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Rheological Characterization and Performance Evaluation of Magnetorheological Finishing Fluid

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ABSTRACT

The novel controllable behaviour of magnetorheological (MR) fluid is the backbone of magnetorheological fluid-based finishing processes. MR fluid-based finishing processes facilitate better control over finishing forces as the stiffness of MR finishing fluid used in these processes can be controlled in accordance with the applied magnetic field and MR finishing fluid composition. Therefore, a detailed experimental investigation was carried out to find the effect of MR finishing fluid constituents on its yield stress through the Taguchi Design of Experiments. Rheological data obtained from a magneto-rheometer (MCR-102) was characterised by using Bingham plastic, Herschel–Bulkley and Casson's fluid constitutive modelling. The coefficient of regression (R^2) values of Herschel–Bulkley model were found to be best suited for all compositions of MR finishing fluid. Analysis of variance (ANOVA) has been used to find the contribution of selected parameters for improving the response characteristics. The optimized fluid has been then used for the finishing of biocompatible stainless steel AISI 316L, and the finishing results show that the average surface roughness value decreases down to 58 nm.

Keywords: Magnetorheological finishing fluid; Magnetic field strength; Yield stress; Constitutive models; Surface roughness.

1. INTRODUCTION

Magnetorheological finishing fluids are unique fluids exhibiting field-dependent properties and have applications in MR fluid-based finishing processes. The preparation of MR finishing fluid is based on utilising the novel behaviour of magnetorheological fluids commonly known as 'MR fluids'. MR fluids are composed of micron sized magnetisable particles dispersed in a carrier liquid. MR fluids exhibit a quick transition (with in milliseconds) in the rheological behaviour, when subjected to external magnetic stimuli (Leong *et al.*, 2016a, b; Park *et al.*, 2001; Sarkar and Hirani, 2015). They behave like a viscous liquid (Newtonian fluid) in the absence of a magnetic field whereas in the presence of a magnetic field they attain a semi-solid like structure (viscoelastic material). The dispersed magnetic particles acquire dipolar energy when subjected to a magnetic field and which results in the alignment of particles along or parallel to the magnetic field lines (Mangal and Sharma, 2017). The columnar structure of aligned magnetic particles thus formed exhibits resistance to the flow of MR fluid suspension, showing a rise in viscosity of the fluid suspension. The rheological properties (yield stress and viscosity) of MR fluids depend on the shape, size and concentration of magnetic particles as well as on the applied magnetic field strength. MR fluids are known to exhibit yield stress up to 100 kPa (Ngatu *et al.*, 2008). MR fluids are prepared by uniform mixing of micron sized magnetic particles in a carrier liquid. The micron size ferromagnetic particles are commonly used as a dispersed phase in a non-magnetic carrier liquid such as mineral oil, silicone oil and deionized water (Sukhwani and Hirani, 2007). The high density of the ferromagnetic particles compared to that of the carrier liquid creates severe problems in the MR fluid suspension. The solid content settles down because of density mismatch and aggregates to form hard clusters due to the presence of remanent magnetism in magnetic particles. Various methods to prevent sedimentation and agglomeration of magnetisable particles have been reported by researchers, which include addition of surfactants (Park *et al.*, 2001), viscoplastic media (Rankin *et al.*, 1999), thixotropic (Weiss *et al.*, 1997) or thickening agent, polymer coating of particles, etc.

The commercially available MR fluid usually costs around US $600 per litre, therefore low-cost electrolytic iron-based MR fluid samples with different types of additive have been prepared by Sukhwani and

Hirani. These electrolytic iron-based MR fluid samples exhibit considerable yield stress value under the applied magnetic field. Moreover, among the additives used, xanthan-gum-based sample has exhibited greater stability against sedimentation (Sukhwani and Hirani, 2007). Sarkar and Hirani (2013) observed that the yield strength of synthesized MR fluid increases by incorporation of oleic acid and tetramethylammonium hydroxide. Grease is added as the additive or stabilizer in the preparation of MR fluid and the effect of volume concentration of grease on the sedimentation rate of iron particles in the MR fluid has been investigated. The sedimentation rate was found to be lower at 0.15 volume percent concentration of grease (Premalatha *et al.,* 2012). HongZhe (2011) found that off-state viscosity of MR fluids decreases with the addition of suitable quantity of smaller particles to the MR fluid composition. Here, off-state refers to a condition when no magnetic field is applied to fluid sample. Incorporation of iron nanoparticles in the MR fluid composition results in improved stability of the MR fluid suspension (Chand *et al.*, 2014; Leong *et al.*, 2016 a, b). López-López *et al.* (2010) found that the magnetorheological (MR) effect of an MR fluid suspension decreased considerably with the addition of iron nanoparticles with a size range below 100 nm. These results imply that the relative size ratio and concentration of magnetic particles has significant effect on the rheological properties of MR fluids.

Researchers are much interested in the MR technology because of its unique rheological characteristics. Because of unique rheological characteristics, MR fluids possess potential applications to be used in a wide range of electro-mechanical devices such as artificial joints, clutches, dampers, shock absorbers, control valves, engine mounts (Park *et al.,* 2001). In such kind of devices, MR fluid is used under different modes of operation i.e. shear, squeeze and valve mode (Kumbhar *et al.,* 2015). One of the effective utilizations of MR fluid is in finishing operations. Researchers has been successfully reported the use of MR fluids in finishing of optical glasses and extended this to hard metals and alloys. Suitable quantity of non-magnetic abrasive particles needs to be added in MR fluids to achieve desired finishing action. The dispersion of non-magnetic abrasives and magnetic particles in a carrier liquid with some additives is termed as "Magnetorheological finishing fluid". The presence of non-magnetic solid particles hinders the complete formation of columnar chain structure, due to which on-state yield stress and viscosity of the fluid sample decreases and hence the so-called MR effect. The composition of magnetorheological finishing fluid is very crucial as it decides the magnitude of finishing force acting on workpiece surface at a particular magnetic field. A number of researchers have developed and characterize MR finishing fluids for specific applications. In the rheological characterisation of MR finishing fluids by Jha and Jain (2009), it was determined that the MR polishing fluid exhibits a shear thinning behaviour and the Herschel Bulkley model was found to be the best suited model for the fluid. Sidpara *et al.* (2009) found that the yield stress of the MR finishing fluid increases both with the volume concentration of magnetic particles and applied magnetic field. The effect of temperature on the stability of the fluid was also determined and it was observed that the yield stress decreases with an increase in temperature.

1.1 Motivation for the Research Work

The possibilities for the improvement of surface finish of a work material in MR fluid-based finishing processes greatly depends on the applied magnetic field, composition and chemistry of the MR finishing fluid acting on the selective surface. The applied magnetic field greatly affects the rheological properties of MR finishing fluid. In addition, the composition of the fluid also has a significant effect on the rheological properties. Right selection (type, shape, size) and appropriate concentration of magnetic particles, abrasive particles and carrier liquid along with additives may provide the required levels of strength to MR finishing fluid structure for better finishing of a work material. Based on the literature survey, it is concluded that considerable research has been conducted by researchers on the rheological characterisation of MR fluids (without addition of non-magnetic abrasives) and their sedimentation problems. However, the rheological behaviour of MR fluids becomes more complex with the addition of non-magnetic abrasive particles which needs to be explored. Therefore, this research work is carried out to find the effect of different constituents of MR finishing fluid on their yield stress. Magnetic iron particles and non-magnetic SiC abrasives with variable volume fractions have been mixed in different types of carrier liquids to prepare different compositions of MR finishing fluid samples. Two types of carrier liquids viz. silicon oil and mineral oil have been used along with addition of lithium grease as an additive to improve suspension stability of particles. Rheological tests have been carried out using a magneto-rheometer and the obtained data has been further characterised using Bingham plastic, Herschel–Bulkley and Casson's fluid models. The R^2 value obtained from these constitutive models has been compared to find out the best fit of the data used. The yield stress of the best-fit model has been further used as output response for the Taguchi analysis as per L_{18} orthogonal array (OA). The Taguchi method has been applied to find the optimum settings of a fluid composition that yield higher yield stress in the selected range of parameters. Analysis of variance (ANOVA) has been applied to find the significance of the selected input parameters. Moreover, the optimized fluid sample has been further used to finish biomedical-grade stainless steel SS-316L work material using in-house-developed magnetorheological finishing setup.

2. MATERIALS AND METHODS

2.1 Materials

The key elements used for the preparation of MR finishing fluid samples in the present research work include carrier liquid, micron sized iron particles, abrasive particles and some additives. Commercially available iron particles from Sigma-Aldrich, product number 12310 and 209309, have been used as magnetisable particles. The iron particles are spherical and flake shaped, which has been observed via scanning electron microscopy (Fig. 1(a) & 1(b)). Silicon oil and mineral oil have been used as carrier liquids while green silicon carbide (Fig. 1(c)) has been used as the non-magnetic abrasive for the preparation of 18 samples as per L_{18} OA. Stearic acid has been used as surfactant and white lithium grease has been used as additive to improve stability of dispersed particles in the MR finishing fluid. Vibrating sample magnetometer (VSM) analysis of iron particles have been also performed to evaluate their magnetic properties (Fig. 2(a) & 2(b)).

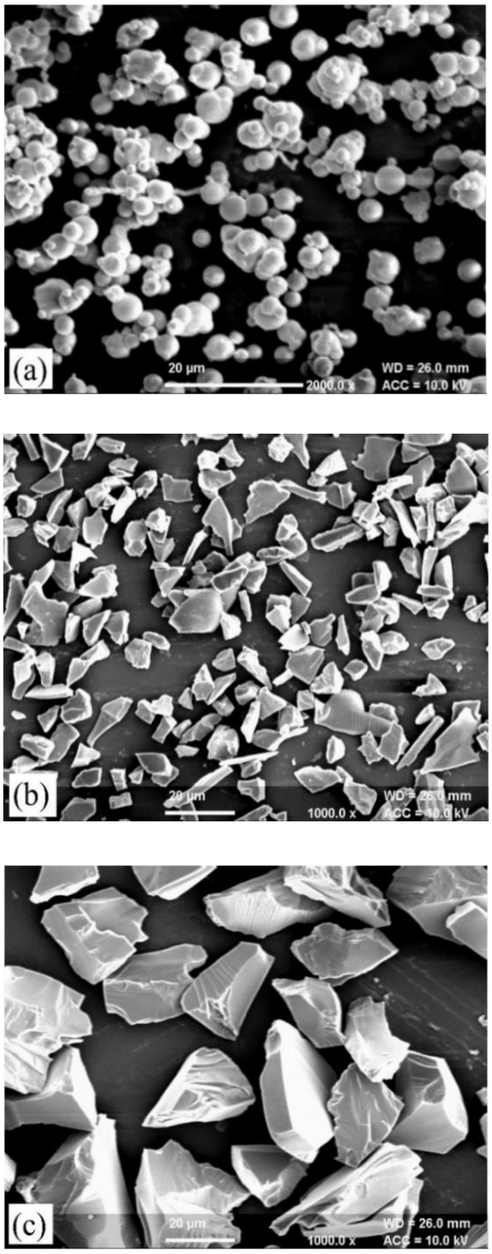

Fig. 1. SEM micrograph of (a) spherical iron particles (b) flake type iron particles and (c) abrasive (SiC) particles.

2.2 Experimental Design

The type of carrier liquid and iron (Fe) particles, and volume% fractions of iron and abrasives particles are selected as input parameters to find the influence on the performance characteristics (yield stress) of the MR finishing fluid. Selected input parameters and their levels are given in Table 1. Taguchi design of experiments has been used to select suitable OA for the selected input parameters and their levels. Taguchi method is a powerful design which is widely used in engineering analysis. It helps to minimize the effect of uncontrollable parameters and to decide optimum setting of parameters. The OA designed by Taguchi's are very helpful in various types of experimental conditions by dramatically reducing the number of experiments. For the selected parameters and levels in the present work, L_{18} mixed type OA has been selected and eighteen samples are prepared on the basis of selected OA design which is given in Table 2. L_{18} is a mixed level OA, where one parameter is varied at 2 different levels and remaining parameters are varied at 3 different levels. The more details about Taguchi's method is given by researchers (Asiltürk and Akkuş, 2011; Karabulut, 2015; Pang *et al.*, 2013; Revuru *et al.*, 2018). 'Larger-the-better' quality characteristics for yield stress has been selected, as the aim of this research work is to maximize the yield stress.

2.3 Synthesis of Magnetorheological Finishing Fluid

MR finishing fluid samples with 'were prepared by using two types of carrier liquids in which different vol.% fractions of iron and abrasives particles with 'were added and mixed uniformly via mechanical stirring. Iron particles of spherical (S) shape, flake shape (F) and mixed type (M) with 'were used in the preparation of 18 different samples. Mixed type particles include 60 wt.% fractions of flake shape particles and 40 wt.% of spherical shape particles. First stearic acid with 5 wt.% of the mass of iron particles was added and mixed with the carrier liquid. Thereafter, white lithium grease (15 wt.% of carrier liquid) was added in the carrier liquid and mixed thoroughly for 30 min., which results in a homogeneous mixture usually termed as the base fluid. After that the iron particles was added slowly (as per required vol. concentration) in the base fluid and mixed simultaneously. Stirring was continued further for 20 min. and then SiC abrasives was added slowly in the required amount with simultaneous stirring. Mixture was stirred for an additional 20 min. for proper distribution of iron and SiC abrasives.

2.4 Experimental Work

The experimentation work involves the rheological characterization of MR finishing fluid samples as it is the utmost requirement before its use in a specific application. The bonding strength of abrasives in the stiffened chain structure of iron particles is very important for their use in a finishing application. By keeping this in mind, the rheological properties of prepared samples were tested by using an Anton Paar modular compact rheometer, MCR-102 (Fig. 3). The parallel plate measuring system was used for rheological testing of samples. The system comprises two flat plates, one (upper plate) of them is coupled to the spindle of the motor mounted to the head unit of the rheometer. The other plate (lower plate) is connected to the base unit of rheometer and kept stationary. The Magnetic field was applied to fluid sample which acts in such a way that the field

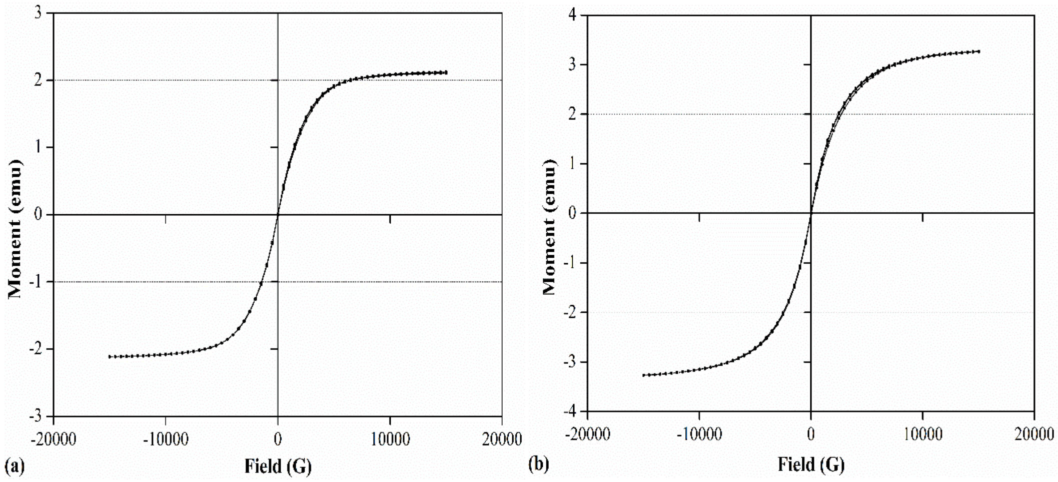

Fig. 2. VSM spectra of (a) spherical type iron particles and (b) flakes type iron particles.

Table 1 Selected input parameters and levels

Parameters	Symbol	Unit	Level 1	Level 2	Level 3
Carrier liquid type	A	--	Silicon oil	Mineral oil	__
Fe concentration	B	vol.%	25	30	35
Fe particles type	C	--	S*	M*	F*
SiC concentration	D	vol.%	5	10	15

S*: Spherical shape; M*: Mixed (Spherical and Flake) type; F*: Flake shape

Table 2 L18 Orthogonal array with selected input parameters, levels and output response

Sr. No.	Carrier liquid type	Fe concentration (vol.%)	Fe particles type	SiC Concentration (vol.%)	Yield stress (kPa) based on HB	S/N ratio (dB)
1	Silicon Oil	25	S	5	18.54	25.3622
2	Silicon Oil	25	M	10	19.76	25.9157
3	Silicon Oil	25	F	15	17.27	24.7458
4	Silicon Oil	30	S	5	20.63	26.2900
5	Silicon Oil	30	M	10	25.39	28.0933
6	Silicon Oil	30	F	15	21.04	26.4609
7	Silicon Oil	35	S	10	24.32	27.7193
8	Silicon Oil	35	M	15	26.45	28.4485
9	Silicon Oil	35	F	5	26.88	28.5886
10	Mineral Oil	25	S	15	17.47	24.8459
11	Mineral Oil	25	M	5	22.41	27.0088
12	Mineral Oil	25	F	10	21.85	26.7890
13	Mineral Oil	30	S	10	22.16	26.9114
14	Mineral Oil	30	M	15	24.92	27.9310
15	Mineral Oil	30	F	5	22.81	27.1625
16	Mineral Oil	35	S	15	22.24	26.9427
17	Mineral Oil	35	M	5	31.46	29.9552
18	Mineral Oil	35	F	10	29.53	29.4053

lines flows perpendicular to the direction of shear flow of fluid sample. Approximately 0.3 ml sample was loaded on the lower plate and the position of upper plate was set at 1 mm apart from lower plate. The temperature was maintained at 25 °C during testing, with the help of a temperature controller unit. The experimental procedure towards steady measurement has been divided into three steps:

1.) Firstly, the Pre-Shearing of fluid samples at zero field and constant shear rate (100 s^{-1}) was carried out for 30 s.

2.) To ensure steady measurement of the data, time sweep test was carried out keeping shear rate and magnetic field constant, which determines the necessary time required by a sample to give steady stress values.

3.) After that, all the fluid samples were tested at a current setting of 3 A, which generated a magnetic field strength of 0.6 T in the shearing zone. The shear rate was varied from 0.1 to 1000 s^{-1} and the time interval of measurement for each experiment was selected on the basis of time sweep test as mentioned in step 2. Accordingly, each shear stress value corresponding to a particular shear rate was recorded in 3 min. time duration.

All 18 samples were tested with three repetitions to reduce possible errors affecting the experimental results and to obtain more accurate and precise results. The flow curves (shear stress vs shear rate) of all the samples are shown in Fig. 4. The commencement of fluid flow starts only after a critical shear stress value, which is termed as yield stress of the MR finishing fluid. It shows the strength of the fluid structure which solely depends on fluid composition and applied magnetic field strength. Yield stress can be calculated by fitting the experimental data in appropriate fluid models.

Fig. 3. Anton-Paar modular compact rheometer (MCR-102).

3. Modelling and Analysis

3.1 Constitutive Modelling

The rheological characterization of an MR finishing fluid is the key aspect for its proposed applications. Bingham Plastic (BP), Herschel-Bulkley (HB) and Casson's fluid (CF) are the most commonly used models for the rheological characterization of MR finishing fluids (Chhrabra and Richardson, 1999). All these models assume that the fluid flow starts only after a threshold stress value (known as yield stress) reached during shearing. The post-yield behaviour of these models acts in a different way. Therefore, all these models were selected to fit the output data obtained from magneto-rheometer in the corresponding equations of these models.

Bingham Plastic model is a two parameter model and model equation is given as (Rankin *et al.*, 1999; Bae *et al.*, 2017):

$$\tau = \tau_y + \eta_p \cdot \dot{\gamma} \tag{1}$$

where τ is the shear stress, τ_y is the yield stress, $\dot{\gamma}$ is the shear rate and η_p is the plastic viscosity of the fluid. It is the simplest model and widely used in characterization of MR fluids. Bingham Plastic model assumes that the fluid sample behaves like a rigid body in the pre-yield region (where stress is below the yield point). In the post-yield region flow curve shows a linear behaviour, where shear stress is proportional to the shear rate (Chaudhuri *et al.*, 2005).

In a case where the post yield behaviour becomes nonlinear i.e post yield viscosity of fluid sample either decreases or increases. For this kind of behaviour, Herschel-Bulkley fluid model can be used (Papanastasiou and Boudouvis, 1997; Bae *et al.*, 2017). The equation of Herschel-Bulkley fluid model is given as:

$$\tau = \tau_y + K \cdot \dot{\gamma}^n \tag{2}$$

where n is the flow behavior index and K is the consistency coefficient. The value of flow behavior index 'n' less than 1 indicates shear thinning behavior of fluid. The consistency coefficient 'K' resembles the viscosity of the fluid.

Casson's fluid model (Dash *et al.*, 1996; Gabriel and Laun, 2009) is a two-parameter model, according to which the shear stress and shear rate relation is given as:

$$\sqrt{\tau} = \sqrt{\tau_y} + \sqrt{n_c \cdot \dot{\gamma}} \tag{3}$$

where n_c is the Casson's viscosity.

The data obtained from the rheometer for all the 18 samples has been fitted in the governing equation of Bingham Plastic, Herschel-Bulkley and Casson's fluid models. The coefficient of regression (R^2) for all the fluid samples as per BP, HB, CF models were calculated to find the goodness of fit of the experimental data with regression models. An R^2 value closer to 1 for a model implies that the data fits better with that particular fluid model. In the present case, R^2 values (Fig. 5) of almost all the analysed samples were found to be higher in the case of HB model. It reveals that the experimental data fits best with the HB model which describe the flow behaviour of the MR finishing fluid. In the literature, the Bingham Plastic model has been shown as the best model for MR fluids (Chaudhuri *et al.*, 2005). However, it does not represent the flow behaviour for the MR finishing fluid realistically because of the presence of non-magnetic abrasive particles in the fluid.

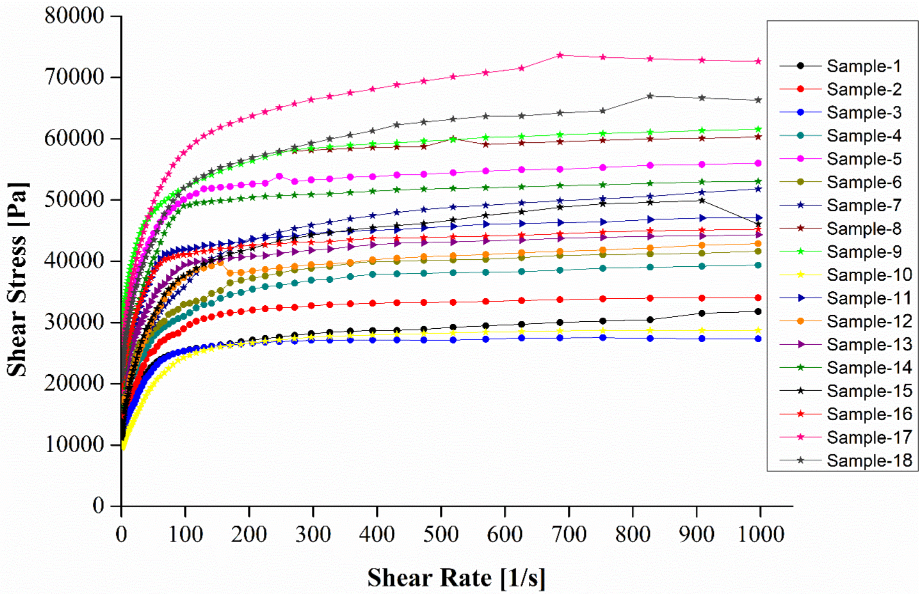

Fig. 4. Flow curves of all the 18 samples at a magnetic field strength of 0.6 T.

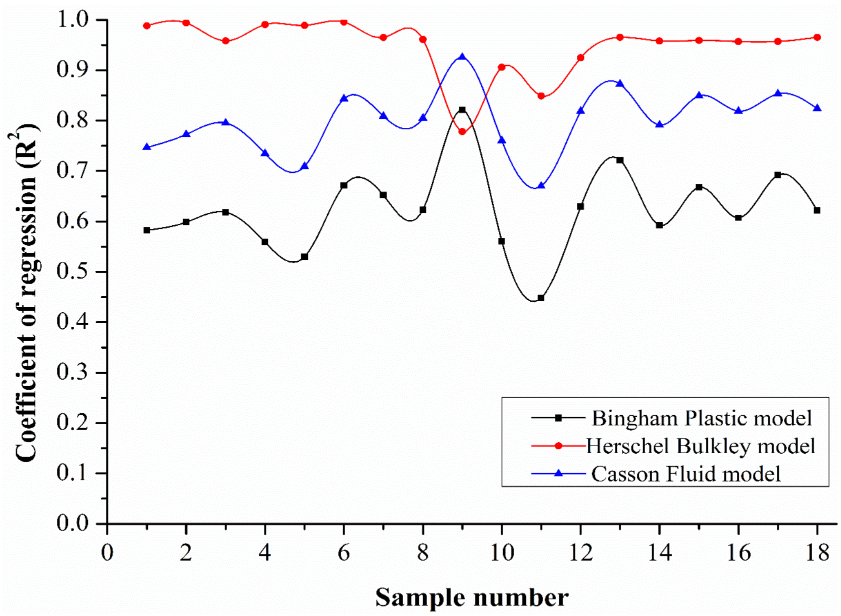

Fig. 5. Coefficient of regression of all the samples as per BP, HB and Casson fluid models.

Therefore, the Herschel-Bulkley mean yield stress values (Table 2) were taken as the output response parameter because of the best fit of experimental data with this model. It was also observed that the all MR finishing fluid samples exhibit shear thinning behaviour as the flow behavior index 'n' values of all fluid samples were found to be less than 1 (Fig. 6). The error bar graph of all the 18 samples for the repeated experiments is shown in Fig. 7. The I-symbol above each bar represents the standard deviations of the experimental data and the numeric value shows the respective mean yield stress values (as per HB model) for all the 18 samples.

3.2 Analysis of Raw Data and Signal-to-Noise (S/N) Ratio

Optimum combination of parameters for higher yield stress has been determined after the analysis of raw data and S/N ratio (Table 3a. & 3b.). The average effect of each parameter level on the output response is shown graphically for both raw data and S/N ratio in Fig. 8. The optimum level of control parameters for the yield stress value were determined as Carrier liquid type (mineral oil), Fe particle concentration (35 vol.%), Fe particle type (mixed), and SiC abrasive concentration (10 vol.%).

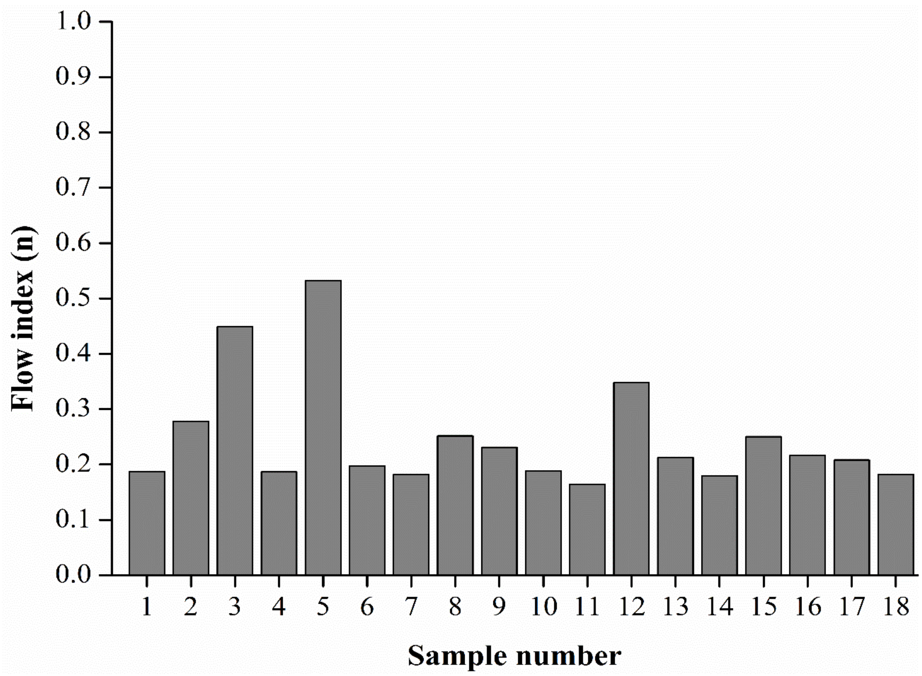

Fig. 6. Flow behavior index 'n' as per HB fluid model.

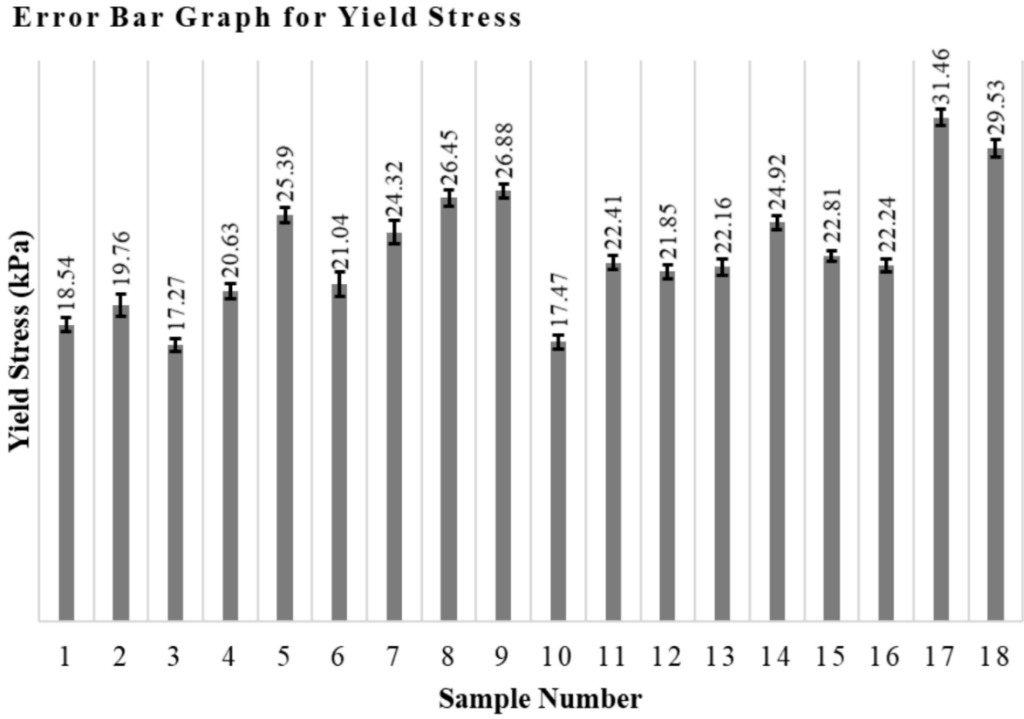

Fig. 7. Error bar graph of all the 18 samples.

3.3 Analysis of Variance for Yield Stress

ANOVA has been carried out to find out the significance of each input parameter and their percent contribution on the yield stress of the MR finishing fluid. The calculated results from ANOVA analysis are given in Table 4a. & 4b. From ANOVA table for S/N ratio, it has been revealed that the concentration and type of iron particles are the most influencing parameters with percent contribution of 62.53% and 20.11% respectively. The carrier liquid type has been found to be the least influential parameter with a contribution of 4.40%. The p-values (at 95% confidence interval) indicate that all the parameters within selected levels significantly affect the response.

Table 3a Response table of mean of means for yield stress

Level	Carrier liquid type	Fe conc. (vol.%)	Fe particles type	SiC conc. (vol.%)
1	22.25	19.55	20.89	23.79
2	23.87	22.82	25.07	23.83
3	------	26.81	23.23	21.57
Delta	1.62	7.26	4.17	2.27
Rank	4	1	2	3

Table 3b Response table of signal to noise ratio for yield stress

Level	Carrier liquid type	Fe conc. (vol.%)	Fe particles type	SiC conc. (vol.%)
1	26.85	25.78	26.35	27.39
2	27.44	27.14	27.89	27.47
3	------	28.51	27.19	26.56
Delta	0.59	2.73	1.55	0.91
Rank	4	1	2	3

Table 4a Analysis of Variance for yield stress

Source	DF	Seq SS	Mean SS	F-ratio	p-value	Percent contribution (%)	Remarks
A- Carrier liquid type	1	11.79	11.794	7.73	0.019	4.56%	Significant
B- Fe concentration (vol.%)	2	158.78	79.388	52.01	0.000	61.42%	Significant
C- Fe particles type	2	52.46	26.230	17.18	0.001	20.29%	Significant
D- SiC concentration (vol.%)	2	20.20	10.098	6.62	0.015	7.81%	Significant
Error	10	15.26	1.526	--	--	5.90%	--
Total	17	258.49	--	--	--	100.00%	--

Model Summary: R-sq.(adj) = 89.96%; R-sq.(pred) = 80.87%

DF: Degree of freedom; Seq SS: Sequential sum of squares; Mean SS: Mean sum of squares.

3.4 Estimation of Optimum Yield Stress

Based on Taguchi's approach, the optimum value of yield stress and confidence interval has been predicted theoretically and for this, optimal combination of input parameters' levels i.e. A2-B3-C2-D2 have been used. The theoretically calculated mean value of yield stress is 30±3 kPa. Confirmation test need to be conducted at the optimal level of input parameters after the estimation of optimum output response to validate the predicted values. An MR finishing fluid sample has been prepared using the optimal combination of input parameters and levels. Rheological characterisation of the newly prepared sample has been carried out using similar conditions.

The obtained results from the magneto-rheometer were further analysed using the Herschel-Bulkley fluid model. The yield stress obtained by using this model is 33.06 kPa, which is very close to the predicted values. Therefore, the predicted and experimental results show successful optimization with the selected combination of parameters and their levels.

4. RESULTS AND DISCUSSION

The effect of different constituents of the MR finishing fluid on the yield stress is discussed as:

4.1 Effect of Iron Particle Concentration

The concentration of magnetic particles has a significant effect on the yield stress of the MR finishing fluid. The yield stress increases with an increase in the concentration of ferromagnetic iron particles as shown in Fig. 8(b). This is because a higher concentration of magnetic particles in a fixed volume of the carrier medium increases the magnetic saturation of the MR finishing fluid. Further, the presence of a greater number of magnetic particles in the MR finishing fluid results in a more-dense structure at the same magnetic field. Therefore, the strength of the MR finishing fluid structure increases sufficiently which impedes its flow and more stress is required to break the structure.

4.2 Effect of Iron Particle Type

The yield stress of the MR finishing fluid containing the mixed-type iron particles have been found to be higher (Fig. 8(c)) because the spherical particles may fill the gap between flake type iron particles, due to which the complete chain formation of particles takes place. The complete chain formation results in a higher strength of the fluid sample.

Table 4b Analysis of Variance for S/N ratio (dB)

Source	DF	Seq SS	Mean SS	F-ratio	p-value	Percent contribution (%)	Remarks
A- Carrier liquid type	1	1.577	1.577	9.94	0.010	4.40%	Significant
B- Fe concentration (vol.%)	2	22.392	11.196	70.56	0.000	62.53%	Significant
C- Fe particles type	2	7.200	3.600	22.69	0.000	20.11%	Significant
D- SiC concentration (vol.%)	2	3.053	1.526	9.62	0.005	8.52%	Significant
Error	10	1.587	0.158	--	--	4.43%	--
Total	17	35.807	--	--	--	100.00%	--

Model Summary: R-sq.(adj) = 92.47%; R-sq.(pred) = 85.64%

DF: Degree of freedom; Seq SS: Sequential sum of squares; Mean SS: Mean sum of squares.

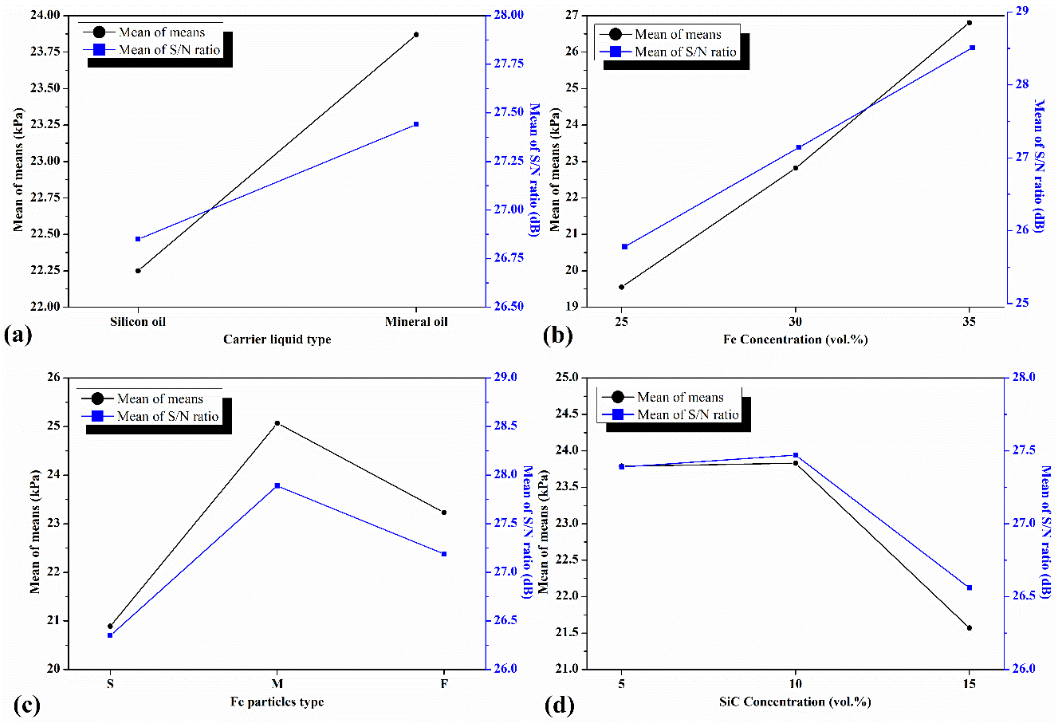

Fig. 8. Main effects plot for Mean of means and Mean of S/N ratio.

The yield stress of the MR finishing fluid samples having flake-type iron particles have been found to be higher compared to samples containing spherical iron particles. It may be due to the higher saturation magnetisation of flake-type iron particles (Fig. 2(b)).

4.3 Effect of Abrasive Particle Concentration

The yield stress of MR finishing fluid samples increases slightly with an increase in concentration of abrasive particles up to a certain value, but thereafter it decreases (Fig. 8(d)). It is because of the inclusion of a large number of non-magnetic abrasive particles in between the magnetic particle chain structure, which act as an impurity site in the chain structure. The inclusion of abrasive particles increases the distance between adjacent magnetic particles due to which the magnetic interaction force decreases. Because of this, the chain structure of magnetic particles becomes weak, disturbed and discontinuous.

In the present study, no considerable change was observed when the abrasive concentration have been increased from 5 vol.% to 10 vol.%. However, the yield stress of fluid sample decreases sharply at 15 vol.% concentration of abrasives, which can affect the finishing process adversely. Therefore, an abrasive concentration of 10 vol.% has been considered better for the finishing application as

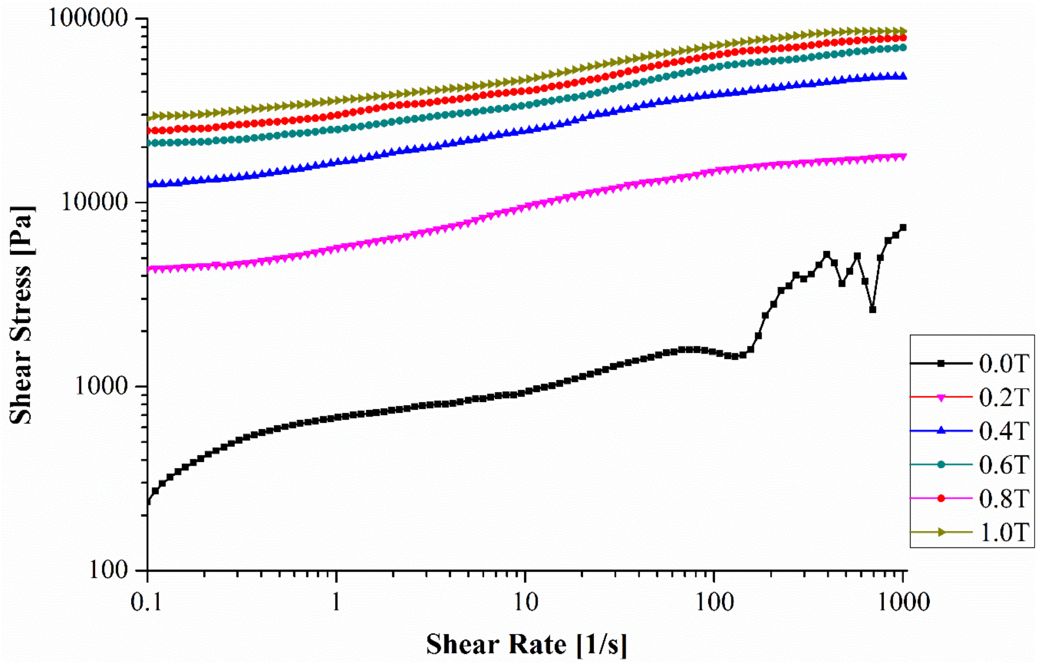

Fig. 9. Yield stress of optimized fluid sample at different magnetic field strengths.

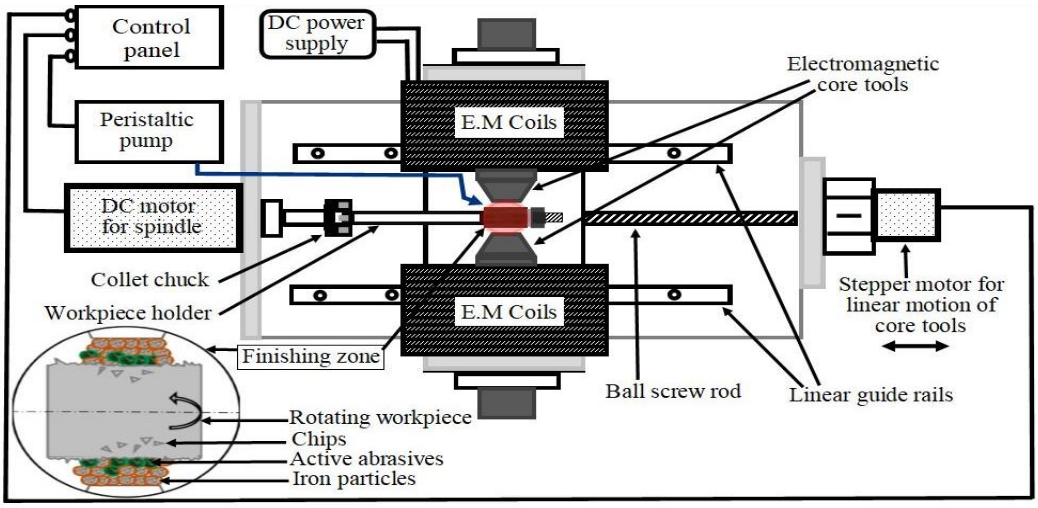

Fig. 10. Schematic of the used MR fluid finishing process.

Table 6 Experimental results

Sr. No.	MR finishing fluid sample	Initial average surface roughness (nm)	Final average surface roughness (nm)	Reduction in surface roughness (R_a)
1.	Sample number 12 (Table 2)	370	161	209
2.	Optimized sample	475	58	417

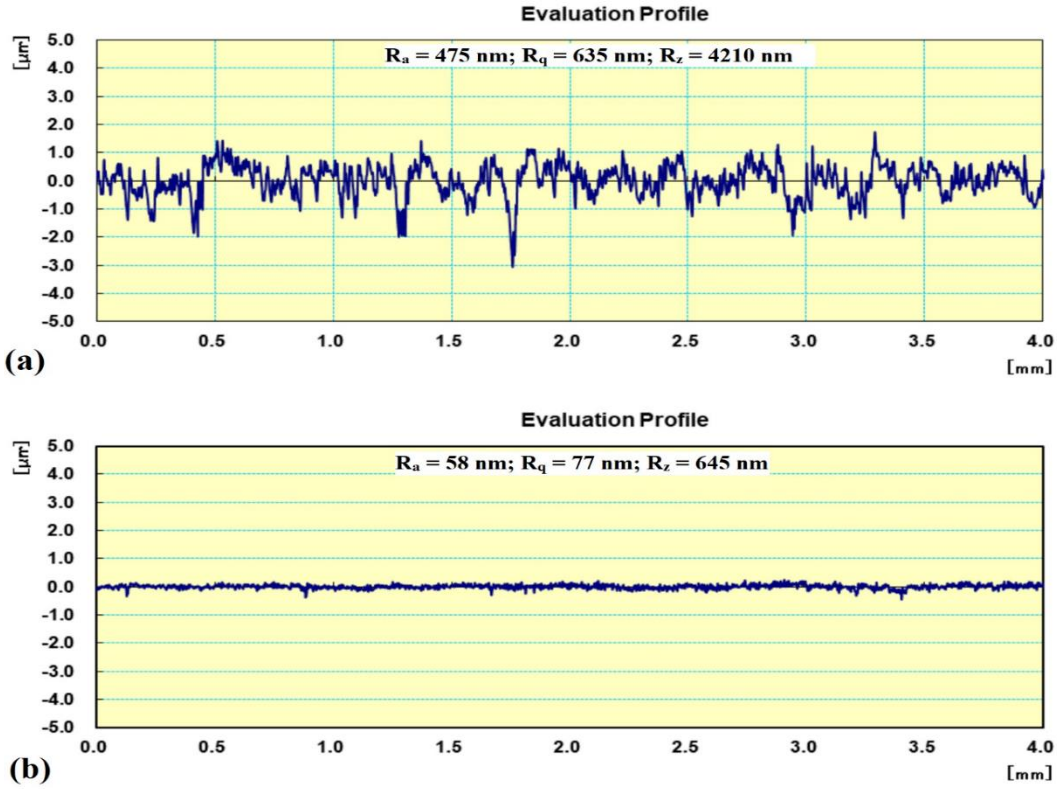

Fig. 11. Surface roughness profile of SS316L workpiece (a) before finishing and (b) after finishing with optimized fluid sample.

it provides more amount of abrasives with a higher yield stress value.

4.4 Effect of Magnetic Flux Density

The optimised MR finishing fluid sample has been tested under various magnetic field strengths and the obtained rheograms (shear stress vs shear rate) are shown in Fig. 9. The magnetic field strength has been found to be a highly contributing parameter for increasing the stiffness of the MR finishing fluid. The magnetic interaction force between iron particles increases with an increase in the applied magnetic field strength, which results in the strong bonding of particles and provides a stronger structure to the fluid sample. However, it is limited up to a certain value of the magnetic field strength because it also depends on the saturation magnetization of magnetic particles that finally restricts the strength of the MR finishing fluid structure. Furthermore, the effect of abrasive particles also becomes dominating beyond the saturation magnetization of magnetic particles.

5. APPLICATION OF OPTIMIZED FLUID SAMPLE IN FINISHING OPERATION

The optimized MR finishing fluid sample possessing maximum yield stress value was further used in the nano finishing of the stainless steel AISI316L workpiece surface. The stainless steel AISI316L material is widely used in the medical industry. The finishing experiments were performed on in-house developed experimental setup for a finishing time of 60 min. The surface roughness of the workpiece was measured before and after finishing using the Mitutoyo surftest SJ-410 roughness tester. In the finishing process, the workpiece was held between the electromagnetic core tools with a certain gap and rotated using a DC motor. The schematic of the finishing process shown in Fig. 10, elaborates the complete finishing operation. To compare finishing performance, finishing experiment was also carried out using the randomly selected MR finishing fluid sample, having low yield stress value (sample no. 12 in Table 2).

The experimental conditions during the finishing operation are given in Table 5.

Table 5 Experimental conditions for finishing experiments

Sr. No.	Experimental parameters	Values
1	Rotating speed	600 rpm
2	Working gap	1 mm
3	Magnetic field strength	0.6 Tesla
4	Linear feed	40 mm/min
5	Finishing time	60 min

The experimental results (Table 6) of the finished surface shows that the surface roughness value is reduced more with the use of the optimized finishing fluid sample. The finishing results show better performance of optimized fluid sample as compared to randomly selected fluid sample. Fig. 11(a) & (b) shows initial and final finished surface roughness profiles of the workpiece sample respectively.

6. CONCLUSIONS

In this research work, the effect of constituents of the MR finishing fluid on its yield stress was studied using the Taguchi technique. After analysis, the following conclusions are drawn:

- The constituents of MR finishing fluid sample have significant effect on the stiffness of fluid structure. The rheological properties of the MR finishing fluid samples changes considerably due to the effect of iron particles shape and vol.% concentration.
- The Hershel–Bulkley model found to be the best fitted model for the obtained experimental data. Therefore, it can be used for modeling of the MR finishing fluids.
- The fluid sample prepared with optimized setting of parameters exhibit higher yield stress value as compared to other samples.
- The fluid sample having higher yield stress results in better finishing performance as compared to sample possessing lower yield stress. Thus, the better finishing results can be obtained by using optimized fluid compositions.

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REFERENCES

Asiltürk, I. and H. Akkuş (2011). Determining the effect of cutting parameters on surface roughness in hard turning using the Taguchi method. *Measurement* 44(9), 1697–1704.

Bae, D. H., H. J. Choi, K. Choi, J. D. Nam and M. S. Islam (2017). Microcrystalline cellulose added carbonyl iron suspension and its magnetorheology. Colloids and Surfaces A: Physicochemical and Engineering Aspects 514, 161-167.

Chand, M., A. Shankar, Noorjahan, K. Jain and R. P. Pant (2014). An improved properties of bidispersed magnetorheological fluids. *RSC Advances* 4, 53960-53966.

Chaudhuri, A., N. M. Wereley, S. Kotha, R. Radhakrishnan and T. S. Sudarshan (2005). Viscometric characterization of cobalt nanoparticle-based magnetorheological fluids using genetic algorithms. *Journal of Magnetism and Magnetic Materials* 293, 206-214.

Chhrabra, R. P. and J. F. Richardson (1999). *Non-Newtonian Flow in the Process Industries: Fundamentals and Engineering Applications*, Elsevier Ltd., Oxford, Butterworth Heinemann.

Dash, R. K., K. N. Mehta and G. Jayaraman (1996). Casson Fluid Flow in a Pipe Filled With a Homogeneous Porous Medium. *Int. J. Engng Sci.* 34(10), 1145-1156.

Gabriel, C. and H. M. Laun (2009). Combined slit and plate–plate magnetorheometry of a magnetorheological fluid (MRF) and parameterization using the Casson model. *Rheol Acta* 48, 755-768.

HongZhe, T. (2011). Particle size polydispersity of the rheological properties in magnetorheological fluids. *Science China Physics, Mechanics & Astronomy* 54(7), 1258-1262.

Jha, S. and V. K. Jain (2009). Rheological characterization of magnetorheological polishing fluid for MRAFF. *The International Journal of Advanced Manufacturing Technology* 42, 656-668.

Karabulut, Ş. (2015). Optimization of surface roughness and cutting force during AA7039/Al2O3metal matrix composites milling using neural networks and Taguchi method. *Measurement* 66, 139–149.

Kumbhar, B. K., S. R. Patil and S. M. Sawant (2015). Synthesis and characterization of magneto-rheological (MR) fluids for MR brake application. *Engineering Science and Technology, an International Journal* 18, 432-438.

Leong, S. A. N., S. A. Mazlan, P. M. Samin, A. Idris and Ubaidillah (2016a). Performance of bidisperse magnetorheological fluids utilizing superparamagnetic maghemite nanoparticles. *AIP Conf. Proc.* 1710, 030050–1-030050–6.

Leong, S. A. N., P. M. Samin, A. Idris, S. A. Mazlan and A. H. A. Rahman (2016b). Synthesis, characterization and magnetorheological properties of carbonyl iron suspension with superparamagnetic nanoparticles as an additive. *Smart Materials and Structures* 25, 025025–1-025025–12.

López-López, M. T., P. Kuzhir, A. Meunier and G. Bossis (2010). Synthesis and magnetorheology of suspensions of submicron-sized cobalt particles with tunable particle size. *Journal of Physics: Condensed Matter* 22, 324106–1-324106–6.

Mangal, S. K. and V. Sharma (2017). Multi-parameter optimization of magnetorheological fluid with high on-state yield stress and viscosity. *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 39, 4191-4206.

Ngatu, G. T., N. M. Wereley, J. O. Karli and R. C. Bell (2008). Dimorphic magnetorheological fluids: exploiting partial substitution of microspheres by nanowires. *Smart Materials and Structure* 17, 045022–1-045022–12.

Pang, J. S., M. N. M. Ansari, O. S. Zaroog, M. H. Ali and S. M. Sapuan (2013). Taguchi design optimization of machining parameters on the CNC end milling process of halloysite nanotube with aluminium reinforced epoxy matrix (HNT/Al/Ep) hybrid composite. *HBRC Journal* 10, 138–144.

Park, J. H., B. D. Chin and O. O. Park (2001). Rheological Properties and Stabilization of Magnetorheological Fluids in a Water-in-Oil Emulsion. *Journal of Colloid and Interface Science* 240, 349-354.

Papanastasiou, T. C. and A. G. Boudouvis (1997). Flows of viscoplastic materials: Models and computations. *Computers and Structures* 64, 677-694.

Premalatha, S. E., R. Chokkalingam and M. Mahendran (2012). Magneto Mechanical Properties of Iron Based MR Fluids. *American Journal of Polymer Science* 2(4), 50-55.

Rankin, P. J., A. T. Horvath and D. J. Klingenberg (1999). Magnetorheology in viscoplastic media. *Rheologica Acta* 38, 471-477.

Revuru, R. S., J. Z. Zhang, N. R. Posinasetti and T. Kidd (2018). Optimization of titanium alloys turning operation in varied cutting fluid conditions with multiple machining performance characteristics. *The International Journal of Advanced Manufacturing Technology* 95, 1451–1463.

Sarkar, C. and H. Hirani (2015). Effect of particle size on Shear Stress of magnetorheological Fluids. *Smart Science* 3, 65-73.

Sarkar, C. and H. Hirani (2013). Synthesis and characterization of antifriction magnetorheological fluids for brake. *Defence Science Journal* 63, 408-412.

Sidpara, A., M. Das and V. K. Jain (2009). Rheological Characterization of Magnetorheological Finishing Fluid. *Materials and Manufacturing Processes* 24, 1467-1478.

Sukhwani, V. K., and H. Hirani (2007). Synthesis and characterization of low cost magnetorheological (MR) fluids. *Proceedings of SPIE - The International Society for Optical Engineering (Proceedings of SPIE)* 6526, 65262R–1-65262R–12.

Weiss, K. D., D. A. Nixon, J. D. Carlson and A. J. Margida (1997). *Thixotropic magnetorheological materials*, 5645752.