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Characterization of Magnetorheological Finishing Fluid for Continuous Flow Finishing Process

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ABSTRACT

Magnetorheological (MR) fluid finishing process is an application of MR technology in which controllability of the MR fluid is used advantageously to finish the workpiece surface. MR finishing fluid changes its stiffness in accordance with the applied magnetic field and hence it behaves like a flexible finishing tool. A relative motion between this tool and workpiece removes the material from the machining surface. The quality of the final finished surface depends on the constituents of the finishing fluid and the applied magnetic field strength as these parameters affect the rheological properties of the fluid. A study on the rheological properties of the fluid at high shear rates is carried out through Taguchi Design of Experiments to characterize its flow behaviour to be used in continuous flow finishing process. Constitutive modeling of the fluid sample is done using Bingham Plastic, Casson Fluid and Herschel Bulkley fluid models to characterize their rheological behavior. The Hershel–Bulkley model is found to be the best suited model for the finishing fluid. Analysis of Variance has revealed that volume percentage of iron particles is the most significant parameter with a contribution of 91.68% on the yield stress and viscosity on the finishing fluid. The highest yield stress of the fluid is observed between magnetic flux density ranges from 0.3 to 0.5 Tesla. An optimised combination is then synthesized to confirm the theoretical results. The effect of temperature is also studied on the optimised fluid which has shown that temperature shares an inverse relation with the yield stress of the finishing fluid.

Keywords: Magnetorheological finishing fluid; Magnetic field strength; Viscosity; Yield stress; Constitutive models; Design of experiments.

1. INTRODUCTION

Rheology is the study of the flow characteristics of materials under the influence of applied stress. The rheological properties of a fluid *e.g.* elasticity, plasticity, viscosity *etc*. are the main features that needs to be understood to describe its behaviour. Magnetorheology is a branch of rheology which deals with the flow behaviour and the deformation of the materials under the influence of some applied magnetic field. A magnetorheological (MR) fluid is synthesised by suspending ferromagnetic particles in a carrier fluid. The carrier fluid forms continuous phase of the MR fluids see Rabinow (1948). The MR fluids exhibit a change in its rheological properties under some magnetic field which is known as on-state condition. In this state, the magnetically induced particles are aligned to form chain like or column like structures in the direction of applied magnetic field. Because of the above, the MR fluids can change itself from viscous liquids to semi-solids and vice versa within milliseconds by Phule. (1998) and Genc and Phule (2002). It behaves as a Newtonian fluid in the off-state condition but in on-state condition it attains some initial yield stress which is a function of its (fluid) constituents as well as the applied magnetic flux density. This feature enabled a rapid response of a mechanical components interface through electronic controls with an ability to transmit force in a controllable manner. This controllable on-state yield strength of the MR fluid is one and the only characteristic that is responsible for its wide area of applications. It, thus, improves the performance of the conventional systems when these replaced by MR fluid technological solution and also makes it attractive for many applications *e.g.* dampers, brakes, journal bearings, finishing, pneumatic artificial muscles, fluid clutches, aerospace, *etc*.

A typical MR fluid contains 20 to 40% by volume of suspended ferromagnetic particles which are generally the pure iron particles. These particles provide a good trade-off between cost and fluid strength (*i.e.* large saturation magnetisation value up to 2.1 T) by Phule. (1998). One of the emerging application of MR fluid technology is in finishing operation which is known as Magnetorheological fluid finishing (MRFF) process see Kordonski and Jacobs (1996). This process is used for finishing of hard & brittle material (*e.g.* glass) as well as soft & ductile material (*e.g.* aluminium) see Shafrir *et al.* (2007) The MRFF process is based on the mechanism of mechanical abrasion in which the material is removed by the non-magnetic abrasives particles and also with the suspended iron particles of the MR fluid. This makes the process more controllable than the classical finishing processes. A proper composition of MR fluid and abrasive particles can be successfully employed to achieve micro to nano level surface finishing/polishing on the workpiece see Rosenfeld *et al.*(2002).

In the past two decades, different MRFF processes have been developed in which the abrading forces have been controlled accurately. Some of these processes includes magnetorheological jet finishing (MRJF) by Kordonski and Shorey (2007), magnetorheological abrasive flow finishing (MRAFF) by Jha and Jain (2004), MR fluid for external cylindrical surfaces by Gheisari *et al.* (2014) and Singh *et al.* (2017), rotational MRAFF by Das *et al.* (2010), wheel based MRFF process by Sidpara and Jain (2012a) and Sidpara and Jain (2012b), ball end MRFF process by Singh *et al.* (2015), ultrasonic magnetorheological compound finishing by Huijun *et al.* (2007), hybrid chemo-mechanical MRFF process by Jain *et al.* (2010), MR finishing for flat surface by G. Parameswari1 *et al.* (2017) *etc.* The MR finishing fluid used in all these developed processes have different rheological characteristics as these fluids have been used for different types of flow and the abrasion phenomena has also varied from process to process. It, therefore, become very important to characterize the MR fluid before it is used for a specific application to get desired outcome.

A number of researchers have developed and characterize MR fluids for specific applications. The fluid used in MRAFF was developed and characterized by Jha and Jain (2009) who have concluded that the MR polishing fluid used in the process has a shear thinning behaviour and Herschel Bulkley model is the best suited model for the fluid. Sidpara *et al.* (2009) characterized the MR polishing fluid used in rotating wheel type MRFF process and the effect of temperature on the stability of fluid was also determined. From the results, it was concluded that the shear stress of the fluid decreases with increased in temperature. Mangal and Sharma (2017) has developed an empirical relation to determine the fluid composition as per the required yield stress and on-state viscosity. From the results, it was concluded that the percentage of iron particles has the maximum contribution on the yield stress and viscosity of the fluid. Shimada *et al.* (2003) developed a magnetic compound fluid (MCF), having magnetite particles of 10 nm average diameter, abrasive particles, CIPs, kerosene and water. Saraswathmma *et al.* (2015) studied the field induced yield stress and shear viscosity using Casson fluid model only and evaluated the effect of composition on these rheological properties using flat plate rheometer.

Explore the key quality performance of the magnetorheological finishing process in achieving nanolevel finish on Ti6Al4V discs.

It was found that the field induced yield stress and viscosity have direct relationship with the iron particles and magnetic field.

In the present study, eighteen MR finishing fluid samples are prepared as per the combinations suggested by L-18 orthogonal array and the fluid is optimized for its desired rheological properties (*i.e.* field induced yield stress and shear viscosity). An Anton Paar MCR 302 parallel plate rheometer is used for the characterization of the fluid samples. The fluid has found to have shear thinning behaviour. All the obtained experimental values are fitted in three different fluid models *viz.* Bingham plastic, Herschel-Bulkley and Casson fluid. Coefficient of regression (R^2) is used to arrive the best fit fluid model among the three. Form the R^2 results, it has been concluded that Hershel Bulkley model is the best suited model for the prepared MR finishing fluid under continuous flow finishing process. Analysis of Variance is conducted on the fluid samples which has revealed that volume percentage of iron particles is the most significant parameter with a contribution of 91.68% on the yield stress and viscosity. An optimised combination is then synthesized to confirm the theoretical results. The highest yield stress of the fluid is observed between magnetic flux density of 0.3 to 0.5 Tesla.

2. SYNTHESIS OF MR FINISHING FLUID

MR finishing fluids consist of four main components *viz.* magnetizable ferromagnetic particles, abrasive particles, carrier medium and stabilizers. The components used in the present study for MR finishing fluid synthesis are as follows:

- Iron powder as magnetizable particles
- Silicon carbide particles as abrasives
- Deionized water/silicon oil as carrier medium
- Glycerol/tetra methyl ammonium hydroxide as an additive

After going through the available literature, iron particles of HS grade (size 600 mesh), silicon oil having viscosity 50 cst, deionized water, green silicon carbide abrasive (size 600 mesh) and glycerol/tetra methyl ammonium hydroxide as anti-sediment agents are selected for the synthesis of the MR finishing fluid. Glycerol is used as an anti-sediment agent with deionised water while tetra methyl ammonium hydroxide is used with silicon oil. The parameters and their corresponding values of various levels for the prepared MR finishing fluid samples are shown in Table 1. Two levels are selected for carrier fluid *viz.* deionised water and silicon oil, while three levels are selected for remaining parameters *i.e.* iron particles, carrier fluid and abrasive particles for the synthesis MR finishing fluid. The anti-sediment agents are taken as residual component.

Taguchi design of experiment using L-18 orthogonal array is shown in Table 2. It is used for finding the optimized combination of its constituents. The MR finishing fluid samples are prepared using in-house developed facilities as per the following procedure:

- The required volume of the carrier fluid is first taken in a graduated cylinder and accordingly the measured quantity of the requisite additive is added to it. This mixture is stirred at 300-500 rpm for 15 minutes using a specially designed stirrer to make the mixture homogenous.
- After that the iron particles are added slowly to it up to the desired volume (as per the combination of orthogonal array) with simultaneous stirring of the mixture. The stirring is continued for 10 more minutes (*i.e.* after the complete addition of all the iron particles) to make the fluid mixture homogenous.
- Then the green SiC particles are added slowly with simultaneous stirring of the mixture. The stirring is continued after 10 more minutes for proper distribution of iron particles and SiC particles. The MR finishing fluid is now ready for characterization/testing and use.

Eighteen samples (as per the combinations of L-18 orthogonal array) are then prepared and the characterised using a modular compact rheometer (MCR).

3. CHARACTERISATION OF MR FINISHING FLUID

The rheological characterization of MR finishing fluid is of the utmost requirement before its specific application as it will describe the behavior of fluid under that flow conditions. The determination of dynamic viscosity and the yield stress under on state condition is necessary, to investigate the flow behavior and the bonding strength of the abrasives in the iron particles' chains during finishing operation. Figure 1 shows schematic representation of finishing region in the MR finishing process for unidirectional continuous fluid flow. The direction of flow of the finishing fluid is perpendicular to the

Table 1 Input parameters and their corresponding levels

Symbol	Parameter	Level		
		I	II	III
A	Type of carrier liquid	Deionised Water	Silicon Oil	----
B	Volume % of iron particles	20	25	30
C	Volume % of carrier liquid	50	55	60
D	Volume % of abrasive particles	4	6	8

Table 2 Experimental results of MR finishing fluid

Exp. No.	Parameters' Values				Response	
	A	B	C	D	Yield stress (kPa)	Shear Viscosity (kPa-s)
1	DI Water	20	50	4	15.856	208.103
2	DI Water	20	55	6	13.869	182.025
3	DI Water	20	60	8	12.062	158.308
4	DI Water	25	50	4	24.691	324.059
5	DI Water	25	55	6	21.057	276.364
6	DI Water	25	60	8	18.426	241.833
7	DI Water	30	50	6	31.758	416.81
8	DI Water	30	55	8	26.363	346.003
9	DI Water	30	60	4	29.412	386.02
10	Silicon Oil	20	50	8	14.281	187.432
11	Silicon Oil	20	55	4	15.169	199.087
12	Silicon Oil	20	60	6	13.307	174.649
13	Silicon Oil	25	50	6	24.462	321.053
14	Silicon Oil	25	55	8	20.769	272.584
15	Silicon Oil	25	60	4	19.594	257.163
16	Silicon Oil	30	50	8	30.913	405.720
17	Silicon Oil	30	55	4	27.584	362.028
18	Silicon Oil	30	60	6	29.105	381.991

magnetic flux lines. The abrasive particles are embedded in between the iron particle chains and exert two types of force *i.e.* first one is tangential force to the workpiece surface (F_t) because of the flow of fluid and another one is the normal to the workpiece surface (F_n) because of the direction of magnetic field. The penetration of the abrasive particles into the workpiece is because of the force acting normal (F_n) whereas the continuous flow of the finishing fluid exerts shear force (F_t) on the workpiece surface. A higher on-state yield of MR finishing fluid is responsible for larger penetrating force exerted by abrasives embedded in between the iron particle chains whereas a higher flow exerts larger shear force on the workpiece surface. Considering all the constrictions of fluid flow, an Anton Paar modular compact rheometer MCR 302 is used for the characterization of the fluid samples. The testing phenomena of the rheometer has the following features which makes it the best for the characterization of MR finishing fluid under continuous flow finishing application:

- The direction of magnetic field is perpendicular to the direction of fluid deformation which is similar to the proposed MR finishing process.
- A magnetic field strength obtainable from the MRD is of around 1.3 Tesla which is sufficient enough to study saturation state of MR finishing fluid samples.
- It is simple to operate and predict accurate results for yield stress and dynamic viscosity.

3.1 Testing Equipment

The characterization of the prepared MR finishing fluid samples is conducted on Anton Paar MCR 302 rheometer fitted with Magnetorheological device (MRD) accessory. The rheometer has two parallel plates of diameter 20 mm with an adjustable gap ranging from 50 µm to 2000 µm. These parallel plates are made up of non-magnetized metals to prevent these from the magnetic effect of MRD accessory which may affect the proper characterization of the fluid.

The MRD is used in combination with an MCR rheometer to investigate the effect of a magnetic field on the MR fluids. The MRD consists of an in-built electromagnetic coils that can produce a homogenous magnetic field up to 1.3 Tesla. This magnetic field lines are perpendicular to the air gap of the plates. The direction of applied magnetic field during testing of the fluid samples is shown in Fig. 2. The MRD consists of a temperature-controller system (having a range from -10 °C to 170 °C). It employs liquid temperature control for the bottom plate while Peltier temperature control is used for the yoke. These plates are prevented from the abrasive action of MR finishing fluid by using an

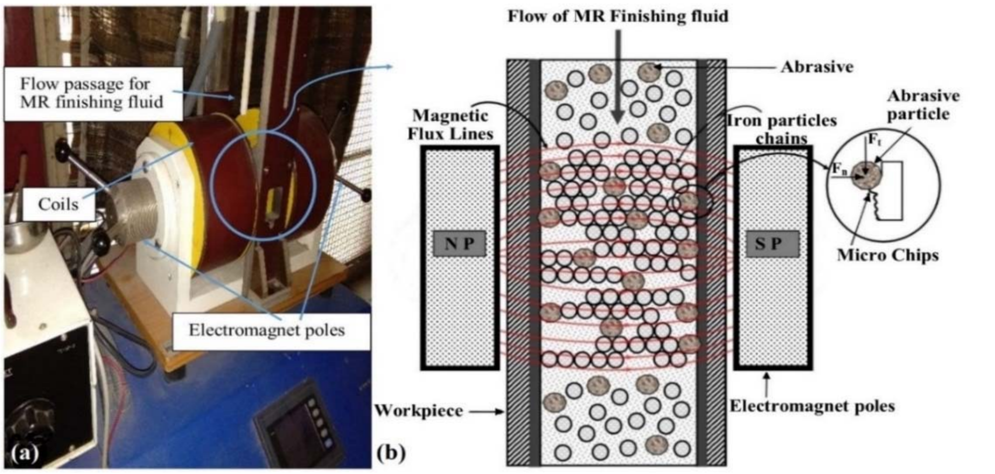

Fig. 1. (a) Photograph of the MR fluid finishing process and (b) Schematic drawing of the MR finishing phenomenon showing the direction of flow of MR finishing fluid along with magnetic field in the finishing region and the forces exerted in process

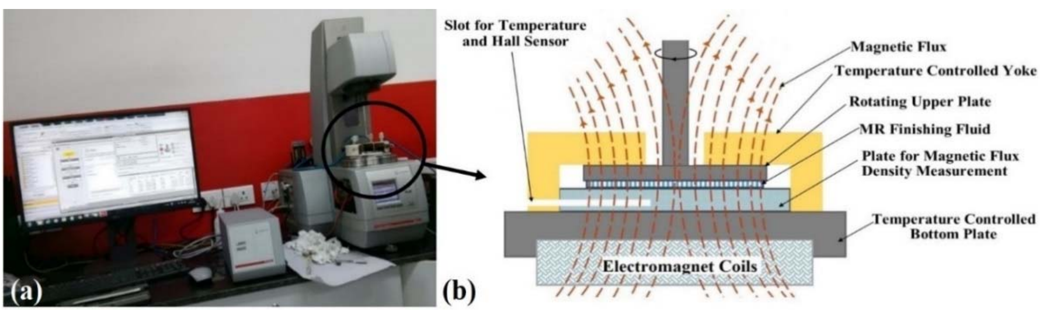

Fig. 2. (a) Anton Paar MCR 302 rheometer with MRD accessory and (b) the schematic representation of the phenomenon used by MRD for testing of MR finishing fluid samples

Aluminium foil of 0.1 mm thickness on the active surfaces.

For testing of the MR finishing fluid, approximately 0.4 ml of the fluid sample is placed between the gaps of the parallel plates. The lower plate is kept stationary while the upper plate is rotated to provide shearing action on the fluid sample. The direction of shear flow is perpendicular to that of the magnetic flux lines. The data is collected for shear stress at different shear rate which is varied from 0 to 1000 s^{-1} in 20 minutes time interval. The torque on the upper plate is measured by a sensor which is used to determine the corresponding value of exerted force. This force gives the shear stress on the rotating plate at that point which is the yield stress of the fluid. The magnetic field density is varied from 0.0 to 1.0 Tesla and the temperature during the test is maintained at 22 °C.

3.2 Rheological Experimentation

Experiments were carried out on all the eighteen fluid samples to evaluate the effects of various components on the rheological properties at different magnetic field strength using Anton Paar MCR302 rheometer with MRD accessory. Constituents of the MR finishing fluid samples are shown in Table 1. Using these constituents, the fluid samples are prepared as per orthogonal array listed in Table 2. The testing of each sample is repeated three times for getting the precise and accurate results and also to eliminate the human & other errors besides other environmental effects on experimentation. Figure 3 shows the error bar graph for the repeatability of experimental data for all the eighteen samples for yield stress and shear viscosity. The I-symbol above each bar represents the standard deviation for the corresponding fluid sample and the corresponding mean yield stress and mean shear viscosity is represented by the numeric value above each bar in Figs. 3 (a) & (b) respectively. Table 2 also shows respective experimental results *i.e.* on-state yield stress and shear viscosity obtained after error analysis for all the eighteen fluid samples.

3.3 Modelling Of MR Finishing Fluid

The rheological characterization of MR finishing fluids on the basis of its viscosity and yield stress are the key aspects for its proposed application. In the present characterization of the synthesised MR finishing fluid samples, at higher shear rates (> 600 s^{-1}) the behaviour of curve for every sample is almost at lower shear rates the pattern of the curves are different. One cannot predict the fluid behaviour just by looking at the curves for its entire range of shear rate. For determining the non-Newtonian behaviour of the synthesised fluid samples that weather it is Dilatant, Pseudo plastic, Bingham plastic, Herschel Bulkley or Cason fluid, one has to study the experimental data and to determine the best suited fluid model. It is clear from the experimental data that the fluid is not a Dilatant or Pseudo plastic type as these fluids have flown under infinite small shear stress and these have not attain any initial yield stress. Hence, the remaining three

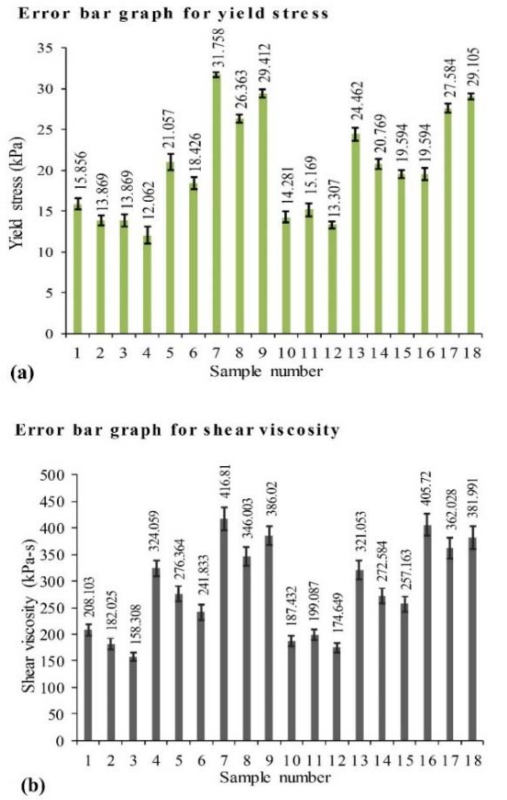

Fig. 3. Error bar graphs showing repeatability of experiments (a) for on-state yield stress and (b) for shear viscosity

models *i.e.* Bingham plastic, Herschel Bulkley and Cason fluid models are studied. Also these three models that are most commonly used for the rheological characterization of any MR finishing fluid see Chhabra and Richardson (1999). The rheological data from the MCR 302 rheometer is utilized in the three constitutive models to fit in the fluid models and to obtain the respective characteristics. All these three models assumes that the fluid flows only beyond a critical stress value (which is known as the yield stress of the fluid) but post-yield behavior of every model is different. According to Bingham Plastic model, the fluid behaves like a rigid body in pre-yield condition and after that its behavior is linear just like a Newtonian fluid. It is the simplest model used for the modelling of the MR fluids see John *et al.* (2002), Chaudhuri *et al.* (2005) and Jolly *et al.* (1996). According to Bingham Plastic model by Macosko (1994), shear stress and shear rate is related in the following manner:

$$\tau = \tau_y + \dot{\gamma}\eta \qquad (1)$$

where τ is the shear stress, τ_y is the yield stress, $\dot{\gamma}$ is the shear rate and η is the viscosity of the fluid. Herschel-Bulkley fluid model characterize the rheological behavior of a fluid having pseudo-plastic properties using the relationship given by Macosko (1994) and Papanastasiou and Boudouvis (2007) is as follows:

$$\tau = \tau_y + K\dot{\gamma}^n \qquad (2)$$

where τ is the shear stress, τ_y is the yield stress, K is the consistency index, $\dot{\gamma}$ is the shear rate and n is the power law index which indicates the shear thickening/thinning behavior of the fluid. Power law index '*n*' when greater than 1 represents shear thickening fluid behavior and when it is less than 1 represents shear thinning behavior. The consistency index *i.e.* '*K*' resembles the viscosity of the fluid.

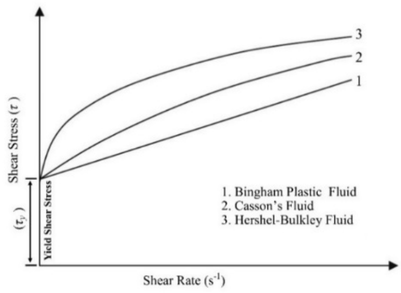

Fig. 4. Flow curves of Bingham Plastic, Herschel-Bulkley and Casson's fluid model see Chhabra and Richardson (1999)

The Casson's fluid model mainly represent particulate suspension flow behavior using two parameters *i.e.* yield stress (τ_y) and Casson's viscosity (η_c) see Casson (1959). This model considers that rigid primary particles flocculate into rod-like structures in a fluid and under the flow conditions a relation can be derived for tension in the rods. These rods break beyond a critical value of shear stress. With further increase in the shear rate, the length of the rods progressively reduces until the rods is completely broken down into primary particles at very high shear rates by Dash *et al.* (1996). According to Casson's fluid model, the shear stress and shear rate relation is given as:

$$\tau^{1/2} = \tau_y^{1/2} + (\dot{\gamma}\eta_c)^{1/2} \quad (3)$$

where τ is the shear stress, τ_y is the yield stress, η_c is the Casson's viscosity and $\dot{\gamma}$ is the shear rate. Fluid flow curves of all the above three models are shown in Fig. 4.

The data obtained from the rheometer for all the eighteen samples is plotted and fitted in the governing equation of Bingham Plastic, Herschel-Bulkley and Casson fluid models. The resulting rheological parameter *viz.* yield stress for all the three models, consistency *(K)* and flow index *(n)* for Herschel-Bulkley and Casson's viscosity are tabulated in Table 3. The nature of curves as per Herschel Bulkley and Casson Fluid models varied according to the fluid composition and applied magnetic flux density. It is pertinent to mention that the shear thinning behaviour is observed for all the fluid samples.

Table 3 Modelling of MR finishing fluid samples

Fluid Sample No.	Bihgham Model $\tau = \tau_y + \dot{\gamma}\eta$		Herschel-Bulkley $\tau = \tau_y + K\dot{\gamma}^n$			Casson Fluid $\tau^{1/2} = \tau_y^{1/2} + (\dot{\gamma}\eta_c)^{1/2}$	
	Y S (Pa)	Vis. (Pa-s)	Y S (Pa)	*K*	*n*	Y S (Pa)	C. Vis. (Pa-s)
01	13178.04	216.31	6060.82	3117.21	0.344	9091.23	41.23
02	11526.97	176.67	5310.34	2216.62	0.351	7965.45	33.35
03	10025.46	140.62	4627.83	1397.62	0.722	6941.74	26.09
04	20519.38	392.56	9397.79	2821.53	0.461	14096.69	76.48
05	17499.75	320.07	8025.24	3474.57	0.473	12037.86	61.96
06	15313.55	267.58	7031.51	3582.03	0.803	10547.27	51.49
07	26391.62	533.55	12067.43	4324.62	0.428	16601.24	104.68
08	21908.71	425.92	10029.31	3579.39	0.641	15043.97	83.15
09	24442.23	486.75	11180.92	2861.31	0.838	16771.38	95.32
10	11869.31	184.89	5465.95	2403.36	0.641	8198.92	34.94
11	12607.19	202.61	5801.34	2805.83	0.614	8702.01	38.49
12	11059.98	165.46	5098.07	1961.91	0.684	7647.15	31.06
13	20329.09	388.59	9311.36	4017.78	0.490	13966.98	75.57
14	17260.44	314.32	7916.46	3343.97	0.875	11874.69	60.83
15	16284.09	290.88	7472.66	3811.41	0.647	11208.99	56.14
16	25689.47	516.69	11747.84	5941.63	0.718	17621.76	101.38
17	22923.28	450.28	10490.48	4432.79	0.756	15735.72	88.02
18	24187.14	480.62	11064.96	5122.17	0.839	16597.44	94.09

3.4 Coefficient of Regression

Although, Bingham plastic, Herschel–Bulkley and Casson Fluid models are the most commonly used models for characterization of rheological properties of MR fluid. It is important to study suitability of a models for a particular application under consideration. It can be measured by several ways. However, coefficient of regression (R^2) is the most popular method to find the goodness of fit of a given model Sidpara *et al.* (2009). Higher the R^2 value means the better is the chance that the fluid resembles to that particular fluid model. The value of R^2 = 1 implies that the curve (the regression model) will pass through from all the data points. The coefficient of regression (R^2), after solving the equations of all the three models for the experimental data, is shown graphically in Fig. 5. The value of R^2 is 0.7243 for Bingham Plastic, 0.4627 for Casson fluid model and 0.8608 for Herschel–Bulkley model. The results from regression analysis thus reveals that the Herschel–Bulkley model is the best to describe the flow behaviour of MR finishing fluid (at different flux densities) because of its flow consistency index (*n*). In the literature, the Bingham Plastic model has been shown as the best model for MR fluid by John *et al.* (2002), Chaudhuri *et al.* (2005) and Jolly *et al.* (1996). But it does not represent the flow behaviour for the MR finishing fluid realistically because of the presence of non-magnetic SiC abrasive particles in the fluid.

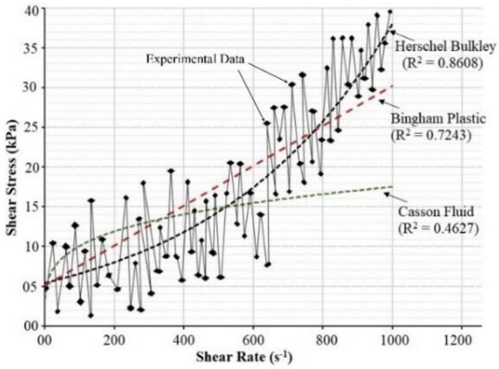

Fig. 5. Fitting of experimental data in the three consecutive models

The coefficient of regression (R^2) of the above three models (for the fluid samples) is determined and is shown graphically in Fig. 6. It is clear from the figure that the R^2 value of Herschel Bulkley Model for almost all the experimental run is higher when compared to the other two fluid models used *i.e.* Bingham Plastic and Casson Fluid model. The higher R^2 value for Herschel Bulkley model (based on the mean values of the results) indicates that the fluid samples resembles the most with this model as compared with the other two models. Therefore from these results, it is found that Herschel Bulkley model suited best to the experimental data among all the three models. The value of R^2 fluctuate for each run from 1 to 18 because all the eighteen fluid samples have different values of yield stress, which depends upon the fluid composition. The run number 19 is for the optimised MR finishing fluid sample at 0.3 T magnetic flux density, which is similar to the experimental condition of experiment number 1 to 18. Whereas run number 20, 21 and 22 is the R^2 for the optimised at a magnetic flux density of 0.4 T, 0.5 T and 0.6 T respectively. The reason for selecting the range of magnetic flux density from 0.3 T to 0.6 T is that the saturation magnetisation of the MR finishing fluid lies in this range.

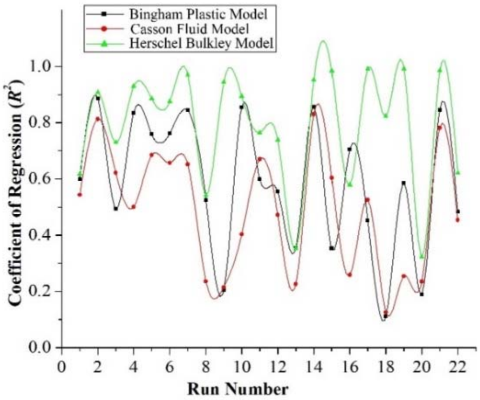

Fig. 6. Comparison of the coefficient of regression (R^2) for the three fluid models

Therefore based upon the R^2 results yield stress values from Herschel Bulkley model is taken as a response parameter in the ANOVA. Viscosity is taken as second response parameter whose values are obtained from Bingham Plastic model as it is an exceptionally simple model and suitable for the post-yield viscosity of MR fluid see Casson (1959), Dash *et al.* (1996) and Rabinow (1948). It clearly shows that the sample has its resemblance with Bingham Plastic fluid model.

4. ANALYSIS OF VARIANCE FOR YIELD STRESS

Analysis of variance (ANOVA) has been carried out to find out the significance of the model and also the contribution of each input parameter on the yield stress. The significance of each input parameter on yield stress is shown in Table 4. The results from the ANOVA reveals that iron particles volume percentage has the highest influence with 91.68% contribution while the type of carrier fluid has found to be the least influential parameter. The carrier fluid volume percentage has found to have 5.25% contribution and the abrasive particles has 1.54 % contribution. The interaction between iron particle and carrier fluid is found to be significant with *p-value* of 0.013 and have a contribution of 1.44% but interaction between iron particle and abrasive particle is found to be insignificant. Figure 7 depicts the plot of main effect for the yield stress. The analysis has been carried out with a quality characteristics taken as larger is the better. The S/N ratio analysis has also reaffirms that iron particle volume percentage is the highest influential factor on the yield stress of the MR finishing fluid.

Regression equation for yield stress of the MR finishing fluid can now be given as:

Yield stress = $21.593 - 0.0939\ A_1 + 0.0939\ A_2 - 7.5026\ B_1 - 0.0934\ B_2 + 7.5959\ B_3 + 2.0679\ C_1 - 0.8406\ C_2 - 1.2273\ C_3 + 0.6444\ D_1 + 0.602\ D_2 - 0.7047\ D_3 - 1.099\ B_1C_1 + 0.799\ B_1C_2 + 0.300\ B_1C_3 + 0.766\ B_2C_1 + 0.487\ B_2C_2 - 1.253\ B_2C_3 + 0.333\ B_3C_1 - 1.285\ B_3C_2 + 0.952\ B_3C_3 + 0.314\ B_1D_1 - 0.079\ B_1D_2 - 0.235\ B_1D_3 - 0.179\ B_2D_1 - 0.041\ B_2D_2 + 0.219\ B_2D_3 - 0.135\ B_3D_1 + 0.119\ B_3D_2 + 0.016B_3D_3$

While the Regression equation for shear viscosity of MR finishing fluid can be given as

Shear Viscosity = $283.402 - 1.232A_1 + 1.232A_2 - 98.468B_1 - 1.226B_2 + 99.694B_3 + 27.140C_1 - 11.032C_2 - 16.108C_3 + 8.458D_1 + 0.790D_2 - 9.249D_3 - 14.43B_1C_1 + 10.49B_1C_2 + 3.94B_1C_3 + 10.05B_2C_1 + 6.39B_2C_2 - 16.44B_2C_3 + 4.37B_3C_1 - 16.87B_3C_2 + 12.50B_3C_3 + 4.12B_1D_1 - 10.3B_1D_2 - 3.09B_1D_3 - 2.35B_2D_1 - 0.53B_2D_2 + 2.88B_2D_3 - 1.77B_3D_1 + 1.56B_3D_2 + 0.21B_3D_3$

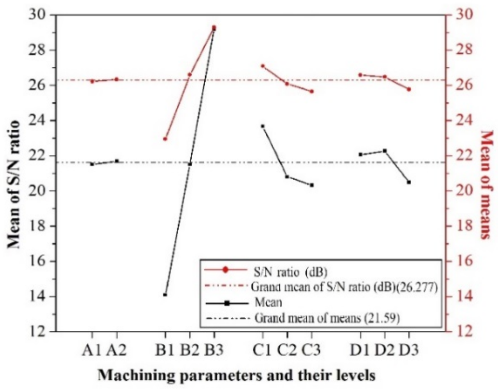

Fig. 7. Main effects plot for mean of means and mean of S/N ratios for yield stress as response parameter

From ANOVA, the optimum values of the on-state yield stress and shear viscosity is predicted as 31.758 kPa and 416.81 kPa-s respectively at 'A_2 - B_3 - C_1 - D_2' combination of the input parameter's levels.

The fluid sample with the suggested combination is then synthesised and experiments are conducted on it to confirm the predicted results. For this sample, the on-state yield stress has come out as 32.05 kPa and shear viscosity as 420.7 kPa-s. Both of these values lies between 95% conformation intervals of the predicted values. The characteristic curves of the optimised fluid sample are shown in the following sections.

5. RESULTS AND DISCUSSION

The characterization of MR finishing fluid is based upon two rheological properties *i.e.* yield stress which governs the commencement of fluid flow and the shear viscosity which represents the behaviour of fluid under flow. For MR fluids, the off-state viscosity is to be the minimum while the on-state yield stress of the fluid is to be the maximum by Bica (2002).

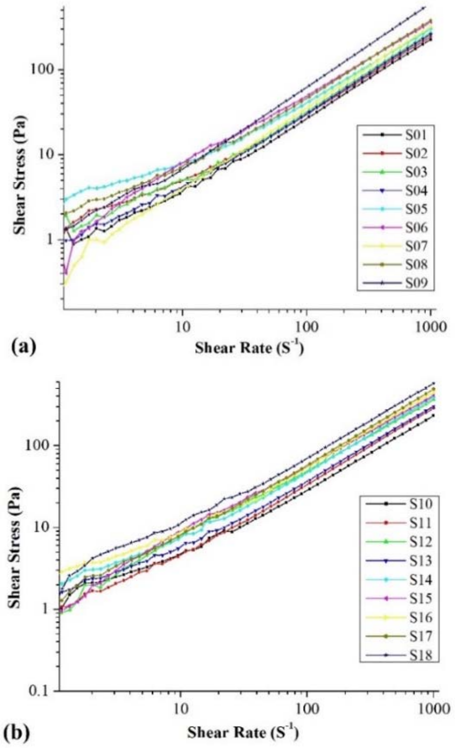

Fig. 8. Shear rate v/s shear stress for MR finishing fluid samples (a) From sample 1 to 9, having carrier medium as deionised water and (b) from sample 10 to 18, having silicon oil as carrier medium

Table 4 ANOVA results for response parameter as on state yield stress

Source	DF	Seq SS	Mean SS	F-value	p-value	Remarks
A-Type of carrier Fluid	1	0.159	0.159	4.56	0.166	
B-Iron particles Vol.%	2	683.973	341.986	9831.23	0.000	Significant
C-Carrier Fluid Vol. %	2	39.154	14.600	419.72	0.002	Significant
D-Abrasive Particles Vol.%	2	11.506	2.060	59.22	0.017	Significant
B×C	4	10.755	2.625	75.46	0.013	Significant
B×D	4	0.412	0.103	2.96	0.268	
Error	2	0.070	0.035			
Total	17	746.027				
Model Summary						
SD = 0.186509; R-sq. = 99.99%;			R-sq.(adj) = 99.92%;		R-sq.(pred) = 99.24%	

For the present study, the presence of non-magnetic abrasives particle plays a major role in deciding the rheological behaviour of MR finishing fluid as these particles act as a defect site in the iron particles lattice and affect the stress required for the commencement of the MR finishing fluid to flow *i.e.* yield stress. Shear stress v/s shear rate data are plotted to ascertain the flow behaviour of the fluid and is shown in Fig. 8 for all the fluid samples at a constant magnetic field (0.3 Tesla). Figure 8 (a) is showing the plots of fluid samples (from 1 to 9) having deionized water as carrier medium while Fig. 8 (b) shows for the fluid samples (from 10 to 18) having silicon oil as carrier medium. These variation of shear stress is plotted up to shear rate of 1000 s^{-1}. The highest shear stress value obtained is 31.758 kPa for sample no. 7 while the lowest shear stress value is 12.062 kPa for sample no. 3.

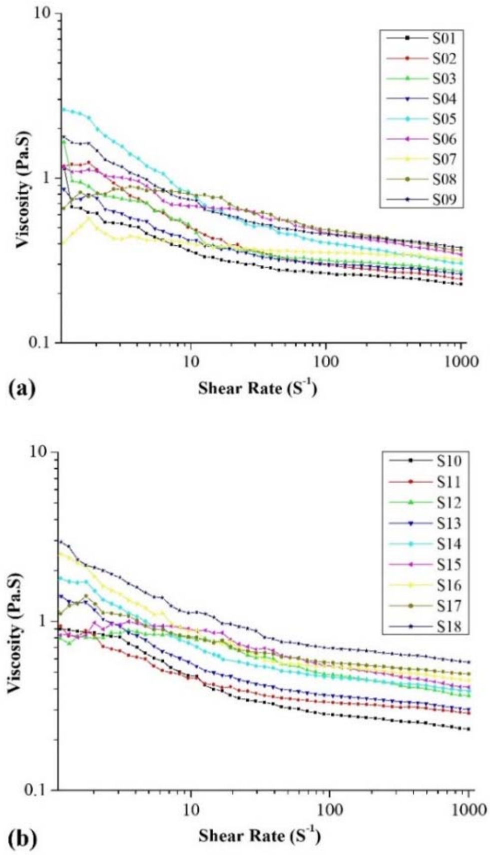

Fig. 9. Shear rate v/s dynamic viscosity for MR finishing fluid samples (a) From sample 1 to 9, having deionised water as carrier medium and (b) From sample 10 to 18, having silicon oil as carrier medium

Figure 9 (a) & (b) shows the variation of viscosity with shear rate for all the prepared fluid samples and from these graphs a typical shear thinning behaviour can be observed. It is because of the randomly breaking and reformation of the iron particles' chains. The variation of viscosity up to a shear rate of 1000 s^{-1} has been undertaken because after that no considerable change has been observed in the viscosity. It is because that after a specific level of shear rate, the time available for reformation of the iron particles' chain is insufficient. At lower shear rates, there has not been any particular followed pattern by the fluid samples while at higher shear rates, all the fluid samples follows the same pattern so the role of magnetic flux density at higher shear rate is not understandable. The dynamic viscosity of the fluid samples at a shear rate of 1000 s^{-1} varies from 158.308 Pa-s for fluid sample no. 3 to 416.81 Pa-s for fluid sample no.7. Figure 10 shows the variation of shear stress and dynamic viscosity at varying shear rate of the optimised fluid. On state yield stress and shear viscosity of the optimised fluid sample came out as 32.05 kPa and 420.7 kPa-s respectively.

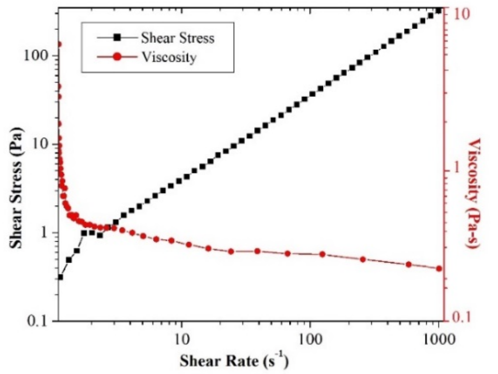

Fig. 10. Shear rate v/s shear stress and shear rate v/s dynamic viscosity for the optimised MR finishing fluid samples

5.1 EFFECT OF MAGNETIC FLUX DENSITY

The yield shear strength of the MR finishing fluid has found to be mainly depended on the volume percentage of the iron particles as well as on the applied magnetic field. The variation of shear stress of the MR finishing fluid samples with applied magnetic flux density is shown in Fig. 11.

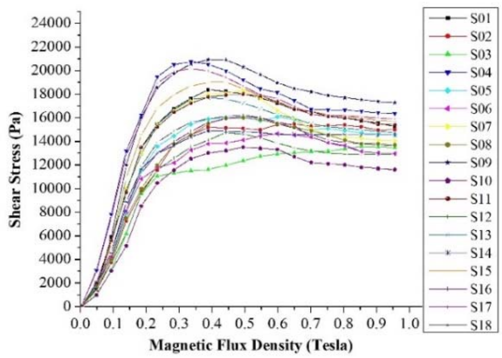

Fig. 11. Variation of shear stress with applied magnetic flux density for the eighteen prepared samples

From this figure, the shear stress of the MR finishing fluid samples have found initially increasing with magnetic flux density of around 0.3 Tesla and after that it is dropped a little from this highest attained value. The presence of non-magnetic abrasives particles act as a defect site in the iron particles lattice which is dominant beyond the saturation point and affects the stress for the commencement of the MR finishing fluid flow *i.e.* yield stress. The increase in shear stress is found to be nonlinear as the iron particles used in the fluid samples are of ferromagnetic in nature and the magnetisation of these at a particular magnetic field strength is different at different parts of the particles. The shear stress of the MR finishing fluid is restricted by the magnetic saturation of iron particles. Figure 12 shows the various interaction curves for yield stress variation with other experimental factors. From Figs. 12 (a) & (b), it is clear that iron particles and magnetic field strength both have positive impact on the yield stress of the fluid *i.e.* it increases with increase in both the parameters. Figure 12 (c) & (d) shows the effect of abrasive particles on the yield strength at different iron particles volume fraction and different magnetic field strength respectively. It is clear from these figures that the abrasive particles have negative impact on yield strength of the MR finishing fluid as these particles act as a defect site in the iron particles lattice and break the continuity of iron particles' chains which in-turn lowers the yield strength.

Figure 13 shows the interaction curves for viscosity of MR finishing fluid. Figure 13 (a) shows the variation of viscosity of MR finishing fluid with abrasive particle at different magnetic field strength. It is clear from the figure that the viscosity of fluid decreases with an increase in the volume fraction of abrasive particles while it increases with an increase in magnetic flux density. Figure 13 (b) shows the interaction of viscosity with volume percentage of the iron particles and the abrasive particles. The viscosity of MR finishing fluid increases with iron particles volume percentage but decreases with abrasive particles volume percentage.

5.2 Effect of Temperature on Shear Stress

The operating temperature of the finishing region during the finishing process increases due to the friction present between the circulating MR finishing fluid and workpiece surface which ultimately generates heat. Sometimes a high temperature during any mechanical process causes thermal expansion of elements of the machinery and workpiece which may results in poor precision. An unregulated high temperature also lowers the shear strength and shear viscosity of MR fluid at higher shear rates by Sidpara *et al.* (2009). A temperature related study is also carried out on the optimised fluid sample so as to find the effect of temperature on shear stress at varying magnetic flux density. The fluid sample is first tested at 22 ºC in the rheometer and thereafter at 10 ºC, 32 ºC and 50 ºC. The results are represented graphically in Fig. 14. This figure reveals an inverse relation of the shear stress with temperature *i.e.* an increase in temperature decreases the highest shear stress value attained by the fluid sample as well as the shear stress saturation value at a particular shear rate. The yield stress of an MR finishing fluid is thus found to be dependent on the magnetic flux density as well as on the temperature. In the initial phase of any

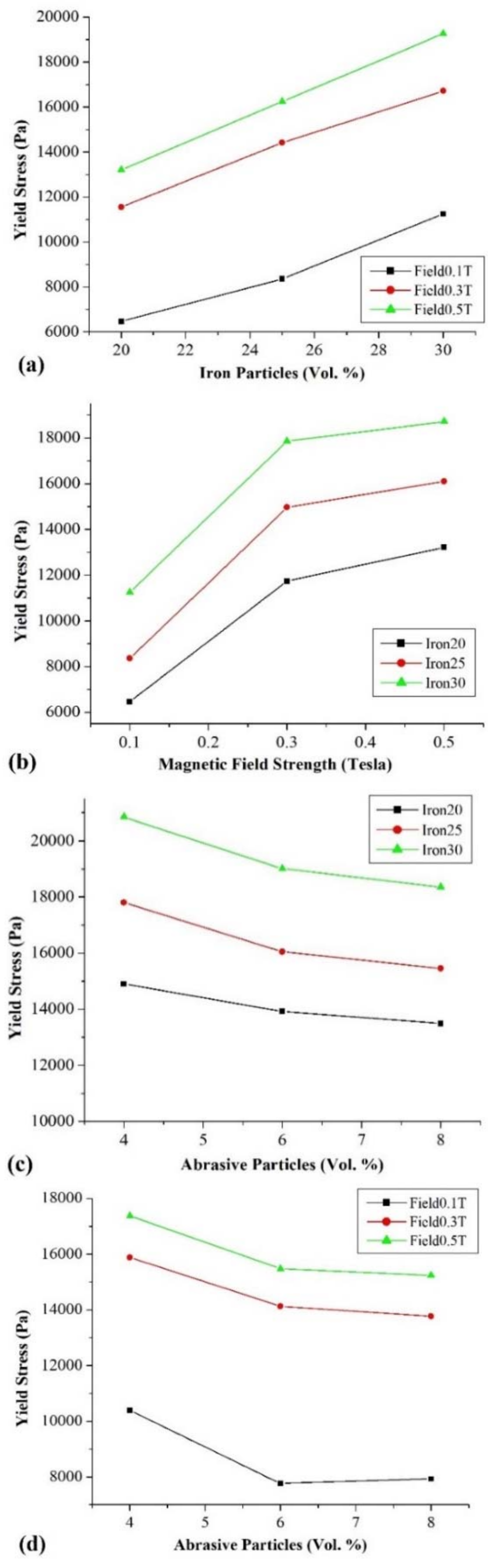

Fig. 12. (a) Effect of iron particle volume percentage on yield stress at different magnetic flux densities, (b) Effect of magnetic flux density on yield stress at different at different iron particle percentage, (c) Effect of SiC abrasive particles on yield stress with varying iron particle concentration (magnetic flux density of 0.7 T) and (d) Effect of SiC abrasive particles on yield stress with varying magnetic flux density at iron particle concentration as 25%

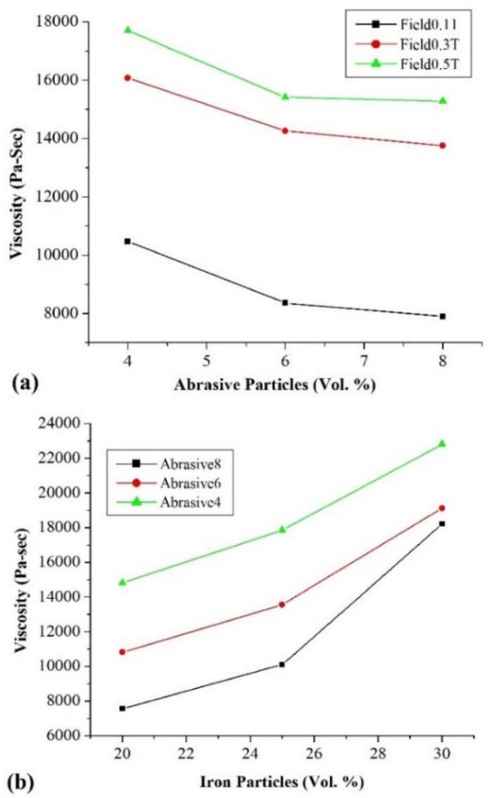

Fig. 13. (a) Effect of abrasive particles volume percentage on viscosity at different magnetic flux densities and (b) effect of iron particle volume percentage on viscosity at different abrasive particle concentration

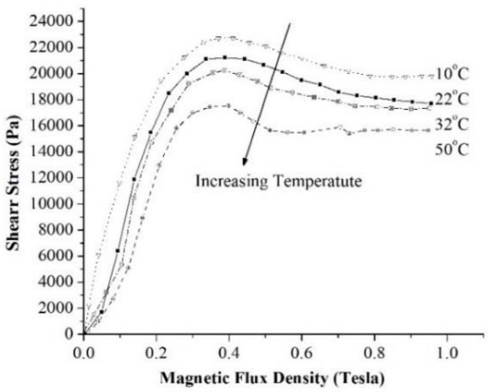

Fig. 14. Effect of temperature on yield stress of optimized fluid sample at varying magnetic flux density

MR finishing process, the active fluid exhibits a high yield stress but it reduces continuously as the temperature increases. To maintain a lower temperature, researchers must use some cooling arrangements like cooling coils which maintains the MR fluid temperature at a particular level.

6. CONCLUSIONS

In this study, MR finishing fluid has been characterised for a continuous flow finishing process. The rheological behaviour of the fluid has been investigated on an Anton Paar MCR 302 rheometer at temperature of 22 ºC, shear rate variation up to 1000 s^{-1} on different magnetic flux densities. Based on the rheological experimentation, following conclusions are drawn:

- Comparison of coefficient of regression (R^2) for the three constitutive models has concluded that Hershel–Bulkley model fits the best with the experimental data than the other two models (Bingham Plastic and Casson Fluid). One can, thus, use this model in continuous flow MR fluid finishing process for the modelling of MR finishing fluid.
- ANOVA results for output response as yield stress and shear viscosity with larger is the better characteristic has concluded that the volume percentage of iron particles is the most influential parameter having 91.68% contribution, whereas the type of carrier fluid has the least contribution of 0.02%.
- The rheographs of the fluid samples has showed shear thinning fluid behavior but at higher shear rates (*i.e.* > 600 s^{-1}) the difference between the rheological properties is not significant.
- The highest value of on state yield stress lies between a magnetic flux density ranges from 0.3 to 0.5 Tesla. Beyond this, the yield stress drops as the presence of non-magnetic abrasives particle acts as a defect site in iron particles chain lattice. Hence one has to operate the MR finishing process between 0.3 and 0.5 Tesla to get better material removal rate.
- From the interaction curves, it is concluded that the on state yield stress and the shear viscosity have a direct relationship with magnetic flux density and volume percentage of iron particles whereas volume percentage of abrasive particles has inverse relationship.
- By testing the optimized fluid sample at various temperatures, it is concluded that the yield stress shares an inverse relation with temperature *i.e.* with rise in temperature, the highest attained value of shear stress as well as the shear stress saturation value falls.

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