following main components:

(a) MRP fluid reservoir—volume=130 cm^3;
(b) stainless steel capillary—radius=1.9 mm, length=102 mm;
(c) hydraulic actuator;
(d) Hydraulic system—constant pressure; and
(e) Electromagnet.

The design used the MRAFF experimental setup with add-on capillary attachment. Figure 2 shows the schematic of the rheometer setup. Before starting experiments, the MRP fluid of known composition is filled inside the MRP fluid cylinder of MRAFF setup, here acting as fluid reservoir. The rheometer plate with stainless steel capillary of diameter 1.9 mm and length 140 mm is then fixed at the bottom of reservoir with the help of two supporting bars. Hydraulic pressure on MRP fluid reservoir is maintained with the help of a constant pressure hydraulic unit. The friction between piston and walls of MR fluid reservoir is taken in to account by subtracting friction pressure from the hydraulic pressure applied in calculating shear stress. Friction pressure is estimated by applying hydraulic pressure in absence of MR polishing fluid and observing the pressure required to start piston movement. The pressure before experiment is adjusted with the help of a lever on variable delivery pump and measured from the pressure gauge mounted on the system. To evaluate rheological properties of MRP fluid, the fluid was forced through a fine capillary, and the viscosity and yield shear stress were determined from the measured volumetric flow rate, applied pressure and the capillary dimensions.

6 Rheological experiments

Experiments were conducted to evaluate the rheological properties of MRP fluid with carbonyl iron CS grade and different particle sizes of SiC under different magnetic field strength. The MRP fluids prepared from CIP-CS (Table 1) and four different mesh sizes of silicon carbide abrasives (Table 2) as per composition mentioned in Table 3 are summarised in Table 4. MRP fluid with 20 vol.% carbonyl iron powder, 20 vol.% silicon carbide abrasive powder and 60 vol.% of viscoplastic base medium (20 wt.% AP3 grease and 80 wt.% paraffin liquid heavy) was prepared by uniformly mixing abrasives and carbonyl iron particles into continuous phase (grease + oil) and stirring with the help of specially designed multiple blade mixer for 1 h. Stopwatch is used for measuring the flow time to calculate flow rate for each measurement after steady-state flow is observed. To calculate yield stress and viscosity, flow rate is calculated against various pressures for a particular fluid and magnetic field strength. The magnetising current for different magnetic field strength is given in Table 5.

Table 5 Magnetising current in electromagnet coils and field produced

Magnetising current (A)	Magnetic field strength (G)
0.9	1,500
1.6	1,750
2.4	2,000

7 Results and discussions

The three constitutive models, viz. Bingham plastic (BP), Herschel–Bulkley (HB) and Casson fluid (CF; Fig. 3) [27], are used to characterise the rheological behaviour of MRP fluid by fitting the rheological data and evaluating respective constants in their constitutive equations. From the experimental data obtained from capillary magneto-rheometer, flow curves in terms of wall shear stress vs. shear rate for all fluids (listed in Table 4) at three magnetic flux densities are plotted. Constitutive equations and flow curves for MRP fluid with SiC-800 abrasives at three magnetic flux densities are shown in Fig. 4. Similar curves were obtained for all other compositions.

The rheological parameters obtained for BP, HB and CF curves are tabulated in Table 6. In these fluid models, it is assumed that the pre-yield behaviour is rigid and that the fluid flows if and only if the local shear stress is greater than the yield stress. For BP model, once the local shear stress exceeds the yield stress, the post-yield behaviour is linear. The BP model is a two-parameter model with yield shear stress, τ_0, and plastic viscosity, η_{pl}. For the HB model,

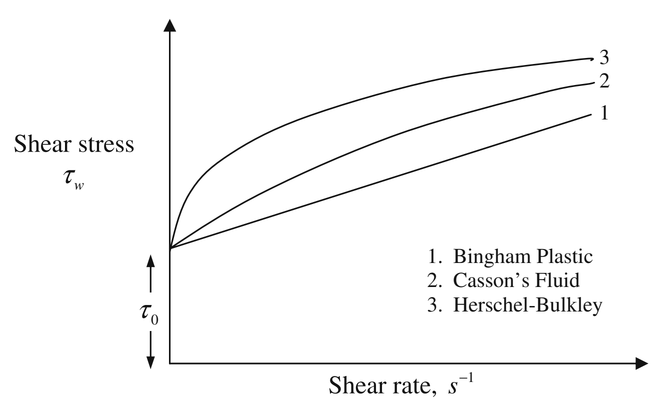
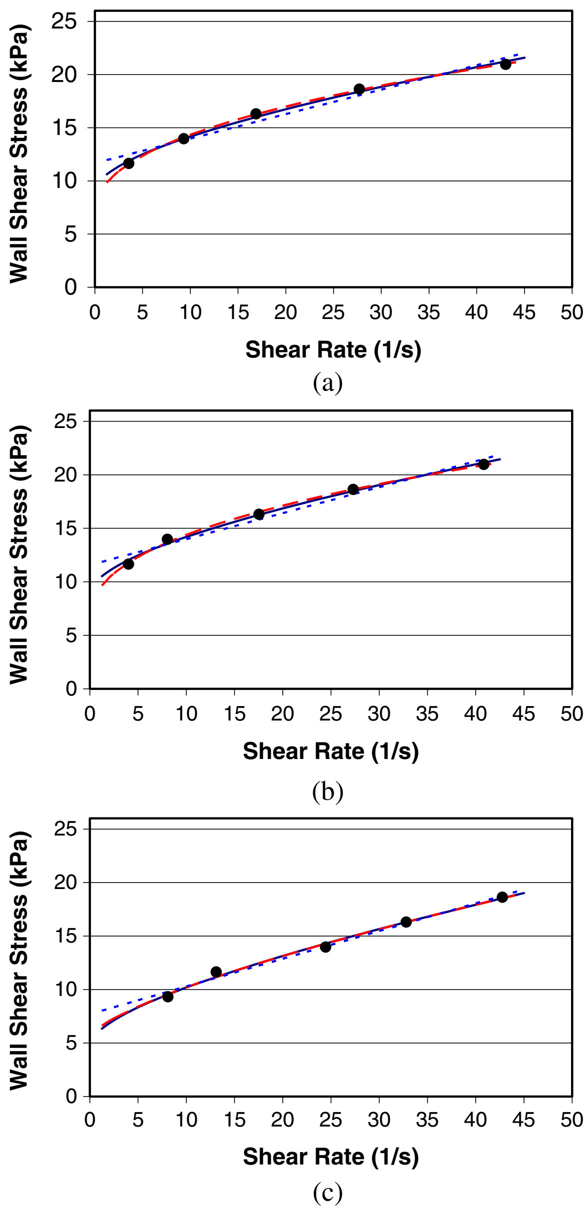


Fig. 3 Constitutive models for MRP fluid flow characterisation [27]

the post-yield behaviour is nonlinear. The HB model employs three parameters: yield shear stress, τ_0, consistency, K, and flow index, n. Flow index $n>1$ indicates a shear thickening fluid, and $n<1$ indicates a shear thinning flow. The CF model is a two-parameter model which represents closely the particulate flow. The parameters are yield shear stress, τ_0, and Casson's viscosity, η_c. The yield shear stress values obtained from three models differ in magnitudes because of deviation in their nature at low shear rates, as can be seen in Fig. 4.

The curvature in HB and CF models (Fig. 4) indicates shear thinning of the fluid, and it varies from fluid to fluid based on their constituents and magnetic flux density. In HB model, the extent of shear thinning can be evaluated from flow index. Value towards zero indicates more shear thinning, while its value towards 1 indicates Bingham plastic fluid with no shear thinning (Fig. 5). The MRP fluids having value of $n<0.5$ shear much faster and have low viscosity at higher shear rate. The flow index of all MRP fluids as per Table 6 lies between 0.305 and 0.852, which is evident for shear thinning behaviour of MRP fluids.

The coefficient of multiple determination (R^2) of all the three models for all fluids are calculated and summarised in Table 7. It is the ratio of regression sum of squares and error sum of squares. R^2 measures the proportion of variation in the data points which is explained by the regression model. For example, if $R^2=0.95$, the 95% of the variation in the dependent, or response variable Y, is explained by the regression model. A value of $R^2=1.0$ means that the curve passes through every data point, and a value of $R^2=0.0$ means



(a)

Bingham Plastic (------)

$$\tau_y = 11670.286 + 230.241\dot{\gamma}$$

Herschel Bulkley (– – – –)

$$\tau_y = 6761.459 + 2786.709\dot{\gamma}^{0.434}$$

Casson Fluid (——)

$$\sqrt{\tau_y} = \sqrt{8890.845} + \sqrt{61.50\dot{\gamma}}$$

(b)

Bingham Plastic (------)

$$\tau_y = 11552.881 + 242.783\dot{\gamma}$$

Herschel Bulkley (– – – –)

$$\tau_y = 6226.436 + 3103.083\dot{\gamma}^{0.419}$$

Casson Fluid (——)

$$\sqrt{\tau_y} = \sqrt{8744.389} + \sqrt{65.891\dot{\gamma}}$$

(c)

Bingham Plastic (------)

$$\tau_y = 7698.551 + 258.732\dot{\gamma}$$

Herschel Bulkley (– – – –)

$$\tau_y = 5586.049 + 895.634\dot{\gamma}^{0.711}$$

Casson Fluid (——)

$$\sqrt{\tau_y} = \sqrt{4627.997} + \sqrt{108.529\dot{\gamma}}$$

Fig. 4 Flow curves for MRPF-20CS-20SiC800 at 0.200 T (**a**), 0.175 T (**b**) and 0.150 T (**c**) magnetic flux densities

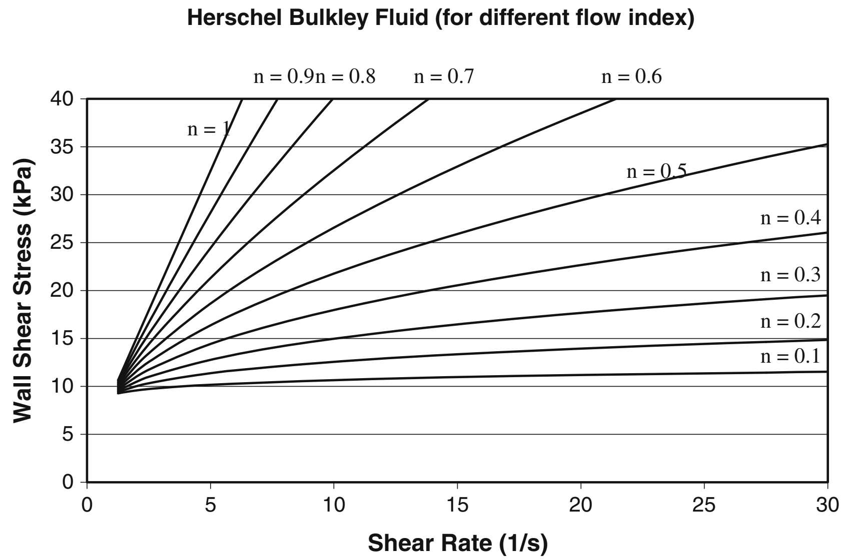


Fig. 5 Hershel–Bulkley fluid with different flow index

that the regression model does not describe the data any better than a horizontal line passing through the average of the data points.

The R^2 values for Bingham fit to rheological data of all compositions at different magnetic flux density are least as compared to Casson and Hershel–Bulkley models, although the difference is small. Hershel–Bulkley represents best the flow behaviour of all fluids at all flux densities. Bingham plastic model for MR fluids, as described in literature [9, 19], is not a realistic model to represent flow behaviour of magnetorheological polishing fluid, which may be due to the presence of non-magnetic abrasive particles in it. All fluids flow as shear thinning fluid with nonlinear nature of flow curve. Hence, Bingham model is not found suitable to explain the rheological behaviour of MRP fluid. Herschel–Bulkley model fits better to the data points as compared to other models (Fig. 4). This is evident from R^2 values which lie between 0.992 and 0.999 for all fluids. Casson fluid model represents a continuous shear thinning behaviour of the fluid with decrease in viscosity from infinity at zero shear rate to zero at infinite shear rate. The yield stress and Casson's viscosity evaluated after fitting Casson's model for all MRP fluids are listed in Table 6. Casson's model also fits rheological data well, with R^2 ranging from 0.981 to 0.998.

Understanding MRP fluid structure at micro level in the presence of external magnetic field is very difficult due to the complex nature of the fluid. The rheological properties evaluated in literature are of MR fluid which does not contain non-magnetic particles. The presence of non-magnetic SiC

Table 6 Rheological characterization of MRP fluids with CIP-HS

MRP fluid constituents			Bingham model $\tau_y = \tau_0 + \eta_{p1}\dot{\gamma}$		Herschel–Bulkley model $\tau_y = \tau_0 + K\dot{\gamma}^n$			Casson fluid $\sqrt{\tau_y} = \sqrt{\tau_0} + \sqrt{\eta_c\dot{\gamma}}$	
CIP grade	SiC mesh	B gauss	Yield stress τ_0 (Pa)	Plastic viscosity η_{pl} (Pa^{-s})	Yield stress τ_0 (Pa)	Consistency (K)	Flow index (n)	Yield stress τ_0 (Pa)	Casson's viscosity (Pa^{-s})
CS	800	2,000	12,649.69	216.76	6,352.09	4,670.73	0.305	10,461.22	45.96
CS	800	1,750	12,577.19	220.87	6,596.60	4,477.76	0.311	10,446.54	46.81
CS	800	1,500	8,482.48	270.53	6,031.82	1,216.36	0.639	5,660.35	97.20
CS	1,000	2,000	11,649.02	230.84	6,088.85	3,211.68	0.408	8,831.51	62.39
CS	1,000	1,750	11,552.88	242.78	6,226.44	3,103.08	0.419	8,744.39	65.89
CS	1,000	1,500	7,698.55	258.73	5,586.05	895.63	0.711	4,627.99	108.53
CS	1,200	2,000	10,775.24	239.21	5,480.53	3,615.98	0.379	8,373.61	64.88
CS	1,200	1,750	9,367.49	260.52	6,133.63	1,660.09	0.568	6,520.36	88.67
CS	1,200	1,500	7,780.13	276.57	6,031.35	814.26	0.742	4,757.84	113.46
CS	1,500	2,000	10,428.84	437.74	6,764.69	2,937.37	0.485	7,914.72	125.35
CS	1,500	1,750	9,728.25	367.23	6,494.79	2,169.28	0.544	7,046.97	116.09
CS	1,500	1,500	8,975.22	391.81	5,874.19	1,845.84	0.606	5,934.07	145.26

Table 7 Comparison of coefficient of multiple determination of Casson, Herschel–Bulkley and Bingham plastic model for MRP fluids

MR polishing fluid	Magnetic flux density (G)	Coefficient of multiple determination (R^2)		
		Casson	Hershel–Bulkley	Bingham
MRPF-20CS-20SiC800	2000	0.984	0.999	0.926
	1750	0.984	0.996	0.938
	1500	0.994	0.994	0.987
MRPF-20CS-20SiC1000	2000	0.994	0.999	0.963
	1750	0.993	0.994	0.968
	1500	0.993	0.993	0.989
MRPF-20CS-20SiC1200	2000	0.981	0.999	0.919
	1750	0.994	0.995	0.978
	1500	0.997	0.999	0.998
MRPF-20CS-20SiC1500	2000	0.998	0.998	0.983
	1750	0.995	0.996	0.975
	1500	0.986	0.992	0.934

abrasives of different sizes affects significantly the rheological properties and makes it difficult to predict the nature of such fluids. Though in the current scope of work it is difficult to explain all such variations in the complex rheology of MRP fluids, an attempt has been made to explain results in the following paragraphs.

7.1 Variation with SiC mesh sizes

Comparison has been made between flow properties (yield stress and viscosity) of MRP fluids with same CIP size and varying SiC particle size, keeping the same volume concentration. The results are analysed from Herschel–Bulkley model as well as Casson's fluid model. The variation of yield stress, consistency coefficient (K) and flow index (n) of MRP fluid with different SiC abrasive mesh sizes at 0.150, 0.175 and 0.200 T is shown in Fig. 6a–c, respectively. The yield stress for a given magnetic flux density depends on the MRP fluid structure formed by magnetic CIPs and different size of non-magnetic abrasive particles.

The yield stress in HB and Casson's model are obtained after extrapolation of the flow curve to intercept shear stress axis at zero flow rate. In HB model, the yield stress (Fig. 6a) first decreases and then increases at 1,500 mesh size. Yield stress value of a particular fluid composition is governed by fluid structure and the interparticle magnetic attractive forces. For the same iron particle size and volume concentration, the fluid structure developed in the presence of magnetic field for different SiC particle size is more complex and difficult to predict. As volume concentration of SiC and CIP is kept constant, the smaller the particle size, the more the number of particles. For smaller particle size, the

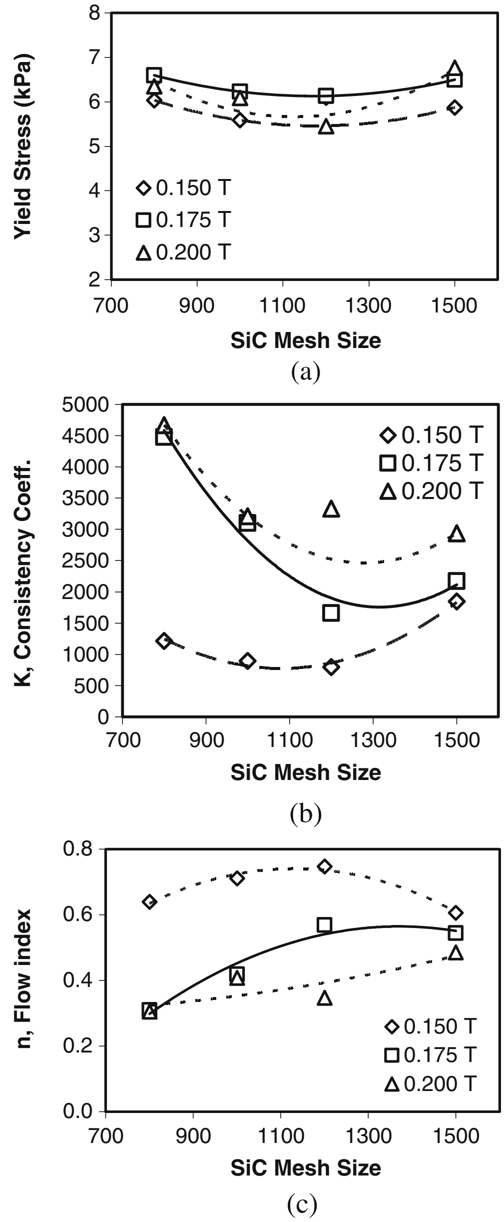


Fig. 6 Variation of yield stress (**a**), consistency (**b**) and flow index (**c**) with SiC mesh sizes at 0.150, 0.175 and 0.200 T as per Hershel–Bulkley model

magnetic force on CIPs is shared by more number of SiC particles (or smaller force on each particle), but at the same time, smaller particles form denser structure filling up the voids between CIP chains (or larger force per unit area). The yield stress variation shown in Fig. 6a is attributed to these two counteracting phenomena. Figure 7a shows variation of yield stress of MRP fluid as per Casson's model with different SiC abrasive mesh sizes at 0.15, 0.175 and 0.200 T.

The Casson's yield stress decreases with increase in mesh size at all magnetic fields except at 0.150 T. The

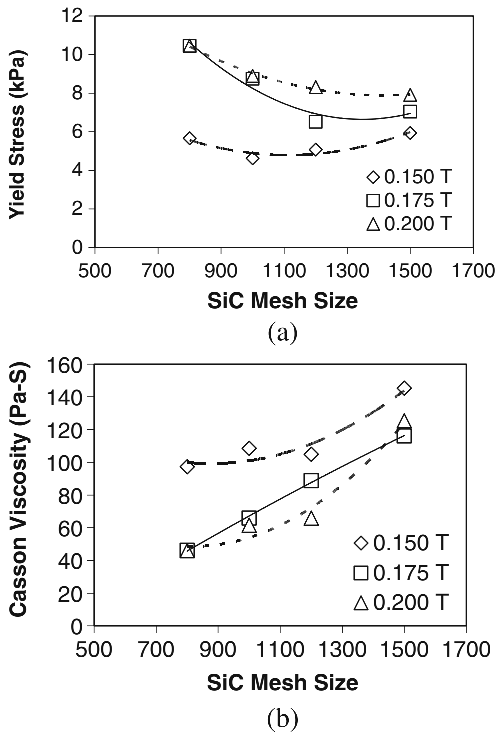


Fig. 7 Variation of yield stress (**a**) and Casson's viscosity (**b**) with SiC mesh sizes at 0.150, 0.175 and 0.200 T as per Casson's fluid model

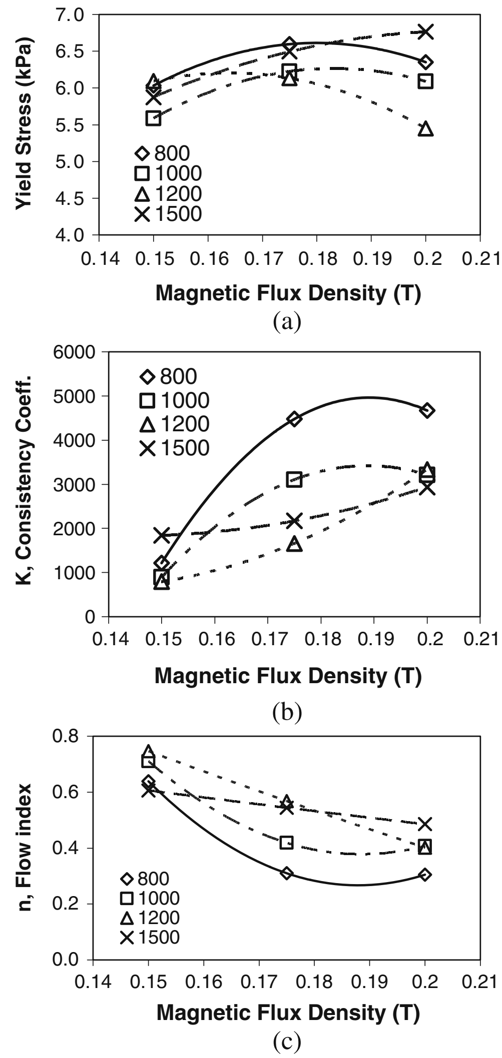


Fig. 8 Variation of yield stress (**a**), consistency coefficient (**b**) and flow index (**c**) of MRP fluid with magnetic flux density as per Hershel–Bulkley model

average diameter of CS grade CIP is 18 μm and SiC of mesh size 800 is 19 μm. They are comparable in size and form a closed knit interlinked structure at 0.175 and 0.200 T; hence at 0.15 T, the structure may not be that strong. Yield stress at higher magnetic field is more for most of the fluid compositions. As the abrasive particle size reduces towards 1,500 mesh with particle diameter of 10.13 μm, for the same volume percentage, the number of SiC particles increases per CIP. This results in sharing of magnetic force on CIP by more number of abrasives as compared to 800 mesh size, which results in weak bonding between CIP chains. In MR polishing fluid, the bonding between CIP chains is limited by magnetic attraction forces due to magnetic field and CIP size. Forces on abrasive particles are coming due to magnetic force on CIPs in MR polishing fluid. Even though smaller abrasive particles are more capable of filling voids between CIP chains, due to their non-magnetic nature, they can form dense structure but are weak in bonding strength. During flow of such fluids, due to the presence of more number of non-magnetic smaller size abrasive particles, the magnetic force per particle becomes lower; hence, the MR polishing fluid structure has a higher tendency to rupture. Due to the presence of more number of non-magnetic abrasive particles, there are more sites for chain breakage, which yield more shear thinning once flow starts. The chain structure modelling and effect of particle size on MRAFF performance has been reported elsewhere [28]. MRP fluid with bigger SiC particles has a higher consistency coefficient (Fig. 6b) than smaller SiC combination with CIP-CS. The flow index in HB model shows an interesting trend with variation of SiC particle size in the MRP fluid. The polishing fluid exhibits more shear thinning with bigger abrasive particles in it as compared to smaller SiC particles. The value of flow index as seen in Fig. 6c is low for SiC 800 mesh size than higher mesh size composition.

The variation of Casson's viscosity of MRP fluid with CIP-CS grade and different SiC abrasive mesh sizes is shown in Fig. 7b. High Casson's viscosity is observed for CIP-CS with smaller SiC particle size as compared to bigger abrasive particles. This may be because of more flow resistance due to the presence of more number of smaller particles in the fluid. At high shear rates, the effect

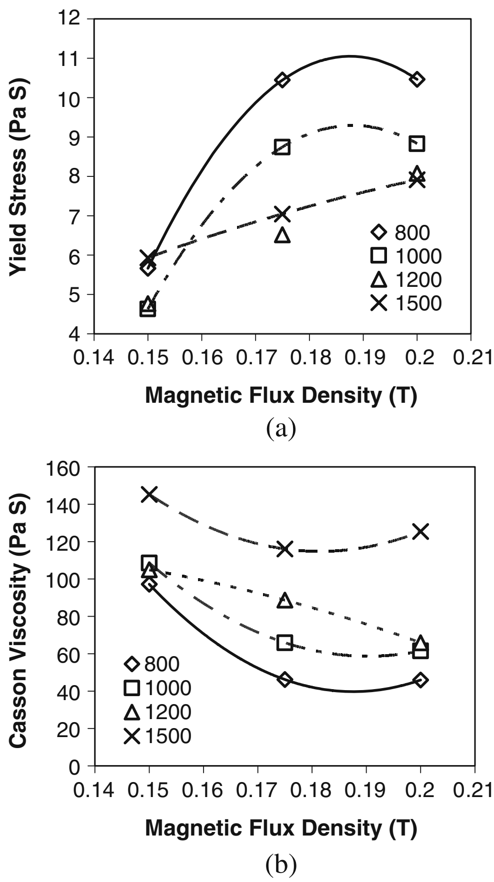


Fig. 9 Variation of yield stress (**a**) and Casson's viscosity (**b**) of MRP fluid with magnetic flux density as per Casson's fluid model

of magnetic bonding between CIPs is not predominant and has less effect on flow behaviour. The viscous and frictional resistance of the fluid and particles at high shear rate governs the Casson's viscosity of the fluid. As Casson's viscosity is a measure of viscosity at high shear rates, the lower value with bigger SiC is observed.

7.2 Variation with magnetic flux density

The effect of magnetic flux density on rheological properties of MRP fluid is explained with the help of Hershel–Bulkley and Casson's fluid model, as their R^2 values are near 1. Increase in yield stress of magnetorheological fluid with magnetic flux density is widely reported in the literature. In the present study, the presence of non-magnetic abrasive particles in the MRP fluid may act as a defect site in the CIP lattice in the fluid and affect the stress required to initiate flow, hence yield stress. As reported in the previous section, the MRP fluid behaves as a shear thinning fluid. The formation and breaking of CIP chain structure in the fluid is random, and after a specific level of strain rate, there is insufficient time available for reformation of chain structure; hence, the role of magnetic flux density in affecting fluid viscosity at higher shear rate is not clearly understandable. Variation of yield stress, consistency coefficient (K) and flow index in HB model representing MRP fluids are plotted in Fig. 8a–c. Effect of magnetic flux density on yield stress and Casson's viscosity of MRP fluids is shown in Fig. 9a,b, respectively. The possible explanation of variations in yield stress and viscosity with fluid composition at different magnetic flux densities is described in the following subsections.

Yield stress Yield stress value as per HB model increases for all combination of SiC mesh sizes except 1,200 mesh (Fig. 8a). An initial increase in Casson's yield stress of MRP fluid with CIP-CS is observed with increase in magnetic flux densities for all grades of SiC abrasives (Fig. 9a). The yield stress value remains almost the same after certain magnetic flux density in case of MRP fluid with SiC 800 and 1,000 mesh size. This may be due to magnetic saturation of iron particles. The reported magnetic flux density has been measured in air. The flux density inside carbonyl iron particles is more due to high permeability. Flux density depends on magnetic field strength H and magnetic permeability of medium. There is a possibility that with the applied magnetic field strength, the flux density inside CIPs may reach saturation. It is previously reported that the strength of the MR fluid increases as the applied magnetic field increases, but this increase is nonlinear, since the particles are ferromagnetic in nature and magnetisation in different parts of the particles occurs non-uniformly. The ultimate strength of MR fluid is limited by magnetic saturation [11].

Casson's viscosity Casson's viscosity represents fluid flow characteristics at high shear rates. Decrease in viscosity of MRP fluid with CIP-CS is observed with increase in magnetic field for all combination of SiC particle sizes. The MR polishing fluid is characterised by the following two main rheological properties: (a) yield shear stress (developed due to magnetic field) and (b) fluid viscosity. Yield shear stress governs the flow commencement, while viscosity represents the flow behaviour once flow starts. Yield stress increases with magnetic flux density for all fluids because at higher flux density, fluid structure gains more strength, and hence higher resistance against applied pressure. Once the flow starts, the breakage of chain structure and reformation of clusters during flow is represented by viscosity. Nonlinear relation between shear stress and shear rate indicating shear thinning behaviour of MR polishing fluid is observed. Owing to this behaviour, viscosity is a function of shear rate and it is not constant. Different models are used to represent the MR-polishing fluid viscosity. From Fig. 8c, it is observed that Herschel–Bulkley flow index decreases with increase in magnetic flux density. This indicates more shear thinning at higher magnetic field. It is difficult at this stage to understand the reason for this behaviour, but it is observed experimentally. As viscosity decreases because of shear thinning in MR polishing fluid, Casson's viscosity also decreases with magnetic flux density. For shear thinning fluid, viscosity is not constant and varies with shear rate. Therefore, to represent such behaviour of viscosity, Casson's fluid model is used, which gives viscosity value at high shear rates.

Flow index The flow index in Hershel–Bulkley model signifies shear thinning or thickening behaviour. For all fluids under study, the value is less than 1, so it shows shear thinning behaviour of MRP fluids. The flow index decreases for all fluid composition with magnetic flux density (Fig. 8c). This indicates more shear thinning behaviour at higher magnetic field. No appropriate explanation is identified from the present study for this behaviour.

8 Conclusions

- Due to nonlinearity in flow curve, the MRP fluid cannot be characterised as Bingham plastic fluid. The behaviour of all MRP fluids observed is of shear thinning viscoplastic nature due to rupturing of CIP chains at faster rate at high shear rates.
- Except for few fluids, all the three rheological models, viz. Bingham plastic, Herschel–Bulkley and Casson fluid, fit the data points well in the experimental range. There is deviation in their nature at low shear rates. Because of this, the yield stress obtained from three models differs in value.
- Herschel–Bulkley and Casson's fluid models fit the data points with better R^2 value than Bingham plastic model.
- More shear thinning behaviour of MRP fluids is observed at higher magnetic fields and for bigger SiC particles.

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