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Characterization and Optimization of Rheological Parameters of Polymer Abrasive Gel for Abrasive Flow Machining

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Abstract

Abrasive flow finishing is an advance machining process used to deburr, radius, polish, and remove recast layer of the complex geometries and hard materials. Abrasive media plays a major role in finishing because of its ability to precisely finish the selected surfaces along the media flow passage. A polymer abrasive gel (PAG) based alternative media for Abrasive Flow Machining (AFM)was developed keeping in view the properties like adhesiveness, self-deformability, visco-elasticity, porosity and permeability using natural polymer base, additives, and abrasives of different mesh sizes and concentration. In this study, the characterization of developed polymer abrasive gels(PAGs)were done by using Field Emission Scanning Electron Microscopy (FESEM), Thermo-gravimetric Analysis (TGA) and Fourier Transform Infrared Spectroscopy (FTIR).The Power law, Bingham Plastic, and Herschel–Bulkley fluid models were used to illustrate the rheological nature of developed PAGs. Experimental analyses were carried out using statistical design of experiments (DOE) to characterize rheological properties of developed PAGs. The effects of the control variables on viscosity of PAGs were analyzed using Taguchi technique. Analysis of variance (ANOVA) was used to determine contribution of each control variable on yield stress and viscosity of polymer abrasive gels.

Introduction

To overcome difficulties associated with traditional finishing process, advanced finishing processes are used for finishing intricate shapes and for superior quality surface finishing. Abrasive Flow Machining (AFM) process was developed by Extrude Hone Co. in the 1960s. In AFM, deformable cutting tool known as AFM media is extruded over the surfaces to be finished. During the finishing process a small quantity of material is removed by flowing a abrasive laden viscoelastic media over the surface to be finished. By using AFM as a base process, a lot of hybrid finishing process like magnetic abrasive finishing, magneto rheological finishing, magnetic float polishing, elastic emission machining, etc. have been developed having component and material specific finishing capabilities. Researchers have attempted to enhance the performance capabilities of AFM and also in development of superior and alternative to commercially available media. Media usually contains two major components as the carrier (a viscoelastic material, e.g. gels and oils) and the solid phase (abrasives and other particles to assist the abrasion). The physical (appearance), chemical (constituents and their proportion in the carrier, inertness, etc.) and rheological (viscosity, shear stress, yield stress, thixotropic, critical strain, critical temperature, etc.) characteristics significantly influence the overall performance of the AFM process.

A polymer based media was developed containing Easter group and Naphthenic based processing oil for varying the viscosity of media. FTIR and TGA tests were performed for characterization of the developed media. After experimentation, it was concluded that average surface roughness (R_a) and material removal rate (MRR)improves with increase in abrasive concentration and extrusion pressure[1].An alternative media has also been developed using co-polymeric soft styrene butadiene based polymer, plasticizer and abrasives. Rheological characterization of media was done to study the effect of creep recovery, shear viscosity, stress relaxation and storage modulus on the MRR and the R_a during finishing of Al alloy as well as its metal matrix composites using rotational abrasive flow finishing (R-AFF).It was found that in butyl-based rubber media, temperature, shear rate and creeping time had a significant impact on rheological properties and percentage ingredients in the media [2].

AFM media was developed using abrasive particles and silicone rubber and experiments were performed for removing recast layers on the electro discharge machined (EDM) surfaces. After experimentation high efficiency in AFM was observed with silicon media of high viscosity at constant temperature [3].A butyl rubber viscoelastic carrier based AFM media was developed and characterized. During rheological observation, temperature, shear rate, creeping time and frequency were found to be mainly impacting the rheological properties. It was also investigated that the oil loading beyond 12% reduced the surface quality while using abrasive mesh size of 220 [4].Studies have been made to create the power law in CFD-ACE+ software using relations of viscosities and shear rates of different abrasive media. The flow model of abrasive media was set up by the power law and the comparisons between the simulated and experimental results were made. The simulated results indicate that the media with high viscosity could fully deform in the complex hole than the media with low viscosity because media with high viscosity generated a better shear force than the media with low viscosity in the similar area [5].To study effects of abrasive concentration, mesh size and temperature of media on its viscosity some experiments were done using a capillary viscometer. Their results indicated that the viscosity of the media increases with increase in the abrasive

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concentration and decreases with the increase in abrasive mesh size and media temperature. During finishing with the developed media, an increase in material removal and decrease in surface roughness value was observed with increase in viscosity [6]. Viscosity and fluidity could be adjusted during the processing period in self-modulating abrasive media. Experiments were made on a fabricated complex micro channel of stainless steel (SUS304) using developed abrasive media. During experimentation in AFM, results proved that, at high viscosity and abrasive concentration the surface roughness of the micro channel with coarse particle size is lower than that of a media with fine particle size. Machining quality of the micro channel also improves as the extrusion pressure and the machining time increase due to increase in the fluidity of the media [7].Styrene butadiene rubber (SBR) based media was developed and studies were made using TGA and characterized by mechanical, as well as rheological properties with the help of a universal testing machine and a rheometer. After rheological investigation, it was found parameters; namely, strain, temperature, shear rate, time of applied constant stress, cyclic loading mainly impacted on mechanical and rheological properties of the developed media. After finishing on AFM setup, 88% improvement in surface finish was found using the SBR based media [8].Natural polymer based environmental friendly AFM media synthesis was done to form polymer abrasive gels (PAGs) of various grades and upon trial on a developed AFM setup the results were encouraging. Taguchi technique was used to analyze the effect of AFM process variables on surface finish and material removal. Based on experimental study, it was observed that abrasive mesh size and percentage of abrasive concentration in media are the most significant parameters for material removal and improvement in surface roughness. Also viscosity of media was found as significant parameter for material removal for the considered size and shape of the work-piece [9]. Looking at the multiple variables affecting the output of the system artificial neural network (ANN) technique was used to simulate the machining variables during the finishing of Al/SiC_p metal matrix composites (MMCs) components by abrasive flow machining [10].

In this article, an attempt was made to study rheological properties like yield stress and viscosity of the developed polymer abrasive gels (PAGs) based AFM media under the influence of the shear rate that help in understanding of mechanism and modelling of finishing process. To study the thermal stability and nature of compounds present in media, TGA and FTIR tests were used. For characterizing the rheological properties of developed PAG, the media compositions have been varied at different shear rate. Effect of temperature change on rheological properties of developed PAG was also studied.

Experimental

Synthesis of Polymer Abrasive Gel

Major constituents of PAG were polymer carrier, liquid synthesizer and abrasive particles. PAG was prepared by thoroughly mixing abrasives of various mesh sizes in the semisolid polymer carrier prepared in bulk with different weight percentages whose viscosity could be controlled by the amount of liquid synthesizer. Similarly PAG of 25 different viscosity grades were prepared based on the percentage of liquid synthesizer added into the abrasive mixed polymer carrier. 11 to 27 % of liquid synthesizer was added into the abrasive mixed polymer to obtain various media viscosity grades. Different mesh sizes of silicon carbon (SiC) abrasive were used in synthesization of AFM media. The prepared PAG samples were given nomenclature and a method of nomenclature for a sample is as shown in Fig.1.

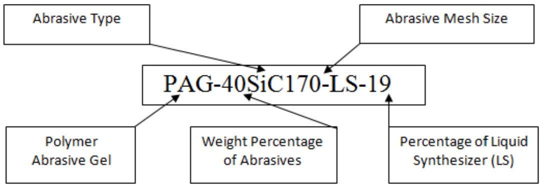

Figure 1: Nomenclature of developed Polymer Abrasive Gel (PAG)

Characterizations

Field Emission Scanning Electron Microscope (FESEM) Analysis

To check abrasive geometry and bonding with polymeric gel, randomly selected samples of PAG were tested by scanning electron microscope (SEM) for determination of the orientation of its constituents. Experiments were carried out on NOVA Nano SEM 450instrument. FESEM images shows that the abrasives have sharp cutting edges which helps in material removal of work piece surface which is to be finished. The average size of abrasives were observed to be 31 to 102 micron (µm)(Fig.2 (a) to Fig.2(d)). Fig.3 shows the interface between the constituents of the additives polymeric base and abrasive particles.

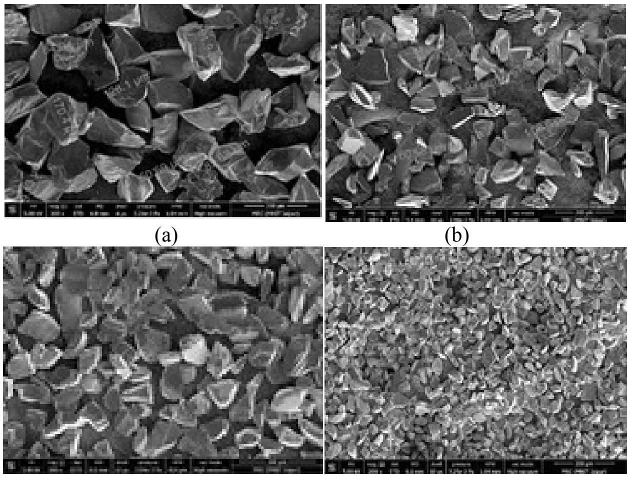
(a) (b)
(b) (d)

Figure 2: FESEM images of SiC abrasives (a) SiCAbrasive 120 Mesh Size, (b) SiCAbrasive 220 Mesh Size, (c) SiC Abrasive 170 Mesh Size, (d) SiC Abrasive 320 Mesh Size

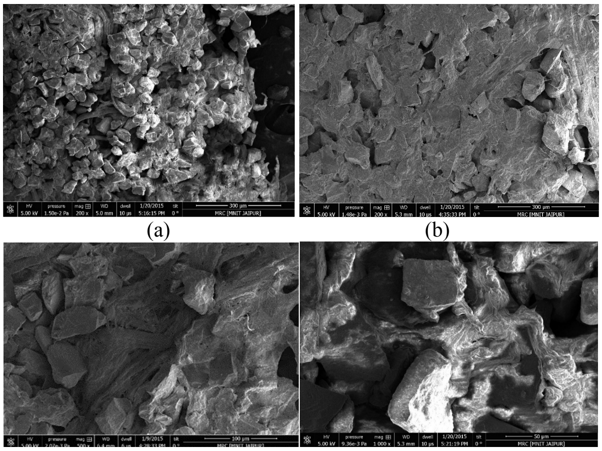
(a) (b)
(b) (d)

Figure 3: FESEM images of developed PAG showing interference of abrasives and base (a) PAG-40SiC170-LS-19, (b) PAG-60SiC270-LS-15, (c) PAG 30SiC220-LS-19, (d) PAG-60SiC220-LS-11

The polymeric constituents activated by the additives which generate enough adhesive force to hold the abrasive particles in place even after continuous use in AFM. Fig.3 (a) to Fig. 3(d) shows abrasives surrounded by the adhesive forces of the base material in increasing magnification. It is clearly visible in Fig. 3(d) that the reason of abrasives bonding in the media is the polymeric chains activated by the additives.

FTIR Analysis

FTIR identifies chemical bonds in a molecule by producing an infrared absorption spectrum. The spectra produce a profile of the sample, a distinctive molecular fingerprint that can be used to screen and scan samples for many different components. FTIR is an effective analytical instrument for detecting functional groups and characterizing covalent bonding information.

FTIR spectrometer operates on a different principle called Fourier transform. The mathematical expression of Fourier transform can be expressed as,

$$f(x) = \frac{1}{2\Pi}\int_{-\infty}^{+\infty} F(\omega)e^{-i\omega X}\, d\omega \qquad (1)$$

where ω is angular frequency and x is the optical path difference in our case. *F(ω)* is the spectrum and *f(x)* is called the interferogram. It is clear that if the interferogram *f(x)*, is determined experimentally, the spectrum *F(ω)* can be obtained by using Fourier transform.

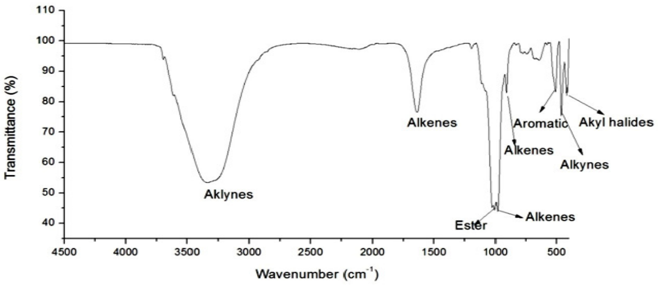

Figure 4: FTIR analysis of developed alternative polymer abrasive gel

For developing the new alternative carrier, it is very important to know the details of structure of compound that is used for synthesizing the abrasive polymer gel. So FTIR analysis was used to identify the structure and type of compounds present in carrier. Perkin Elmer Frontier FT-IR/FIR Spectrometer was used for FTIR analysis. Fig.4 shows the FTIR analysis of developed media. The functional groups were identified using IR chart, at different wave number. During FTIR analysis Alkenes, Alkynes, Esters, Aromatic and Akyl Halides groups were present in PAG media. It was observed that Alkenes, Esters, Amines and Aromatic were more dominating which provides the elastic nature, thermal stability and tensile strength to the PAG. But major Alkenes and Alkynes present in PAG that shows presence of these groups were more dominating which provided elastic nature to media.

Thermogravimetric Analysis (TGA)

TGA is a method of thermal analysis in which changes in physical and chemical properties of materials are measured as a function of increasing temperature (with constant heating rate), or as a function of time (with constant temperature and/or constant mass loss). TGA experiments were carried out on Simultaneous Thermal Analyzers (Make Perkin Elmer) under dynamic N_2 gas atmosphere of 200ml/min flow rate, with heating rate of 10°C cover a range of 20° C to 300°C.

A total 25 samples have been prepared and analyzed according to experimental design Taguchi L_{25} orthogonal array as shown in Table 1.

Table 1: Coded levels and corresponding actual values of PAG

Factor	Level 1	Level 2	Level 3	Level 4	Level 5
Mesh Size	120	170	220	270	320
%Abrasive Concentration	30	40	50	60	70
% Liquid Synthesizer	11	15	19	23	27

In Fig. 5 TGA graphs for three random samples were shown representing the critical temperature limit. Fig. 5 shows TGA analysis of developed PAG at different abrasive concentration, abrasive mesh size and percentage of liquid synthesizer, where the effect of temperature on derivative weight loss during heating of media is presented.

Analysis of Variance (ANOVA) was applied to know variables which are having most significant effect on the critical temperature of PAG. Table 2 shows summary of experiments done at different media composition and response variable i.e. critical temperature.

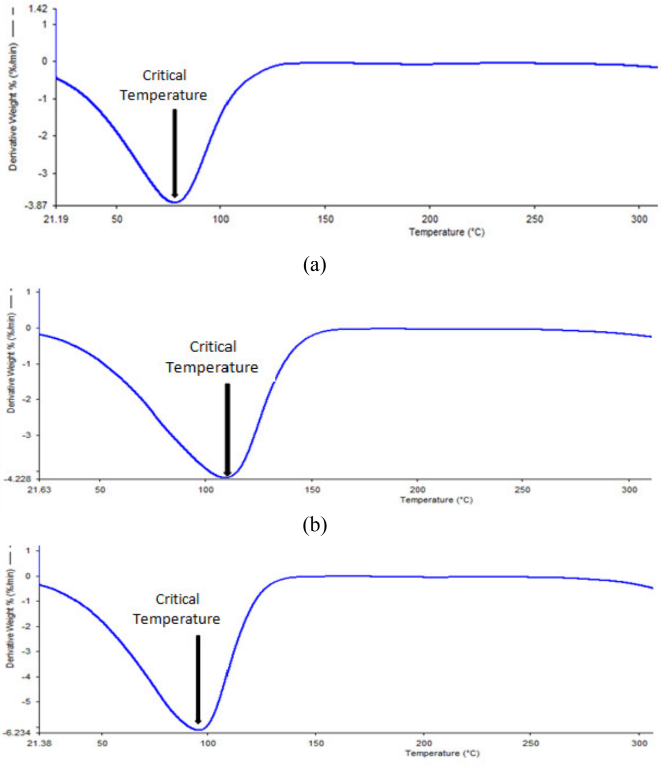

Figure 5: TGA graphs of different PAG sample (a) PAG 30SiC120-LS-11, (b) PAG 30SiC170-LS-15, (C) PAG 30SiC220-LS-19

Table 2: Critical temperature for different polymer abrasive gel

Sr. No.	Ab Conc.(%)	Mesh Size	LS %	Critical Temp.(°C)
1	30	120	11	78.43
2	30	170	15	109.59
3	30	220	19	95.99
4	30	270	23	114.18
5	30	320	27	99.14
6	40	120	15	115.28
7	40	170	19	91.85
8	40	220	23	117.55
9	40	270	27	126.37
10	40	320	11	91.26

Sr. No.	Ab Conc.(%)	Mesh Size	LS %	Critical Temp.(°C)
11	50	120	19	81.14
12	50	170	23	107.35
13	50	220	27	101.71
14	50	270	11	103.96
15	50	320	15	108.88
16	60	120	23	87.25
17	60	170	27	102.90
18	60	220	11	95.09
19	60	270	15	108.58
20	60	320	19	103.11
21	70	120	27	91.84
22	70	170	11	73.82
23	70	220	15	94.44
24	70	270	19	83.47
25	70	320	23s	90.20

Modelling of developed polymer abrasive gel

Characterization of rheological properties such as yield stress and viscosity are very important for finishing performance. The Power Law, Bingham Plastic and Herschel–Bulkley are major models used to define the behavior of viscoplastic fluid. Different variables of rheology were characterized using the data obtained from rheometer in terms of shear yield stress, apparent viscosity and shear rate.

Power Law fluid

Power law model is used mainly to defines the shear-thinning and shear thickening behavior of fluids [11].

$$\sigma = K\dot{\gamma}^{n} \qquad (2)$$

Where, K is consistency coefficient, Exponent n is the flow behavior index, For Newtonian fluid (n = 1), the consistency index K is identically equal to the viscosity of the fluid, η.

When the magnitude of $n< 1$ the fluid is shear-thinning and when $n> 1$ the fluid is shear-thickening in nature.

Taking logarithmic of equation (2)

$$\log\sigma = \log K + n\log\dot{\gamma} \qquad (3)$$

The parameters K and n are determined from a plot of $\log\sigma$ versus $\log\dot{\gamma}$, and the resulting straight line's intercept is $\log K$ and the slope is n.

Bingham Plastic Model

This model shows that developed polymer abrasive gel acts like rigid fluid before a critical shear stress values is achieved, is known as yield stress (σ_y). Polymer abrasive gel beyond value of yield stress behaves as a Newtonian fluid [11].

Bingham Plastic fluid with yield stress (σ_y) is represented by

$$\sigma - \sigma_y = \eta'\dot{\gamma} \qquad (4)$$

η' is called the Bingham plastic viscosity. Bingham plastic model can be described by straight lines in terms of shear rate and shear stress. Major two parameters η' and σ used to describe the Bingham plastic fluid behavior.

Hershel Buckley Model

Herschel–Bulkley model is used to illustrate the rheological behavior of a Non-Newtonian fluid with shear thinning properties. Shear thinning properties of fluid shows decreased in apparent viscosity as increase in shear rate [11].

Equation for Herschel Bulkley Model

$$\sigma = \sigma_y + K\dot{\gamma}^{n}\text{; for } \sigma > \sigma_y \qquad (5)$$

Where K is the consistency index, n is the power-law index if $n<$ 1 the fluid is shear-thinning behavior, $\dot{\gamma}$ is shear rate (S^{-1}), σ is shear stress (Pa), σ_y is yield stress. If the yield stress of a sample is known from an independent experiment values of K and n can be determined form graph of $\log(\sigma - \sigma_y)$ and $\log\dot{\gamma}$.

Experimental results were fitted with Power Law, Bingham Plastic and Herschel–Bulkley model. The values of their Rheological parameters (σ_y- yield stress, K-consistency index, Exponent n-flow behavior index and η' - Bingham plastic viscosity) are shown in Table 3. Polymer abrasive gels of 25 samples have been synthesized according to detailed composition shown in design of experiment (Table 4).

Correlation Coefficient of Fluid Models

To study rheological properties of viscoelastic fluids majorly Power Law, Bingham Plastic and Herschel–Bulkley model were found extensive use in the analysis of the flow behavior and simulation. The Correlation Coefficient was derived to find the usefulness of these fluid models. It signifies as the proportion of the variance in the dependent variable that is predictable from the independent variable derived from regression analysis Fig. 6 shows graphically fitting of model equations for above fluid models with actual experimental data (run no. 15).

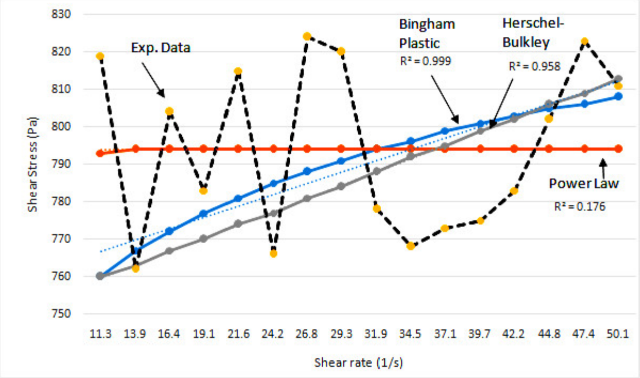

Figure 6: Fitting the constitutive model equations to actual experimental data (run. 15)

It reveals that R^2 values of Bingham Plastic (R^2=0.9997) was highest as compared to Herschel–Bulkley model (R^2=0.9587) and Power law model (R^2=0.1765).Viscoelastic fluid behaves mainly shear-thinning (pseudoplastic) or shear-thickening (dilatant behavior) at high shear rate is mainly represented by Herschel–Bulkley model compared to other fluid model. So viscosity and yield stress were calculated from Bingham Plastic model.

Media process parameter optimization for rheologycontrol

Design of Experiments

Design of experiment is most significant tool for investigation of effect of control variables on output responses. Initially in design of experiment main difficulty is selection of control variables, maximum number of variables is to be included to study the significant variable. Literature review on abrasive media developed shows that variables abrasive mesh size, percentage abrasive concentration, percentage of liquid synthesizer and temperature majorly effect on viscosity and yield stress of polymer abrasive gel[2, 6].In current study, mainly four main parameters namely abrasive mesh size, percentage abrasive concentration, percentage liquid synthesizer, and temperature were considered for rheological investigation. Taguchi method-based design of experiment [12] and L_{25}orthogonal array was used for parametric design. Table 4 represents the various parameters considered with their levels for conducting the rheological experiments.

The S/N ratio for maximum viscosity can be expressed as ‘‘higher is better” characteristic, which is calculated as logarithmic transformation of loss function as shown below

Higher is a better characteristic

$$\frac{S}{N} = -10\log\frac{1}{n}\left(\sum 1/Y^2\right) \tag{6}$$

where ‘*n*’ the number of observations, and *y* the observed data.

Taguchi analysis was performed to evaluate the effect of individual parameter on response variables viz. yield stress and viscosity of developed PAG using Minitab software.

Table 3: Rheological variable for three selected models

Run no.	Power law ($\sigma = K\dot{\gamma}^{n}$)		Bingham Plastic Model ($\sigma - \sigma_y = \eta'\dot{\gamma}$)		Herschel–Bulkley ($\sigma = \sigma_y + K\dot{\gamma}^{n}$)		
	K	*n*	σ_y (*Pa*)	η' (*Pa·s*)	σ_y (*Pa*)	*K*	*n*
1	577.68	-0.0805	447	-0.6	424.00	-0.71175	0.88285
2	1,098.3	0.027427	1,157	1.41	1206.30	0.00021458	3.7148
3	482.76	0.14736	632.89	4.2784	1160.00	7,097	0.01
4	297.83	0.12425	142.17	6.891	314.66	0.0068464	3.001
5	408.22	0.1421	545.14	3.4109	1220.50	9934.9	0.01
6	440.62	0.16236	497.04	5.7569	316.87	75.395	0.46053
7	625.55	0.14668	948.38	2.0671	943.00	1.1152	1.1916
8	467.92	-0.001084	441.86	-0.11	400.58	0.34673	1.3248
9	254.75	0.10468	228.39	2.7278	247.82	0.55431	1.3769
10	21,320	-0.20268	12,610	-65.8	250.00	-185,350	0.01
11	393.47	-0.034654	281.11	1.4219	302.88	0.0035905	2.4769
12	769.36	-0.06045	663.62	-1.21	4295.90	-3,548.7	0.01
13	1,365.4	-0.022009	1,260	-0.255	1243.40	2,289.8	0.01
14	956.69	0.11819	1,184.7	6.156	1432.40	19,446	0.01
15	792.15	0.0006648	744.07	1.3769	4.75	896.25	0.50755
16	956.56	-0.049598	813.83	-0.514	892.45	0.0098983	2.1685
17	320.44	0.038228	240.86	2.4989	272.02	0.051482	1.9456
18	939.49	0.027747	411.2	12.067	430.99	1.8646	1.5065
19	679.16	0.081854	774.79	3.2699	2950.00	3,813.1	0.01
20	514.61	0.042159	533.23	1.448	3810.90	-3,016.6	0.01
21	223.5	0.057142	275.24	-0.404	4224.20	-3,583.3	0.01
22	886.63	-0.33047	290.75	-1.27	4087.10	-3,709.1	0.01
23	2,134.8	0.038841	2,329	3.1603	7450.00	9,554.4	0.01
24	1,925.8	0.014174	1,740.8	2.3503	3260.00	4,909.3	0.01
25	210.99	-0.002295	202.74	0.16823	927.16	-616.25	0.01

Table 4: Experimental Design

Factor	Symbol	Level 1	Level 2	Level 3	Level 4	Level 5
% Abrasive Concentration	A	30	40	50	60	70
Mesh Size	B	120	170	220	270	320
%Liquid Synthesizer	C	11	15	19	23	27
Temperature(°C)	D	25	35	45	55	65

Results and Discussion

Viscosity

Table 5 shows the experimental compositions in percentage volume of constituents of polymer abrasive gel, and summary of responses of viscosity and yield stress based on Herschel-Bulkley Model. Fig. 7shows graphically the effect of the four control factors on viscosity.

The percentage of liquid synthesizer was found to be significant parameter of media contributing 35.76 % on viscosity of media.

Table 5: Plan of experiment and experimental results for viscosity and yield stress of polymer abrasive gel.

Sr. No.	Ab Conc. (%)	Mesh Size	LS %	Temp (°C)	Viscosity (*Pa-sec.*)	Yield Stress*(Pa)*
1	30	120	11	25	12.00	424.00
2	30	170	15	35	34.50	1206.30
3	30	220	19	45	22.60	1160.00
4	30	270	23	55	11.40	314.66
5	30	320	27	65	19.20	1220.50
6	40	120	15	45	20.50	316.87
7	40	170	19	55	30.30	943.00
8	40	220	23	65	13.00	400.58
9	40	270	27	25	9.54	247.82
10	40	320	11	35	32.90	250.00
11	50	120	19	65	9.58	302.88
12	50	170	23	25	17.50	4295.90
13	50	220	27	35	36.80	1243.40
14	50	270	11	45	40.20	1432.40
15	50	320	15	55	23.30	4.75
16	60	120	23	35	7.20	892.45
17	60	170	27	45	9.65	272.02
18	60	220	11	55	25.90	430.99
19	60	270	15	65	25.60	2950.00
20	60	320	19	25	16.70	3810.90
21	70	120	27	55	7.60	4224.20
22	70	170	11	65	19.85	4087.10
23	70	220	15	25	31.60	7450.00
24	70	270	19	35	32.30	3260.00
25	70	320	23	45	5.96	927.16

ANOVA has been performed for viscosity to study the most significant variable which effect the response variable. Table 6 shows ANOVA for viscosity after model reduction. From the ANOVA analysis (Table 6), liquid synthesizer is only significant parameter for viscosity of developed media. It is observed from previous work [6] that with increase in media viscosity, surface roughness decreases. It is due to stiffer medium have more depth of penetration of abrasive article, and it would improve the surface finish. Final regression equation in terms of actual value of parameters is

$$\text{Viscosity (Pa-sec.)} = 36.2004 - 0.05194\,B + 0.03584\,A - 0.8828\,C - 0.09084\,D \tag{7}$$

Table 6: ANOVA table after model reduction for viscosity

Source	DOF	Seq. SS	Adj. SS	Adj. MS	F	P	Percentage Contribution
Ab. Conc. (%)	4	194.05	194.05	48.51	1.02	0.454	7.52
Mesh Size	4	641.94	640.94	160.48	3.36	0.068	24.90
LS (%)	4	922.08	922.08	230.52	4.83	0.028*	35.76
Temp (°C)	4	437.46	437.46	109.37	2.29	0.148	16.98
Error	8	382.18	382.18	47.77			14.82
Total	24	2577.71			*Significant		

Viscosity of AFM media plays major role in surface finishing improvement, so based on the regression equation [Eqs. (7)] obtained after regression analysis, the results in terms of percentage abrasive concentration, abrasive mesh size,percentage of liquid synthesizer and temperature on viscosity have been computed and discussed.

Effect of Abrasive Concentration

Fig. 7 (A) shows the effects of increase in percentage of abrasive concentration on viscosity of PAG. From Graphs it has been observed that PAG viscosity increases continuously with increase in percentage of abrasive concentration. It is due to higher concentration of abrasive particles decreases fluidity of PAG, results indecreased in the mobility of particles in the media. As a result,in a lower volumetric flowrate is observed so viscosity decreased. Steady state condition for this analysis for different variable was 120 abrasive mesh sizes, 11 % liquid synthesizer and 25 °C temperature.

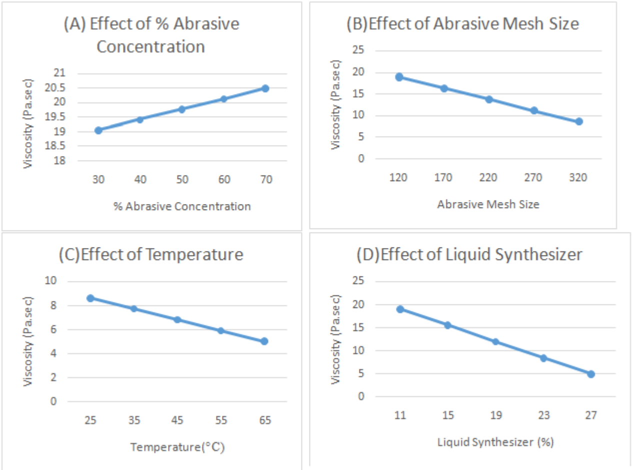

Figure 7: Effect of polymer abrasive gel variables on Viscosity

Effect of Abrasive Mesh Size

Fig. 7(B) shows the effect of increase of abrasive mesh size on viscosity of developed PAG. From graphs it was observed that PAG viscosity decreases with increase in abrasive mesh size. It is due to as increase in the abrasive mesh size (i.e. smaller grits) increases the amount of squeeze out material subsequent in increased pressure gradient and AFM media flow rate. So increased in shear rate and wall shear stress results in decrease in viscosity of PAG. Steady state condition for this analysis for different variable was 30% abrasive concentration, 11 % liquid synthesizer and 25 °C temperature.

Effect of Percentage Liquid Synthesizer

Fig. 7(C) shows the effect of increase of Percentage Liquid Synthesizer on viscosity of developed PAG. From graphs it was observed that PAG viscosity decreases with increase in Percentage Liquid Synthesizer. It is due to as increase in the percentage of liquid results more fluidity and decreased in stiffness of PAG. Steady state condition for this analysis for different variable was 120 abrasive mesh sizes, 30 % abrasive concentration and 25 °C temperature.

Effect of Temperature

Fig. 7(D) shows the effect of increase of Temperature on viscosity of developed PAG. From graphs it was observed that PAG viscosity decreases with increase in Temperature. It is due to as temperature of PAG increases, there exist decrease in flow rate (ie decrease in extrude material) which cause decrease in the apparent shear rate and consequentially decreased in the viscosity of PAG.Steady state condition for this analysis for different variable was 320 abrasive mesh sizes, 30 % abrasive concentration and 11% liquid synthesizer.

Yield Stress

Yield stress values obtained from Herschel–Bulkley model (Table 5) were used for ANOVA analysis to know most significant variable that effecting response of polymer abrasive gel. ANOVA has been performed for yield stress also as procedure explained for viscosity in last section.

Table 7: ANOVA table after model reduction for yield stress

Source	DOF	Seq. SS	Adj. SS	Adj. MS	F	P	Percentage Contribution
Ab. Conc. (%)	4	38036978	3803697	9509244	4.01	0.045*	45.81
Mesh Size	4	4167285	4167285	1041821	0.44	0.777	5.01
LS (%)	4	4128145	4128145	1032036	0.44	0.780	4.97
Temp. (°C)	4	17715344	1771534	4428836	1.87	0.210	21.33
Error	8	18971177	1897117	2371397			22.85
Total	24	83018929				*Significant	

Table 7 shows ANOVA for yield stress after model reduction. From the ANOVA analysis Abrasive concentration is most significant parameter which effect the yield stress of polymer abrasive gel.The final regression equation in terms of actual value of parameters is:

$$\textit{Yield Stress (Pa)} = -76.609 + 74.8882\ \textit{Ab Conc.} - 0.99745\ \textit{Mesh Size} - 19.6513\ \textit{LS \%} - 30.9393\ \textit{Temp} \qquad (8)$$

Critical Temperature

The analysis of variance (ANOVA) of experimental results after neglecting contribution of all the insignificant variables is given in table 8. For removing the insignificant variables, model reduction techniques can be used for improvement of model [12]. It is important to check the model hierarchy before reducing insignificant terms. According to hierarchy principle if a model contains a higher order term, it should also contain all of the lower-order terms that comprise it. The model F value 6.36 implies that liquid synthesizer percentage in liquid is most significant for thermal stability of developed media. If the values of 'Prob >F' is less than 0.05 (significance level), then it indicates that the model term is significant. From ANOVA, abrasive concentration and L.S. are only significant parameters which affect the critical temperature of TGA analysis. Percentage contribution for L.S. and abrasive concentration was found 35.62% and 29.82% respectively. Final equation in term of actual variables is given as

$$\textit{Critical Temp.} = 91.7272 + 0.6928\ \textit{LS} + 0.0513.4\ \textit{M.S.} - 0.345\ \textit{Ab. Conc} \qquad (9)$$

Table 8: ANOVA results after experimentation

Source	Sum of Square	D.O.F.	Mean Square	F	Prob>F	Percentage contribution
Ab. Conc. (%)	1212.12	4	303.031	5.32	0.0106*	29.82
L.S.(%)	1448.01	4	362.003	6.36	0.0055*	35.62
M.S.	720.83	4	180.207	3.17	0.0542	17.73
Error	683.21	12	56.934			16.80
Total	4064.17	24			*Significant	

Conclusion

After characterization and rheological investigation of developed abrasive polymer gel leads to following conclusions:

1. Scanning electron microscopy results shows average size of abrasives used in polymer abrasive gel are observed as 31 to 102 micron (μm) for abrasive flow machining. Also images of Polymer abrasive gel show interface between the constituents of the additives polymeric base and abrasive particles.
2. After FTIR analysis Alkenes, Alkynes, Esters, Aromatic and Akyl Halides groups are found in developed abrasive polymer gel. It was observed that major Alkenes and alkynes are present in media that shows presence of these groups are more dominating which provided elastic nature to media.
3. Thermogravimetric analysis for each sample show thermal stability (critical temp.) of polymer abrasive gel. From ANOVA analysis it has been observed that abrasive concentration and liquid synthesizer are only significant parameters which effect the critical temperature in TGA analysis.
4. Correlation coefficient derived shows graphically fitting of model equations for above fluid models with actual experimental data. From comparative graph, R^2 values of Bingham Plastic (R^2=0.9997) is observed highest compared to Herschel–Bulkley model (R^2=0.9587) and Power law fluid (R^2=0.1765).
5. The percentage of liquid synthesizer was found to be significant parameter of media contributing 35.76 % on viscosity of media. Steady state analysis shows that viscosity of developed PAG increased with increased in abrasive concentration and decreased with increased in abrasive mesh size, percentage liquid synthesizer and temperature.
6. ANOVA analysis for yield stress shows that abrasive concentration is most significant parameter which affects the yield stress of polymer abrasive gel.

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