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ELECTROCHEMO-MAGNETO ABRASIVE FLOW MACHINE SETUP FABRICATION AND EXPERIMENTAL INVESTIGATION OF THE PROCESS ALONGWITH MATHEMATICAL MODELING AND OPTIMIZATION

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ABSTRACT

In abrasive flow machining, there are two sets of piston-cylinder arrangements, i.e. machine and media. the machine ram pushes the media piston two and fro so that media filled inside it flows past the inner wall of workpiece and the material is removed. The extrusion pressure is the main mechanism of material removal. Various authors have made the process more effective in terms of material removal and surface roughness by providing rotational and magnetic force.

Keywords: Mathematical; Modeling; Optimization; Process

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1. INTRODUCTION

In abrasive flow machining, there are two sets of piston-cylinder arrangements, i.e. machine and media. the machine ram pushes the media piston two and fro so that media filled inside it flows past the inner wall of workpiece and the material is removed.

The extrusion pressure is the main mechanism of material removal. Various authors have made the process more effective in terms of material removal and surface roughness by providing rotational and magnetic force.

The authors of Kenda, Pusavec and Kopac (2014) found that the AFM polishing process novelty study having movable mandrels in order to obtain improved performance of the product manufactured in the process. In the paper of AFM process, bevel gears are micro manufactured using special tools in (VENKATESH et al., 2014).

The high temperature in the AFM process decreases the viscosity of the polymer media used for cutting action or finishing process as shown in (UHLMANN; MIHOTOVIC; COENEN, 2009). The hybrid AFM process increases the efficiency of the conventional process (JAIN, 2008). The design of the optimum results, media and AFM setup has effect on the process as explained in (ZHANG et al., 2009).

For extrusion pressure used in AFM, dies and molds are made of Al and steel that resulted in optimum output (WILLIAMS; WALCZYK; DANG, 2007). The AFM process used turbulent flow model and volume of fluid (VOF) model in case of zigzag channel to check the regularity of process in (TANG; JI; TAN, 2010).

The authors of Williams and Melton (1998) found that in AFM process, the MRR was affected by various factors like abrasive grit size, pressure, etc. If EDM and ECM lapping was used then surface roughness was improved upto 0.07 mm in 2 min as shown in (KURITA; HATTORI, 2006). The grinding of tool was 15 times lesser in AECG as compared to mechanical grinding (ZABORSKI; ŁUPAK; PORO, 2004).

In rotary EDM with ball-burnishing of Al_2O_3/6061 Al composites, the parameters were peak current, dielectric flushing pressure, electrode rotational speed, non-load voltage explained in (YAN, et al., 2010). In the paper, ECM was used and surfaces obtained were smoother as compared to that obtained by laser

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and electric discharge machining that produced heat affected zone as shown in (VENKATESH; SHARMA; SINGH, 2015).

The authors of Singh, Jha and Pandey (2012) found that if MRP fluid was conditioned after several cycles of finishing operation, then it was forced to flow, otherwise the already stiffened ball end of fluid continuously flow towards the tool tip. The different variants of the process are listed in table 1 along with the parameters used.

Table 1. Different variants of AFM process

Author, year, area of research/process	Workpiece	Tool	Electrolyte/media/particles	Parameters
Yang et al, 2006, Wire-EDM (YANG et al., 2016)	Graphite (+)	Brass wire (-) of 0.25 mm diameter	KOH electrolyte 300 g/L, SiC #200 abrasive	Non-load voltage 60-120 V
Yan et al, 2003, Electrolytic MAF (YAN et al. 2003)	SKD11, HRC61		abrasive WA, 1.2 μm, 0.4 g, steel grit 180 μm, 3.6 g, unbounded magnetic abrasive 4 g.	magnetic flux 0.85 T, electrode gap 2-5 mm
Niranajan and Jha, 2014, Ball-end MAF (WILLIAMS; WALCZYK; DANG, 2007)	M.S. workpiece	BEMRF tool	55 vol% fluid, 16 and 4 vol% CIPs CS and HS grade respectively, 25 vol% abrasives.	0.7 T magnetic field

2. EXPERIMENTAL SETUP

The abrasive flow machining setup has been utilized for the finishing of internal surface of the workpiece. The to and fro motion of abrasive laden media removes the material and in order to enhance the capacity the machine is made hybrid with the help of magnetic and electrolytic force, in addition to the extrusion pressure.

In the electrolytic method, the ions exchange occurs which causes the removal of material from one material and addition of the same on the other electrode. For this system, DC power source is required. The electrode set up has been fabricated in-house and separate power source i.e. transformer supply voltage 6V, 12V, 18V.

In this process, the flow of polymer media mixed with electrolyte, inside the gap between cathode rod and the internal wall of hollow cylindrical job gets interacted with the electrochemical action between anode and cathode. The

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electrolyte is taken in such a way that the material is removed only from the workpiece surface, and no material removal takes place from cathode rod.

The workpiece is made anode i.e. connected to positive terminal of DC supply, while the rod inside the workpiece is connected to negative terminal. The normal kitchen salt is taken as electrolyte in the molal concentration ratio 1:1. As shown in figure 1, the electromagnets are arranged around the fixture which create magnetic pull on the magnetic particles mixed in the media. Apart from this, the electrolytic rod is placed inside the workpiece and the motor is also used to impart the rotation to the workpiece.

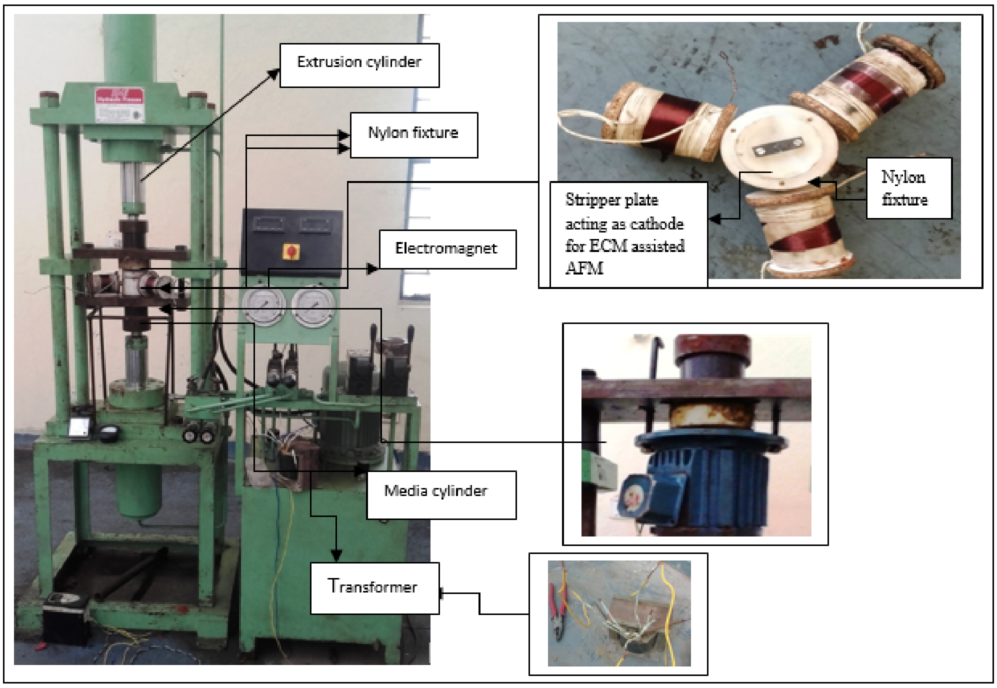

Figure 1: Hybrid AFM set up

The workpiece is placed inside the nylon fixture that is given rotation by motor. The transformer is used to supply the required voltage for the electrochemical and magnetic action. This hybrid AFM setup was used for experimentation.

2.1. Experimental work based on Taguchi L9 OA method

The effect of 9 input parameters on material removal and surface roughness has been found by performing experiments on the AFM setup. The input parameters and their levels taken are explained in table 2.

The Taguchi L-9 orthogonal array OA was used to optimize the value of output results. In this approach the input parameters combination is automatically set and the experiments were performed accordingly.

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Table 2: Input parameters and their levels used

S.No.	Symbol	Prameters	Unit	Level-1	Level-2	Level-3
1	RS	Rotation speed	RPM	100	150	200
2	EP	Extrusion pressure	Bar	15	30	45
3	EV	ECM voltage	V	6	12	18
4	AT	Abrasive type	-	Al_2O_3	SiC	Al_2O_3+SiC
5	AM	Abrasive mesh size	#	100	200	300
6	AR	Abrasive ratio	-	1:2	1:1	2:1
7	NC	Number of cycles	No.'s	3	6	9
8	WT	Workpiece type	-	Brass	Aluminium	Mild Steel
9	MV	Magnetic voltage	V	50	125	200

The effect of these parameters were studied experimentally by taking 3 input parameters at a time. The output results of % improvement in roughness and material removal (MR) are listed in table 3. A total of 9 experiments were performed in each case.

Table 3: MR and % improvement in Ra results based on different input variable parameters

Variable parameters	AT (1), AM(2) and AR (3)		EP (1), NC (2) and WT (3)		MV (1), EV (2) and RS(3)	
Exp. Run	**% imp. In Ra**	**MR (gm)**	**% imp. In Ra**	**MR (gm)**	**% imp. In Ra**	**MR (gm)**
1(111)	23.01	4.8	23.4	4.1	20.37	4.2
2(122)	15.4	4.03	16.9	4.13	16.4	10.8
3(133)	29	3.86	29.9	3.16	50.8	12.4
4(212)	17.8	5.64	17.01	5.14	30.3	14.4
5(223)	13.33	8.19	13.69	8.95	38.1	19.6
6(231)	12.1	7.14	12.98	7.93	62.4	10.2
7(313)	24	6.1	24.91	6.01	36.5	7.2
8(321)	7.9	5.5	7.9	5.19	50.4	8.2
9(332)	9.9	9.5	9.99	2.19	53.9	9.8
Average	16.93	6.08	17.40	5.2	39.90	10.75

2.2. Experimentation based on Response Surface Methodology (RSM)

This method starts with problem recognition, objective formulation, definition of response characteristics and factors related. Then levels are selected, analysed using ANOVA and regression model is formulated.

Then optimization is done using central composite design (CCD), the input variables taken were 5 type of media, pressure 10-30 bar in steps of 5, media volume 175- 275 in steps of 25, number of cycles 4-12 in steps of 2. The different media i.e. natural, nitrile, Styrene butadiene, polyborosiloxane and silicone rubber based media were prepared and the material removal of brass workpiece was

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calculated and listed in the table 4. There are k*(k-1)/2 interaction terms. The second order model is the base of response surface methodology. First of all, the values of parameters to be set are decided, based on their availability on the machine setup. Then experimentation is performed according to the design table.

Table 4: Material removal values for different media

Exp. No.	Run order	Material removal (MR) (mg)				
		Natural rubber	SBR	Polyborosiloxane	Nitrile rubber	Silicone rubber
1	1	2.4	2.7	1.7	3.5	3.8
2	4	2.4	3.5	2.5	3.7	3.9
3	7	2.21	3.1	2.1	3	3.89
4	2	3.12	3.1	2.1	3.6	3.6
5	5	2.34	3	2.4	2.4	3.2
6	8	3.7	3.5	3.2	2.4	3.2
7	3	3.43	3.7	2.6	2.21	3.9
8	6	3.12	3	2.06	3.7	3.35
9	9	3.4	3.6	2.9	3	3.76

3. MODELLING OF THE MAGNETIC FORCE ASSISTED AFM PROCESS

The magnetic force used in the experimental work played a vital role in enhancing material removal. A mathematical model is generated to calculate the magnetic force and material removed from the workpiece and then the experimental results were compared. The magnetic particles are uniformly mixed in the abrasives before the media is used for machining purpose. A magnetic particle is assumed to be a sphere of radius r is displaced through distance δr due to magnetic force. According to conservation of mass, we apply continuity equation 1.

$$\frac{d}{dm}\left(\frac{4}{3}\pi r^3\right) = 1/\rho \quad (1)$$

where ρ is the density of magnetic particles = 5.242 g/cm^3

$$\frac{\partial}{\partial m}\left(\frac{4}{3}\pi r^3 \delta r\right) = -\frac{\delta\rho}{\rho^2} \quad (2)$$

Radius of iron oxide particle, r = 65 nm = 65 $\times$ 10^{-6} mm

Mass, m = 159.6 g/mol

$\frac{4}{3}\pi r^3$.m = -1/ρ + c

Hence c = 0.1908

$\frac{4}{3}\pi r^3$.m = -1/ρ + 0.1908

The equation of motion of the particle is given by equation 3 and 4.

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$\frac{\partial^2 r}{\partial t^2} = - 2\pi r \frac{\partial P}{\partial m} - 2\frac{Gm}{r}$

(3)

The total pressure $P = p + \frac{H^2}{8\pi}$ (4)

where p is extrusion pressure and $\frac{H^2}{8\pi}$ is magnetic pressure.

Differentiating the above equation, we get

$\delta P = \delta p + \frac{H\delta H}{4\pi}$

H is magnetic field at a distance r from the centre of the electromagnetic core by equation 5.

$\frac{\partial^2 r}{\partial t^2} = - 2\pi r \frac{\partial}{\partial m} \delta P + 4\frac{Gm}{r^3}\delta r$ (5)

3.1. Magnetic flux and voltage calculations

The direction of magnetic field is given by right hand rule, i.e. the fingers are curled in the direction of flow of current and the thumb direction denotes the magnetic field direction.

The magnetic field B is given by equation 6.

$B = \frac{\mu_o}{2} . \frac{NIx^2}{(x^2+z^2)^{3/2}}$ (6)

$= 4\pi \times 10^{-7} \times 0.5 \times \frac{3300 \times 4 \times 4.5 \times 4.5}{(4.5^2+11^2)^{3/2}} = 1 \times 10^{-4}$ T = 10 Gauss.

where μ_o is vacuum permeability = $4\pi \times 10^{-7}$ G/Am^2

N is the number of turns on each field coil

I is the current in ampere

x is radius of coil (meters)

z is the axial distance from centre of coil.

The flux φ of magnetic field B = product of area A of coil to the component of B normal to plan of coil.

$\varphi = AB\cos\alpha = \pi \times 4.5^2 \times 10 \times \cos 60^o = 308$ G/A

where α is the angle between B and normal to plan of coil.

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According to Faraday's law of induction,

$$V = -N\frac{d\varphi}{dt} = -NA\cos\alpha.\frac{dB}{dt} \quad (7)$$

$= -3300 \times 4.5^2 \times \cos60^o \times 10/120 = 2784$ V

$B = 0.5\ B_P\cos\omega t$

$\omega = \frac{10}{0.5\times40000} = 0.748$ rad/s

where B_P is the peak value of B and ω is angular frequency of alternating current.

$$\text{Hence } V = 0.5\ \omega NAB_P\cos\alpha.\sin\omega t \quad (8)$$

$$V = M\frac{di}{dt} \quad (9)$$

where M is the mutual induction that depends on number of turns of coils.

The erosion rate i.e. removed particle mass per mass of hitting abrasive particle is given by equation 10.

$$R = \frac{dm}{dA_m} \quad (10)$$

where m is the mass removed and A_m is the mass of abrasive particle.

$$M = k\rho_w V_A N \quad (11)$$

where ρ_w is the workpiece density, N is the number of particles and V_A is volume removed by a single abrasive particle.

Figure 2 shows a schematic drawing of an active particle acted by several forces. A normal load is acted by total pressure in AFM tunnel and a horizontal driving force acted on the profile face of particle. The horizontal driving force is transferred by the media. From fluid dynamics principle, the transferred driving force in the horizontal direction has an uneven distribution.

If a simplified analysis is made, resultant forces acted on a particle can be divided into four concentrated forces as shown in figure 2, that is, normal force mainly produced by cylinder total pressure, driving force transferred by the pressure of the media and two resistant forces from material surface plastic deformation.

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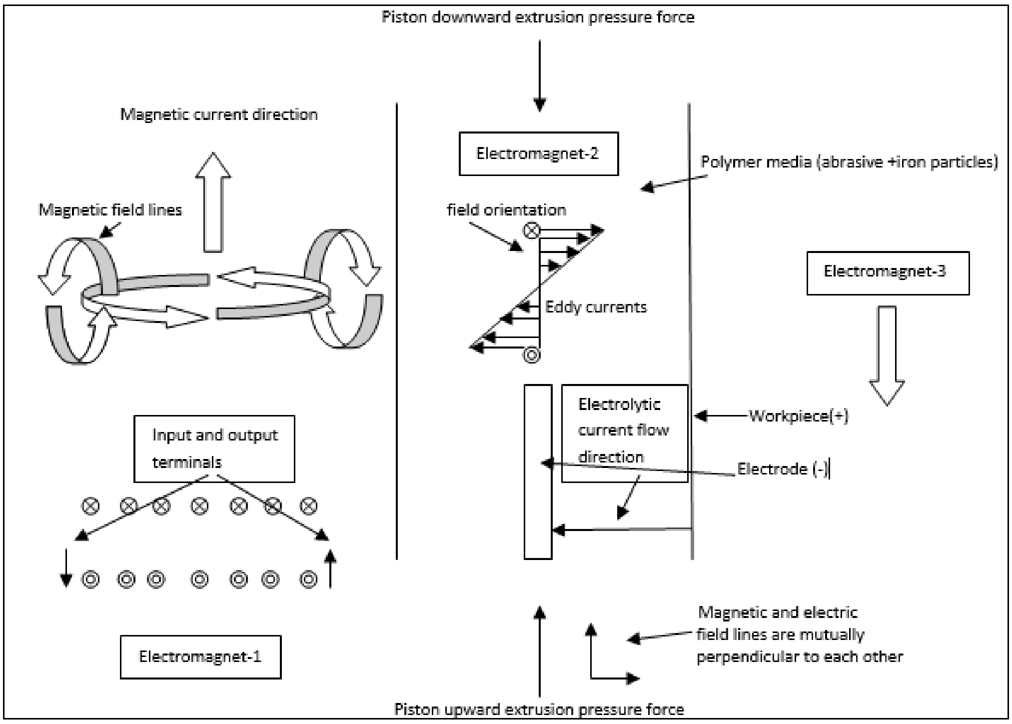

Figure 2: Forces acting on abrasive particle inside the workpiece

4. RESULTS AND DISCUSSION:

The three variable parameters are ECM voltage, ECM rod size and shape as shown in table 2. When workpiece is connected to positive terminal due to more heat generation i.e. 65%, more material removal occurs without tool wear of the rod that is inside the workpiece.

The three variable parameters are media type, media volume and electrolyte used. Styrene butadiene rubber based media gave highest material removal results as compared to nitrile and natural rubber. As the size of abrasive particle increase, the material removal also increased. The coarse grain size abrasive particle resulted in more material removal while fine small particles gave accurate surface finish.

The three variable machine parameters are extrusion pressure, number of cycles and workpiece type. As the number of cycles increase, material removal increase. But after a certain number, the behavior becomes constant. Due to magnetic field, more material removal of workpiece occurs due to higher velocity of hitting of abrasive particle onto the surface due to increased magnetic flux density.

4.1. Effect of magnetic and ECM voltage and rod size on material removal

The hybrid electromagnetic rotational abrasive flow machining (EMR-AFM) setup resulted in higher material removal and better surface integrity. The output

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results in terms of material removal is explained below. In table 4, the three experimental runs of material removal of each workpiece is shown along with mean, variance and sum of squares. The L-9 OA is applied to optimise the result in which 9 experiments have been performed using different combination of 3 input parameters.

The three input variables are magnetic voltage, ECM voltage and rod size. It has been shown that the combined effect of magnetic field and electrolytic field increase the material removal and hence these magnetic and electric lines of forces result in increased velocity of impact of abrasive particles onto the internal walls of worpiece.

Material removal first increases abruptly with ECM rod size but afterwards its increase is gradual. But if ECM voltage is increased, first material removal increase but after a certain voltage, i.e. 12 V, it decreases. The applied magnetic field at starting increases material removal at slower rate but afterwards its increase is high, as shown in figure 3.

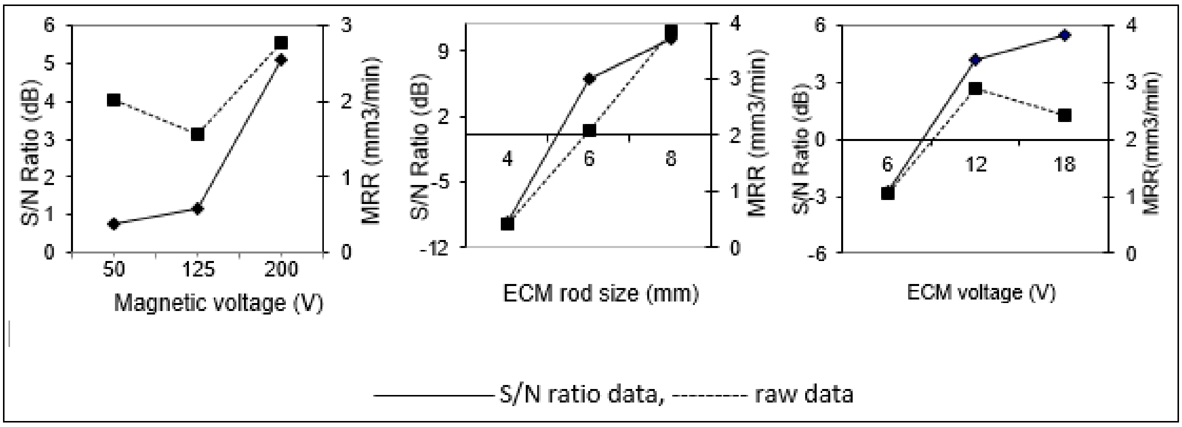

Figure 3: S/N ratio and raw data output graphs of material removal rate vs (a) Magnetic voltage, (b) ECM rod size, (c) ECM voltage respectively

The ANOVA calculations for S/N ratio is as shown in table 5. The response tables i.e. for S/N ratio is found to be significant. All the parameters are found suitable according to their given levels and their values. Hence the optimized results are found correct according to the given conditions.

Table 5: ANOVA S/N ratio table

Source	SS	DOF	V	P	F-Ratio	F-Ratio	Pooling
Magnet	34.114	2	17.057	4.351	16.641	19	No (Significant)
ECM rod	628.343	2	314.171	80.140	306.518	19	No (Significant)
ECM volt	119.545	2	59.772	15.247	58.316	19	No (Significant)
Error	2.049	2	1.025	0.261			
T	784.054	8		100			

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The analysis of the effect of ECM rod and supplied voltage on material removal is done in an exhaustive manner in MiniTab software so that accurate result can be obtained and these results are compared with the actual values obtained after performing a large number of experiments on the prepared hybrid magnetic force assisted electrochemical abrasive flow finishing machine supporting in-house manufactured nylon fixture.

The proper validation has been done for both experimental and analytical output results; so that we can obtain best optimized result i.e. higher material removal and lower surface roughness value. A number of analytical methods were applied so that the complete overview of the various input parameters' effect on output responses can be understood, that included surface plot, interval plot, fitting line plot, Pareto chart, contour plot. The detailed graphs and output results are discussed in the coming explanation.

4.1.1. Response surface methodology results

The response surface methodology (RSM) technique is the optimization software employed in order to get best optimized results as shown in figure 4(a). The material removal is affected by both ECM rod size as well as supplied voltage. The different ECM voltage i.e. 5, 10, 15 V are shown one axis, rod size i.e. 4, 5, 6 mm are shown on another axis while the output response i.e. MR (gm) are clearly depicted in figure 1. If we increase supplied voltage the material removal decreases and if the large sized rod is taken, it resulted in lesser removal of material. This is due to the reason that the electrochemical generally works best if there is minimum gap.

4.1.2. ANOVA output and fitted line plot analysis

In the interval plot explained in figure 4(b), the 3 intervals of rod size taken at 4, 5, 6 mm, the MR results obtained are about 0.17 gm at 4 and 5 mm rod size while 0.125 gm at 6 mm rod size. In the pooled analyses of variance, 95 % confidence interval is taken for the mean and standard deviation was used to calculate intervals. The 0.175 gm, 0.17 gm and 0.118 gm material removal was obtained at the input supplied electrochemical voltage of 6, 12 and 18 V respectively.

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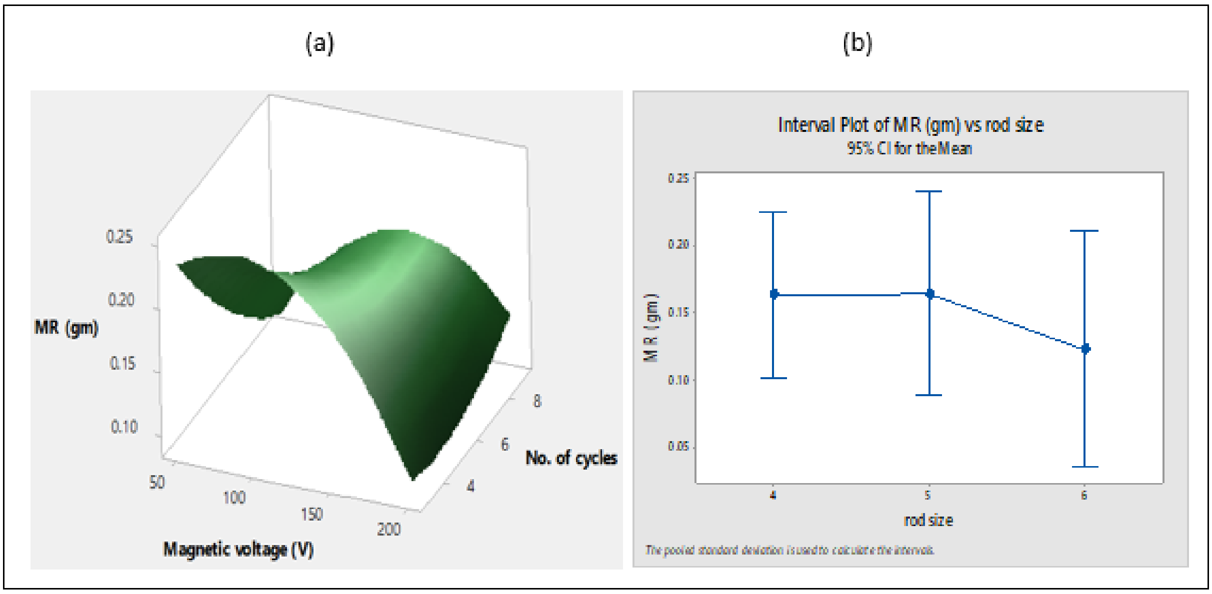

Figure 4: (a) Surface plot of MR vs magnetic voltage, (b) ANOVA interval plot of MR vs rode size

4.2. Comparison of the experimental results with fuzzy logic optimization and grey relational optimization

In fuzzy logic optimization process first of all the membership functions were defined i.e. very low to very high in 5 levels. The output results of material removal and roughness value were calculated using MPCI rank method. Highest MPCI value corresponds to lowest rank as shown in table 6. The results obtained according to Taguchi method was compared to this method.

In grey relational analysis (GRA), we assume that two types of data exist, i.e. black and white. The white data is one whose information is known while black data information is not known. In GRA firstly the normalization of data is done, then for various experiments the grey relational coefficients are calculated, as shown in table 6.

Table 6: GRC and MPCI rank values corresponding to Taguchi L9 OA experimentation

Ra	Normalised	Deviation	GRC	MR	Normalised	Deviation	GRC	MPCI	Rank
20.37	0.09	0.81	0.3817	4.2	0.00	1.00	0.3333	0.06658	9
16.4	0.00	1.00	0.3333	10.8	0.43	0.57	0.4673	0.25	8
50.8	0.75	0.25	0.6666	12.4	0.53	0.47	0.5155	0.55	3
30.3	0.30	0.70	0.4166	14.4	0.66	0.34	0.5952	0.4271	6
38.1	0.47	0.53	0.4854	19.6	1.00	0.00	1.0000	0.65	1
62.4	1.00	0.00	1.0000	10.2	0.39	0.61	0.4505	0.6415	2
36.5	0.44	0.56	0.4717	7.2	0.19	0.81	0.3817	0.315	7
50.4	0.74	0.36	0.5814	8.2	0.26	0.74	0.4032	0.45	5
53.9	0.82	0.28	0.6410	9.8	0.36	0.64	0.4386	0.5484	4

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These values range from 0 to 1. At last grey relational grade is calculated. The equation 12 is used for calculation of GRC.

$$GRC = \frac{d_{min} + e.d_{max}}{d(k) + e.d_{max}} \quad (12)$$

Where d is the value corresponding to the experiment run ranging from k =1-9, e is value taken corresponding to the number of output responses taken, in this case the value of e is 0.5 since there are two output responses whose weightage is assumed to be equal to 0.5 each. As it is clear from table 6, rank 1 corresponds to the condition of 125V magnetic voltage, 12V ECM voltage and 200RPM rotational speed, that will give the optimized result i.e. highest material removal and lowest surface roughness.

4.3. Effect of different media used on MR

It is clearly evident from the experimental results that the material removal is maximum in silicone based rubber media and minimum in polyborosiloxane media and the experimental and response surface methodology results match with each other as shown in table 4. The material removal in case of SBR, nitrile and natural rubber lies in between the values as that of polyborosiloxane and silicon rubber.

The five different types of prepared media, i.e. styrene butadiene, natural, nitrile, silicone and polyborosiloxane rubber are used to check the best usable media in AFM process. The Design Expert software to define the value of factor or input parameter and subsequently RSM value table was generated to set the order of the readings in the experimentation.

The model is significant since F-value is 5.68 and lack of fit, i.e. 2.14 signifies that it is not significant. There is only 0.09% chance that large F-value will occur due to noise. The value of probability greater than F less than 0.05 indicates that model terms are significant.

4.3.1. Variation in 3-D surface

As the graph clearly says that material removal increases with media number, hence it can be concluded that media no. 1 is less efficient and media no. 5 is most efficient, i.e. polyborosiloxane is less efficient while silicone rubber based polymer media results in higher material removal and the material removal capacity of

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natural, SBR and nitrile rubber lies between them, as shown in figure 5. There is 20.75% chance that a larger lack of fit value would occur.

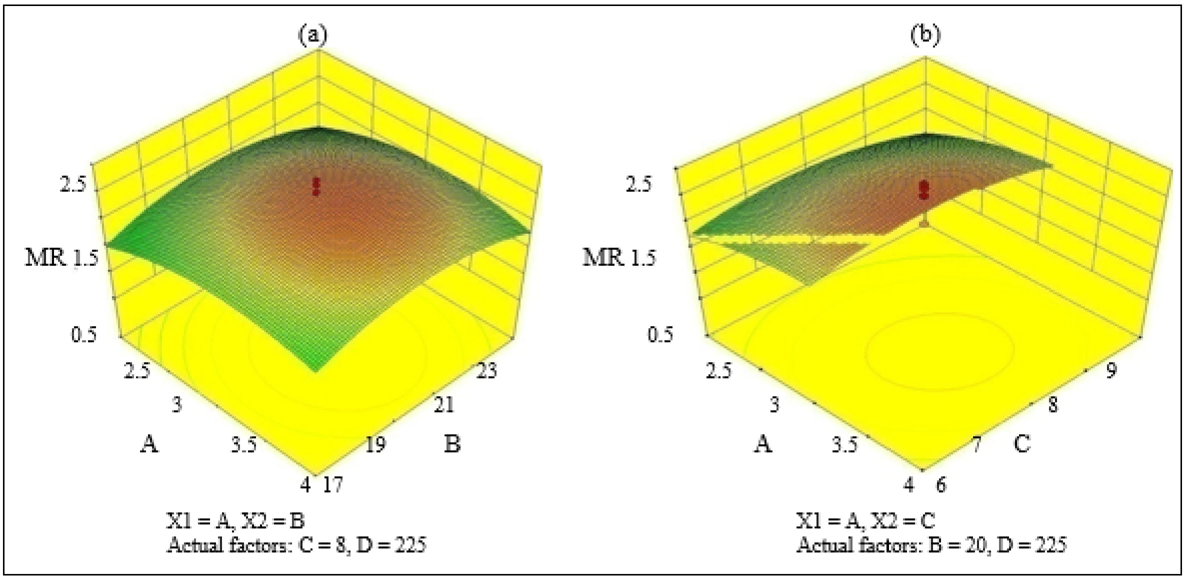

Figure 5: 3D Surface model (a) Type of media (surface view from top), (b) (surface view from front)

The "Pred R-Squared" of 0.2163 is in reasonable agreement with the "Adj R-Squared" of 0.6934; i.e. the difference is more than 0.2. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 7.458 indicates an adequate signal. This model can be used to navigate the design space.

4.3.2. Final equation in terms of coded and actual factors

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels of the factors are coded as -1. The coded factors equation is as shown in equation 13.

$$MR = +1.29 + 0.13*A + 0.016*B - 0.12*C - 0.31*D - 0.018*AB + 0.060*AC - 0.067*AD + 0.098*BC - 0.041*BD + 0.068*CD - 0.047*A^2 - 0.11*B^2 + 0.12*C^2 + 0.077*D^2. \quad (13)$$

This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the center of the design space.

5. CONCLUSION

The efficiency of conventional AFM setup has been increased by making it hybrid using magnetic and electrolytic setup fabrication successfully. It can be

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concluded from the hybrid abrasive flow machining of hollow workpiece that the material removal is 0.17 gm at 4 and 5 mm rod size while 0.125 gm at 6 mm rod size.

The ECM rod size first increases MR but afterwards its increase is gradual and MR first increase with increase in voltage but decreases after 12 V. Different types of media have been developed and used in machining process and it was found that silicone rubber based polymer media results in higher material removal and polyborosiloxane results in less removal.

A mathematical model has been developed successfully to analyse the different forces encountered during the process. The magnetic field B was found to be 10 Gauss and the flux φ of magnetic field as 308 G/A and angular momentum of iron particle due to rotation provided by motor as ω = 0.748 rad/s. The results of experimentation were successfully validated and compared with different optimization techniques i.e. Taguchi L9 OA, RSM, Minitab fuzzy logic and grey relational analysis in order to enhance material removal and obtain better surface roughness.

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