Chapter 13
Development of Novel Abrasive Media Using Granite Dust Powder Waste for Finishing Applications

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Notations and Abbreviations

SiC	Silicon carbide
SR	Surface roughness
PAG	Polymer abrasive gel
MRR	Material removal rate
FEM	Finite element method
AFM	Abrasive flow machine
ANOVA	Analysis of variance
AFF	Abrasive flow finishing
TGA	Thermo gravimetric analysis
R-AFF	Rotational abrasive flow finishing
SDAFM	Self-deformable abrasive flow media
FTIR	Fourier transform infrared spectroscopy
FESEM	Field emission scanning electron microscopy
ΔR_a	The average roughness of a surface
ΔR_p	Max profile peak height
ΔR_q	Root mean square deviation of the profile

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ΔR_z The difference between the tallest "peak" and the deepest "valley" in the surface

Introduction

Marble is widely used in the construction and building materials since ancient times. Disposal of this waste either in the form of powder or aggregates is causing environmental problems worldwide. It is well known that there are two sources of waste generation: One, waste generated from quarries, and two, from processing plants [1]. Further, two more types of wastes are generated through processing plants: solid waste and semisolid waste or slurry [2]. Frame sawing with diamond blades is a widely used machining technique especially by small-scale industries, in which water is widely used as a coolant and the powder generated blends with water form viscous slurry [3].

The granite dust powder produced by marble and granite industries causes a lot of environmental pollution and health problems. In the present work, the same industrial waste is used as the base material for the development of abrasive media which is further used in finishing application. So, abrasive flow machine (AFM) is a finishing process widely used to finish difficult profiles and passage. AFM generates uniform profile and accurate results on a remarkable range of finishing operations. The abrasive media flow through the workpiece in which a very small amount of material is removed by abrasive media. Abrasive media is comprised of a base material, abrasive particles, and rheological additives. Plasticizers are mixed with the base material to improve the viscous properties of abrasive media. Moreover, the abrasives are the key in abrasive media, used as aluminum oxide, silicon carbide, cubic boron nitride, and synthetic diamond. Other constitutes of media are seeded oil, Aloe barbadensis Mill, and Cyamopsis tetragonoloba powder. The media is tested on rheological properties like critical strain, viscosity, shear stress, critical temperature, and yield stress. The nomenclature of developed media is shown in Fig. 13.1.

The desirable properties of AFM media are as follows:

Porosity: It is the proportion of the void volume of void spaces to the mass volume of the material.

Low adhesion to the workpiece: It is an important property of the abrasive media. The abrasive media should not stick to the workpiece surface.

Permeability: The media should have greater permeability to absorb abrasive and capability to hold it for longer duration as possible. These properties of the base can be improved by adding additives.

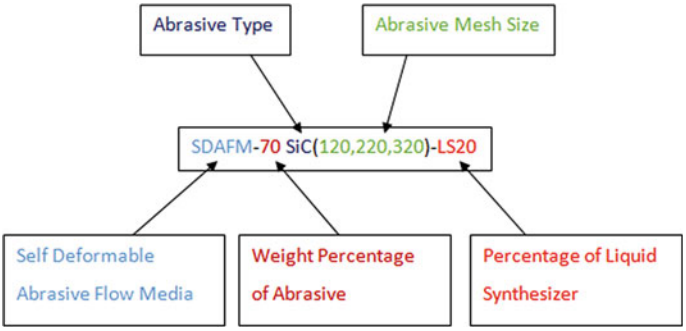

Fig. 13.1 Nomenclature of self-deformable abrasive flow media (SDAFM)

Literature Review

In the current decade, hybriding of AFF process with other non-conventional processes has opened up new vistas for finishing complicated and difficult shapes, which would have been otherwise impossible with another machining process. In the same context, Jain et al. [4] analyzed the variables of the abrasive flow machine process using the finite element method (FEM) for finishing external surfaces. Kar et al. [5] developed a new AFM media and characterized for fine finishing and are used in the abrasive flow machine process. Shankar et al. [6] provided the rotary motion to the workpiece to enhance the performance of AFF and compared the abrasive flow finishing (AFF) and rotational abrasive flow finishing (R-AFF) processes to evaluate their performance in terms of change in MRR and surface roughness. Gorana et al. [7] analyzed the cutting forces during the finishing process and predict the surface roughness produced during the AFM process. Singh et al. [8] improved MRR and surface roughness by applying a magnetic field around the workpiece in abrasive flow machine. Sambharia et al. [9] characterized an alternatively developed polymer abrasive gel (PAG) and characterized using TGA, FTIR, and FE-SEM. Davies et al. [10] conducted experiments using high viscosity, medium viscosity, and low viscosity poly borosiloxane-based media, with SiC abrasive mesh size (60 and 100) for finishing mild steel dies. Mali et al. [11] used fabricated abrasive flow machine to the finished machined cylindrical surface of the aluminum-based metal matrix composite workpiece. Cheema et al. [12] developed efficient, cost-effective, and environment-friendly media. Magnetically assisted AFM process had improved the surface finish on non-ferrous material, and less number of cycles was used for the same MRR when compared with simple AFM. Agrawal et al. [13] synthesized abrasive media at varying temperatures and concentrations from experimental results; they found that the viscosity of the abrasive media decreases with increases in the percentage of abrasive concentration. From the literature, it is found that very less studies have been reported for synthesization and characterization of the environmentally friendly media. Also, few studies have been reported for internal polishing of complex surfaces using friendly and sustainable media. So, the environmental footprint of any commercial activity can't be neglected. Efforts are to be done to make the AFM process environmentally friendly for the cost factor. These industries are still following the manual finishing methods for their parts and are unsuitable for complicated surfaces. Today, the primary challenge in industries is availability of low cost and environmentally friendly media. Many researchers worked on the development of fixture and tooling for the part which varies in geometrical size and shape. But still research work on the development of tooling and fixture for complex part shape is required so that the mass production can be increased and the cost of surface finish can be reduced.

Materials and Method

Experimental Equipment

The vacuumized abrasive flow setup (VAFS) is used, which consists of hopper, media pressurizing equipment, motor, tooling, and workpiece. High-precision weighing machine is used to measure the quantity of material for media synthesization. FTIR spectrum 2 (Perkin Elmer) is used for estimations of bonding of media particles in the range of 4100–400 cm^{-1} for liquid and solid samples. This instrument is used for identifying functional groups and characterizing covalent bonding information. The operational functional groups are identified as IR charts at different wave numbers. FESEM with EDS Nova Nano FE-SEM 450 is used that gives ultra-high-resolution characterization and provides precise, true nanometer-scale data. It gives a resolution of 1.6 nm at 1 kV and <1 nm at 15 nm. FESEM is a scientific instrument that uses a beam of a dynamic electron to observe objects on a fine scale. The SURFTEST SJ-210 is a user-friendly surface roughness measurement instrument used for surface roughness test. It is used to view surface roughness waveforms. Rheology test is used to measure a rheological parameter of a fluid variation of viscosity of the fluid by varying temperature as well as varying the shear rate and shear stress given the effect on viscosity of the fluid. Rheolab QC of Anton Paar make equipment is used for rheological study of developed media.

Material

The granite dust powder, gel (Aloe barbadensis Mill and Cyamopsis tetragonoloba powder), SiC abrasives, and high flash point oil are used for the preparation of self-deformable abrasive flow media (SDAFM). The gel has low flow property and does not stick on the workpiece surface during polishing.

The constitutes of media are: as a base material—granite dust powder; plasticizer—high flash point oil; abrasive—silicon carbide (120, 220, 320), carrier—gel (Aloe barbadensis Mill and Cyamopsis tetragonoloba powder). The following combinations for SDAFM samples are prepared -

1. Granite dust powder + gel + high flash point oil + SiC (120)
2. Granite dust powder + gel + high flash point oil + SiC (220)
3. Granite dust powder + gel + high flash point oil + SiC (320).

Synthesization Procedure

The media composition is varied by adding the percentage of all contents that affects the media property, abrasive concentration, and the viscosity of media. Initially, as per the required amount of abrasive, granite dust powder is mixed with gel using a mixer machine. In the next step, plasticizer is mixed as per the procedure as mentioned in Fig. 13.2.

The self-deformable abrasive flow media (SDAFM) used granite dust powder, high flash point oil, Aloe barbadensis Mill, and Cyamopsis tetragonoloba powder with silicon carbide particles as abrasives. The SDAFM is synthesized by blending abrasive of various mesh sizes (120, 220, 320) semisolid media with various weight percentages whose viscosity could be changed by the amount of liquid synthesizer. Three different sample images of different mesh sizes are shown in Fig. 13.3. The percentage of ingredients of media has been calculated by the formula

$$\%\text{ of the particle ingredients} = \frac{\text{weight of particular ingredients}}{\text{total weight of the compound}} * 100 \qquad (13.1)$$

The components of media with their quantity are listed in Table 13.1.

The gudgeon pin shown in Fig. 13.4 is used as a workpiece for experimentation, which is normally a forged short hollow bar made of a steel alloy of high quality and hardness that found usefull for connecting the connecting bar and piston.

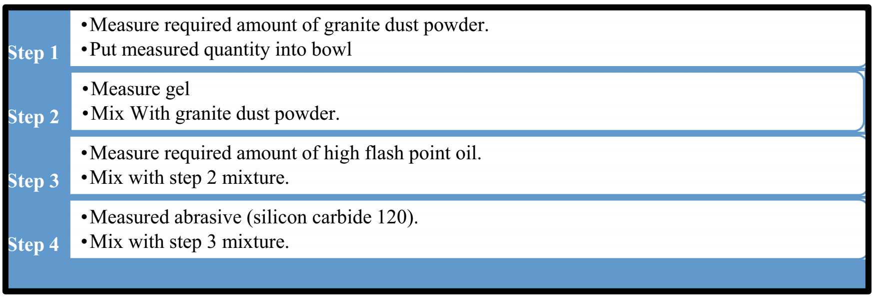

Fig. 13.2 Synthesis method of media

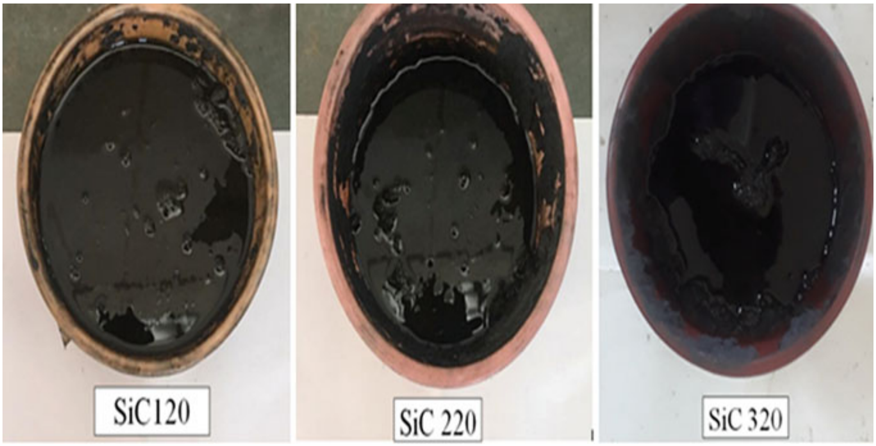

Fig. 13.3 Self-deformable abrasive flow media image

Table 13.1 VAFS parameter with variables

S. No.	Parameters	Variables
1.	Base material	Granite dust powder (50 g)
2.	Carrier	Gel (Aloe barbadensis Mill and Cyamopsis tetragonoloba powder) (6 g)
3.	Abrasive	Silicon carbide
4.	Abrasive mesh size	120, 220, 320
5.	Abrasive concentration (wt%)	30, 50, 70%
6.	Plasticizer	High flash point oil (20, 24, 28%)
7.	Workpiece	Gudgeon pin

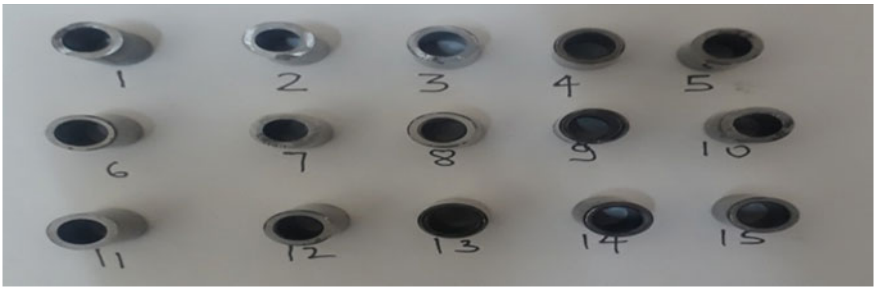

Fig. 13.4 Workpiece images

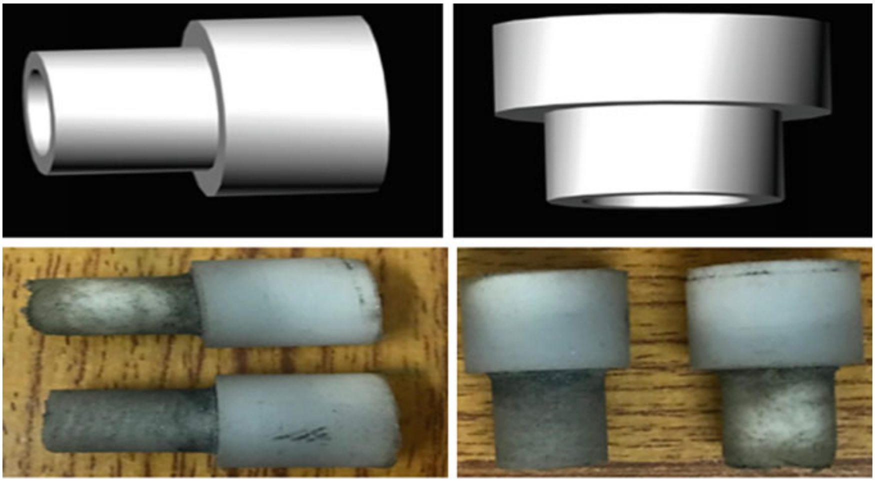

Fig. 13.5 Fixture image

Fixture for holding the workpiece is fabricated using lathe machine and designed ergonomically to reduce the time of workpiece mounting the design, as shown in Fig. 13.5. Fixture material used is nylon which is easy to machine and non-corrosive in nature.

Characterization of SDAFM

Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR study shows the presence of amines, amides, alkanes, and aromatics that produce the elastic nature to the SDAFM. The peaks in Fig. 13.6 show various compounds present in the abrasive media and more present are alkanes in this sample. The more presence of alkanes is dominated, which produces the flexible nature of the carrier.

Field Emission Scanning Electron Microscopy (FESEM)

FESEM study for sample in Fig. 13.7 shows that the high-resolution image is captured by using a FESEM instrument with 500× magnification and 5 μs dwell with field-free lens mode. The image is showing how the abrasive media ingredient is mixed together and bonding between plasticizer and abrasive is observed.

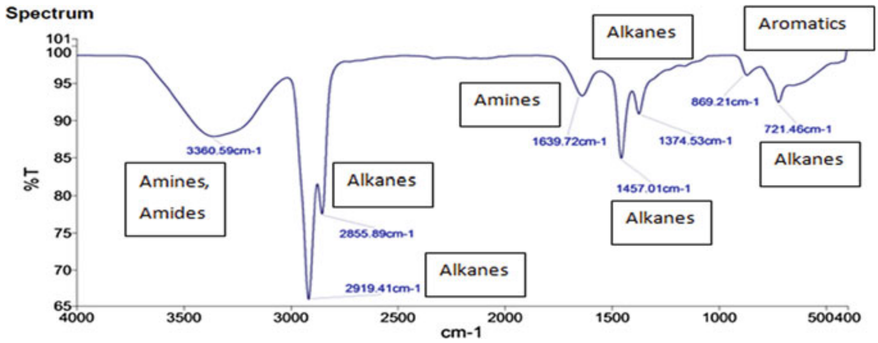

Fig. 13.6 FTIR analyses for media (mesh size 320, 30% abrasive concentration)

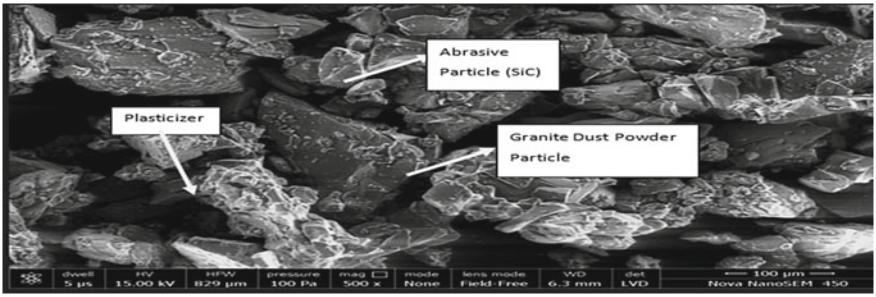

Fig. 13.7 SEM image of SDAFM with 220 mesh size and 70% abrasive concentration at 500× mag. with 5 μs Dwell

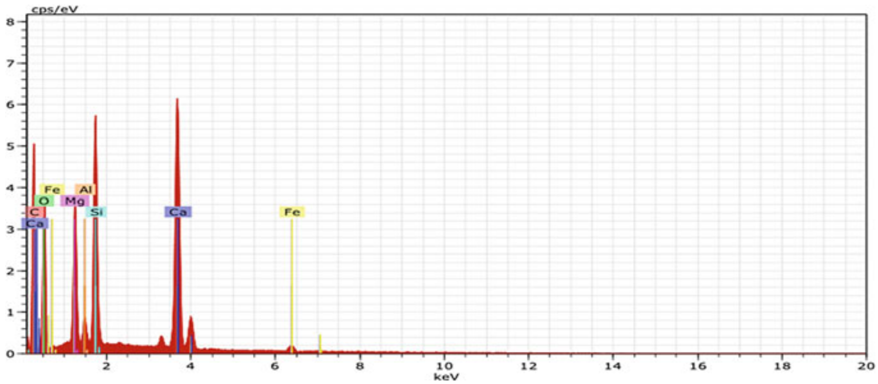

Fig. 13.8 Graph of elements for Sample 1 media

Figure 13.8 shows the graph generated by the data obtained from FESEM-EDS. In the graph, the *x*-axis represents kilo electron voltage (Kev) and the y-axis represents the count per second per electron voltage (cps/eV). From FESEM-EDS study the result shows the data on atomic number, atomic mass, and distribution of electrons in K, L, and M shells for the elements C, Ca, O, Si, Fe, Mg, Al.

Rheological Evaluation of the SDAFM

The rheological property of the media is a significant criterion for optimum surface finishing results in the AFM process. The viscosity of the media has considerable impacts on the AFM process performance. Hence, experimentations were performed to determine the impacts of mesh size, plasticizer %, percentage of the abrasive concentration, and temperature as mentioned in Table 13.2 on the media viscosity and the impacts of viscosity on surface roughness. Rheological studies were carried out for steady shear at various shear rates and the temperature is 20, 32, and 44 °C.

The abrasive (silicon carbide) is mixed with the base material and liquid synthesizer to gain a homogeneous mixture of different abrasive concentration. During the experimentations, the viscosity of abrasive media is additionally assessed by setting the temperature at 32 °C and shear rate at 100 s^{-1} so that the impact of abrasive mesh size, abrasive concentration, and liquid synthesizer on the abrasive media viscosity is determined. The study of the impacts of temperature on the viscosity of SDAFM samples is performed at various temperatures. After the study of the impacts of the media on its viscosity, samples of various grades of viscosity are used to study the viscosity effect on AFM performance. Table 13.3 presents the experimental outcomes for viscosity measurement for 27 set of different samples selected on the basis of design of experiments.

ANOVA Analysis

ANOVA and regression analysis was performed with the help of MINITAB 17 software. The study helps to know about the most significant parameter chosen as an input parameter. In Table 13.4, *P*-value indicates the significance of predictor term, which means if the *P*-value of any predictor term or factor is greater than 0.005 then the factor is insignificant and the effect of this factor on response parameter is less

Table 13.2 Process parameters and levels

Control factor	Level		
	I	II	III
A. Abrasive mesh size	120	220	320
B. % Abrasive concentration	30	50	70
C. % Liquid synthesizer	20	24	28
D. Temperature (°C)	20	32	44

Table 13.3 Viscosity measurement data for 27 set of different samples

S. No.	Abrasive mesh size	% Abrasive concentration	% Liquid synthesizer	Temperature (°C)	Viscosity (Pa s)
1	220	70	28	32	0.051500
2	220	30	20	32	0.037120
3	120	50	24	20	0.067543
4	220	50	28	20	0.107000
5	220	50	20	20	0.074300
6	320	30	24	32	0.121390
7	220	30	24	20	0.322400
8	120	70	24	32	0.231600
9	220	50	20	44	0.154800
10	220	30	24	44	0.041330
11	220	70	20	32	0.035239
12	120	50	20	32	0.070146
13	320	50	24	20	0.214200
14	120	50	28	32	0.087100
15	220	50	24	32	0.078725
16	120	50	24	44	0.388450
17	120	30	24	32	0.049600
18	320	50	24	44	0.125500
19	220	50	28	44	0.172000
20	220	70	24	44	0.430000
21	320	50	20	32	0.021673
22	220	50	24	32	0.094400
23	320	50	28	32	0.021326
24	220	30	28	32	0.050220
25	220	70	24	20	0.002370
26	220	50	24	32	0.102075
27	320	70	24	32	0.031790

than other parameters. Highest F-value with predictor term has the most remarkable input factor.

Table 13.5 shows that the designed model for viscosity fits about 98.74% of data points with an average distance of 0.0154100 from the fitted line and can be able to predict the response of new observations with accuracy of 96.51%.

Regression Analysis

Regression analysis is performed to estimate the relationship between independent and dependent variables. The main reason for creating a regression equation is to minimize the sum of squared error.

Table 13.4 Analysis of variance for viscosity

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Regression	9	0.317293	0.035255	148.46	0.004
Mesh size	1	0.010714	0.010714	45.12	0.008
% Abrasive con.	1	0.002145	0.002145	9.03	0.009
% LS	1	0.000766	0.000766	3.23	0.005
Temp. (°C)	1	0.022905	0.022905	96.45	0.003
% LS * mesh size	1	0.024456	0.024456	102.98	0.007
Temp. (°C) * LS	1	0.052264	0.052264	220.09	0.006
Mesh size * %Abrasive con.	1	0.018442	0.018442	77.66	0.002
Mesh size * Temp. (°C)	1	0.041945	0.041945	176.63	0.008
%Abrasive con. * Temp. (°C)	1	0.125564	0.125564	528.76	0.006
Error	17	0.004037	0.000237		
Total	26	0.321330			

Table 13.5 Predicted summary for viscosity

S	*R*-sq	*R*-sq (adj)	*R*-sq (pred)
0.0154100	98.74%	98.08%	96.51%

The regression equation for viscosity is = −1.403 + 0.004129 Mesh Size—0.03097% Abrasive concentration + 0.3749% LS—0.05466 Temp. (°C)—0.01545% LS * % LS + 0.000628 Temp. (°C) * Temp. (°C)—0.000068 Mesh Size * % Abrasive concentration—0.000085 Mesh Size * Temp. (°C) + 0.001476% Abrasive concentration * Temp.

Relationship of Viscosity with Different Input Factors
The viscosity of media during finishing process has a significant impact on the surface roughness. The effect of liquid synthesizer, temperature, abrasive concentration, and mesh size on viscosity is discussed in below section.

Effect of Mesh Sizes on Viscosity
Figure 13.9 shows the effect of the decrease in viscosity with abrasive mesh sizes. This is due to the increase in the quantity of extruded material that affect the abrasive media flow rate and pressure gradient and results in decrease in viscosity.

Effect of Percentage of Liquid Synthesizers on Viscosity
Figure 13.10 shows the effect of percentage of liquid synthesizer on viscosity. The viscosity will decrease due to the increase in percentage liquid in gel which results in flow ability and viscosity will decrease.

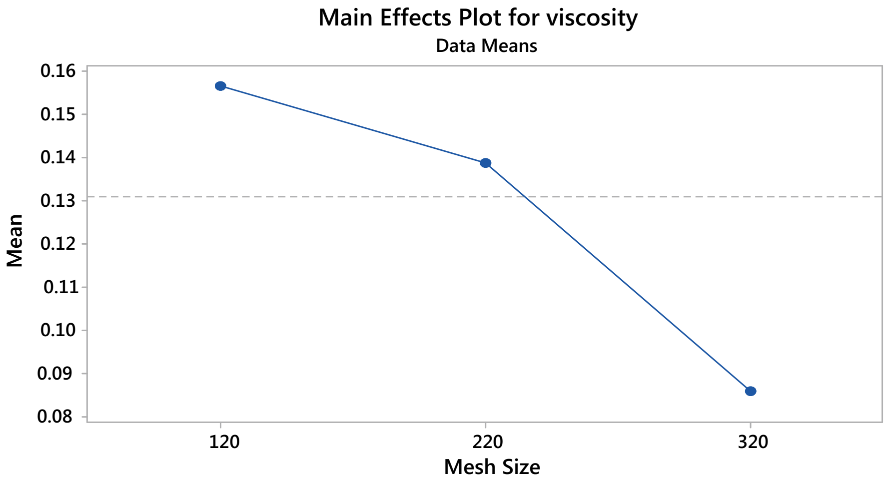

Fig. 13.9 Effect of abrasive mesh size on viscosity

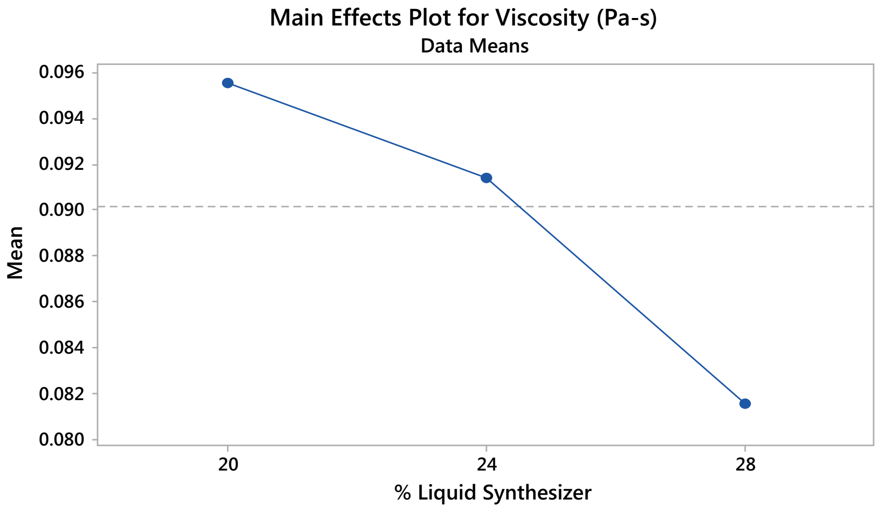

Fig. 13.10 Effect of percentage of liquid synthesizer on viscosity

Effect of Percentage Abrasive Concentration on Viscosity

Figure 13.11 shows the effect of abrasive concentration on viscosity. The viscosity will increase due to the decrease in the mobility of particles in the abrasive media. So with increase in abrasive concentration the viscosity decreases.

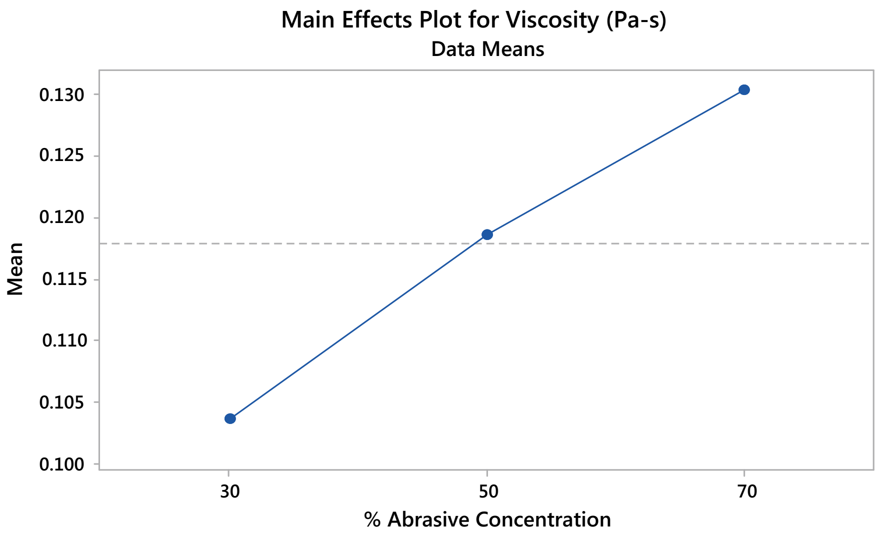

Fig. 13.11 Effect of percentage abrasive concentration on viscosity

Performance Study of SDAFM

Design of Experiment (DOE)

In this experiment, four process parameters, liquid synthesizer, finishing time, mesh size, and abrasive concentration, are considered as control factors. Each parameter has three-levels: low, medium, and high level. Four parameters with three levels are used in response surface design. L27 orthogonal array approach is used for the experiment. Table 13.6 shows the results of experiment performed as per the design of experiment.

Effect of Mesh Sizes on Average Surface Roughness (ΔR_a)

Figure 13.12 shows the decrease in surface roughness value with increase in the abrasive mesh sizes due to finer abrasive particles to create smaller indent on the finishing surface. This action provides a highly surface quality but unable to indent deeper.

Table 13.6 Results of experiment performed

S. No.	Abrasive mesh size	%Abrasive concentration	%Liquid synthesizer	Finishing time (minutes)	Improved surface roughness (μin)			
					ΔR_p	ΔR_a	ΔR_q	ΔR_z
1	220	75	45	9	240	55	68	8
2	220	60	30	9	208	68	145	101
3	220	90	60	9	216	21	67	397
4	220	90	30	9	32	50	13	80
5	120	75	30	9	28	3	5	44
6	220	75	30	11	25	32	14	64
7	220	60	45	11	59	33	28	103
8	220	90	45	11	261	104	141	590
9	320	60	45	9	12	13	5	18
10	320	75	45	7	107	43	51	158
11	120	75	45	11	6	11	2	9
12	120	60	45	9	119	32	24	140
13	220	75	30	7	28	16	22	95
14	120	75	45	7	37	17	29	261
15	220	75	45	9	150	21	40	212
16	220	75	45	9	270	73	96	466
17	220	75	60	11	22	4	6	61
18	320	75	45	11	166	36	76	431
19	220	75	60	7	53	14	22	77
20	220	60	60	9	47	10	14	85
21	120	75	60	9	632	130	303	59
22	220	60	45	7	4	54	2	10
23	320	90	45	9	204	21	53	301
24	320	75	30	9	517	74	187	919
25	320	75	60	9	248	25	83	423
26	220	90	45	7	28	9	3	44
27	120	90	45	9	250	58	80	542

Effect of Abrasive Concentration on Average Surface Roughness (ΔR_a)

Figure 13.13 shows increase in average surface roughness with increase in the abrasive concentration. This is due to more number of abrasive particles taking part in machining process and continues to remove fresh material from the work surface contributing to the increase in average surface roughness.

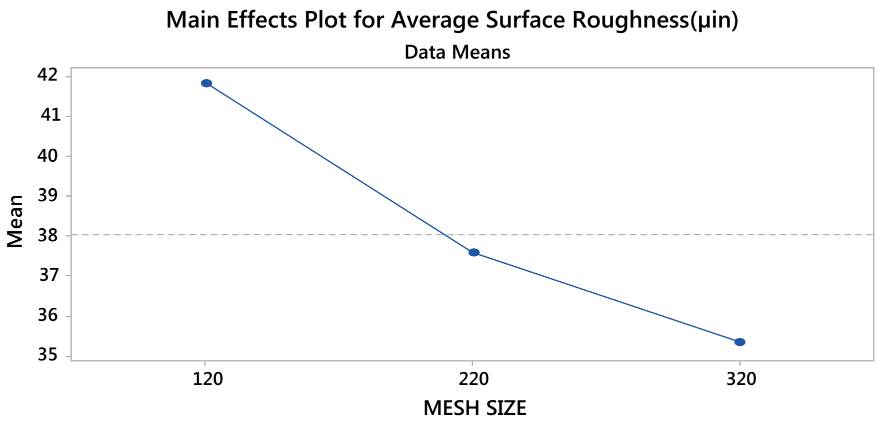

Fig. 13.12 Effect of mesh sizes on average surface roughness

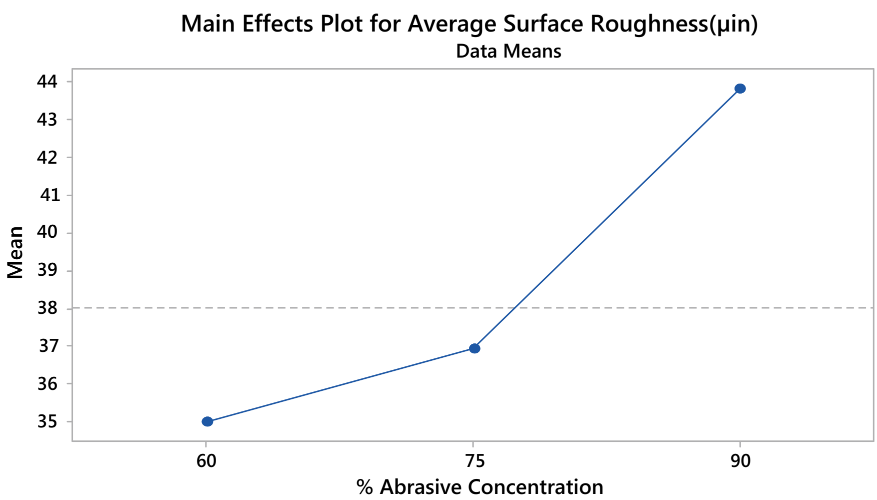

Fig. 13.13 Effect of abrasive concentration on average surface roughness

Effect of Liquid Synthesizer on Average Surface Roughness (ΔR_a)

Figure 13.14 shows decrease in surface roughness with increase in the liquid synthesizer due to weak bonding between the abrasive particles and polymer chains at low values of plasticizer and no effective transfer of radial force and axial force from polymers chains to abrasive particles.

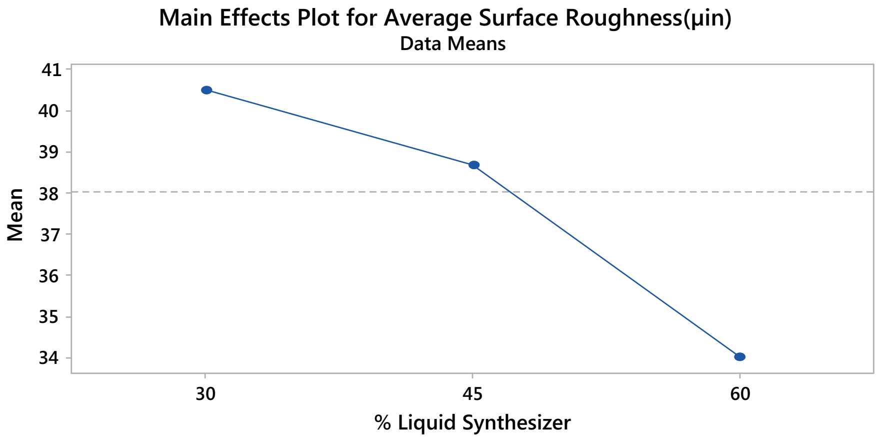

Fig. 13.14 Effect of liquid synthesizer on average surface roughness

Effect of Finishing Time on Average Surface Roughness (ΔR_a)

Figure 13.15 shows increase in average surface roughness with the finishing time. In the initial finishing time, the average surface roughness increases and then decrease in R_a value due to initial peak removed in initial cycles.

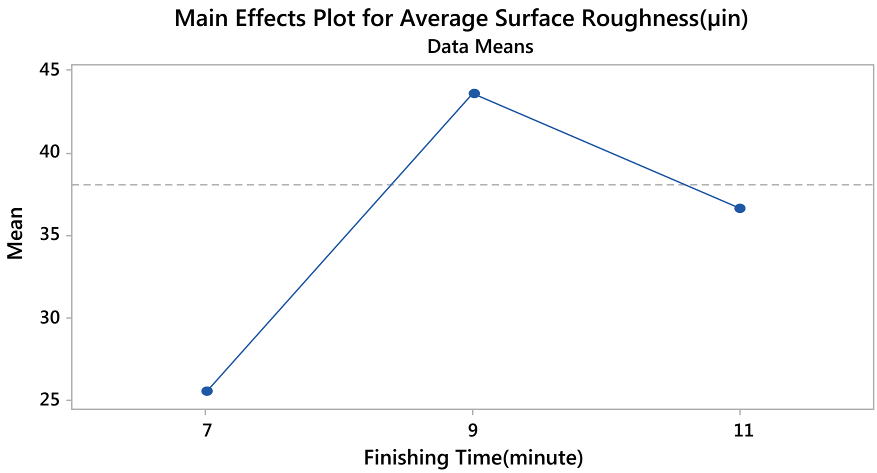

Fig. 13.15 Effect of finishing time on average surface roughness

Conclusion

In the current study the abrasive media (self-deformable abrasive flow media) is synthesized using industry waste, which is further used in abrasive flow machine for finishing application. Abrasive media have the property of no-adhesiveness, permeability, porosity, and thermal stable. During synthesization granite dust powder, gel, high flash point oil, and silicon carbide (abrasive mesh sizes 120, 220, 320) were used in SDAFM. Summary of conclusion is listed in the following:

1. Media developed is environmentally sustainable and less costly as compared with commercially available media.
2. Significant effect of abrasive concentration, abrasive mesh sizes, percentage of liquid synthesizer, temperature on viscosity of media was observed during experimentation.
3. There is significant effect of abrasive concentration, liquid synthesizer, and finishing time on average surface roughness.

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