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Modeling and Simulation of AFM Experimentation of Brass Workpiece Using Different Media

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Abstract: In abrasive flow machining workpiece internal surface is finished using abrasive laden media. In this paper, different polymer media were prepared and their practical usage was checked. Apart from this modeling and simulation using response surface methodology was done. The machine setup fabrication was explained with proper explanation of different equipments. The effect of ECM voltage, number of extrusion cycles and magnetic supply voltage has been studied in detail and explained graphically. Their surface and fitted line plots are studied to explain the material removal and surface roughness obtained after experimentation. The experimental values are in confirmation with values obtained by simulation.
Keywords: media, AFM, modeling

1. Introduction and Literature Review:

To enhance the productivity of traditional abrasive flow machining process, it is made hybrid. If external magnetic field is applied, it is magnetic assisted AFM process, if rotating workpiece is utilized in the machine setup, it is rotational AFM. In some cases, drill bit is placed inside the workpiece, it is known as helical AFM. In order to obtain additional centrifugal effect to properly intermix the abrasive particles in media and increase the active grain density hitting onto the work surface, centrifugal rod is rotated inside the workpiece and the process is known as centrifugal force assisted abrasive flow machining process (CFAAFM). Another variant of AFM is vibration force assisted AFM. The magnetorheological assisted AFM process uses rheological fluids containing magnetic particles. Abrasive flow machining is a fine finishing process in which the media is reciprocated up and down between upper and lower media cylinders. This process has been studied by a lot of scientists and researchers. Kenda et al. (2014) [1] 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 (Venketesh et al. 2014) [2]. The high temperature in the AFM process decreases the viscosity of the polymer media used for cutting action or finishing process (Uhlmann et al. 2009) [3]. The hybrid AFM process increases the efficiency of the conventional process (Jain 2008) [4]. The design of the optimum results, media and AFM setup has effect on the process (Zhang et al 2009) [5]. For extrusion pressure used in AFM, dies and molds are made of Al and steel that resulted in optimum output (Williams et al 2007) [6]. The AFM process used turbulent flow model and volume of fluid (VOF) model in case of zigzag channel to check the regularity of process (Tang et al 2010) [7]. In AFM process, the MRR was affected by various factors like abrasive grit size, pressure, etc (Williams and Melton 1998) [8]. The discussion of the pressure difference between inlet and outlet of the system was extensively done in case of steel pipe in AFM process that used copper and nylon fixture (Zhang et al 2009) [9]. The cleaning of the wall of steel tube in abrasive flow machining process was discussed (Pengfei et al 2009) [10]. The cleaning technology helped to remove the material using the developed the mechanical model in lesser time to get accurate results in case of steel tubes (Pengfei and Jiazhi 2010) [11]. The Ansys and finite element analysis (FEA) software were used to obtain strength and rigidity of rail parts in AFM experiments (Li et al 2010) [12]. The abrasive particular move in such a way that it increase the hardness of workpiece and decrease the groove regime in AFM process, using 3-body abrasion (Fang et al 2009) [13]. The energy consumption and roughness was decreased, flow improved by increasing abrasive concentration, in case of extruding grinding which is affected by cycle time (Yang 2009) [14]. Abrasive flow machining is generally a nano-finishing operation in which the internal surface of the workpiece is finished by the abrading action of the abrasive particles held by polymer media. The semi-paste media is extruded using the machine piston cylinder arrangement. In one way [16] AFM process the media is extruded inside the work piece only in one direction, Two way AFM machine [17] has two hydraulic cylinders and two medium cylinders and in orbital process, good surface finishing is obtained by producing low-amplitude oscillations of the work piece [18]. The various elements are fixture or tooling, the machine, and abrasive laden media. Fixture plays a vital role to increase productivity of the process, it holds the workpiece to be machined. This technique uses a non-Newtonian liquid polymer containing abrasive particles of Al_2O_3, SiC, boron carbide or diamond as the grinding medium and additives [19]. All AFM machines regardless of size are positive displacement hydraulic systems, where work piece is clamped between two vertically opposed media cylinder.

2. Experimental Work:

2.1. Preparation of media:

Commercially available media is expensive and lacks affordability. Media mainly affects the finishing efficiency of the process. In this paper, the development of new media based on viscoelastic carrier is done. It has good processability, low hysteresis, low cost. Silicone Rubber is non reactive and can withstand temperatures upto 300^{o}C. It can easily be manufactured, injection molded and shaped. It can be cured by platinum catalyzed cure system. It is used in electronics, medical devices, footwear, etc. For preparing the flexible polymers mass, a fixed quantity of polymer is taken first and an appropriate quantity of plasticizer is added into it. When this natural rubber sheet passes through this very narrow passage, it is deformed severely and this process keeps on going until it becomes a little bit soft. Ultimately, when all plasticizer gets consumed, we get a non-sticky semi solid mass, which is ready to get mixed with gel.

2.2. Fixture:

POM, Acetal and delrin absorbs little moisture and chemically resistant to every material, hence not used. Turcite is a form of teflon, it has low coefficient friction it is preferable to use over teflon due to hugh rigidity properties. Out of these materials Nylon 66 was selected for manufacturing for workpiece fixture. It absorbs high amount of moisture. Nylon can easily be bonded, this property makes it worth as compared to other materials.

2.3. Design:

In the side view of fixture, two fixtures are clearly shown attached to each other, the upper fixture thickness is lesser as compared to lower fixture. In the lower fixture, three 18 mm through holes are drilled at the periphery at 120^{o} to each other. The upper fixture is made to fix into the media cylinder of AFM setup, for this purpose, 7 mm height surface of diameter 70 mm is provided so as to tightly clamp inside it. The abrasive laden polymer media is given extrusion force by the reciprocating piston cylinder arrangement of AFM setup, that ultimately pushes the media through the inner walls of workpiece. The media first enters the upper fixture, for that a tapered hole of 29^{o} is provided upto the depth of 15 mm so that a jerk is not experienced by the workpiece and hence efficient finishing process is obtained. The 3D model of the fixture, i.e. SolidWorks model is as shown in fig.1.

Fig.1. Nylon fixture view

2.4. Setup explanation:

The hybrid AFM setup shown in fig.3(c) comprises of a pair of extrusion machine piston cylinder arrangement and a pair of media cylinders in which prepared abrasive laden polymer is filled and fixture alongwith electromagnetic coils in between is shown. The transformer for electricity supply to the magnetic system is also arranged in the machine setup. The ammeter and voltmeter for current and voltage output readings respectively are connected. The ammeter is connected in series while voltmeter is connected in parallel in circuit diagram. Similarly, the ending points of all the three electromagnets are connected to each other to form node 2, this node is connected to a wire whose other end can be connected to any of the six output voltage terminals viz. 45-200V so as to receive different magnitude of magnetic flux on the electromagnets. Further, node 1 and the output port of the transformer are connected to the mains AC 220V supply. The full system including ECM working and effect of magnetic current in the fixture holding workpiece i.e. brass, Al, C.I., M.S., etc. is shown in fig.3(c). The electromagnetic solenoid is shown clearly on the left part of the drawing, these are three in number, circumferentially placed at equal angles to one another with their unwrapped part inside the nylon fixture and the copper wire portion outside. The bright bar which is paramagnetic in nature is fixed around the workpiece. The thickness of pole of solenoid is 18 mm, the copper turns are upto the thickness 58 mm from the axis, situated at a distance of 60 mm from the top surface of fixture and the tapered portion of the fixture is upto the depth of 35 mm from the surface that fixes into the media cylinder.

2.5. Working of setup:

Since the internal surface of the prepared piece is not so smooth and requires post finishing process, hence the non-traditional machining process i.e. abrasive flow finishing (AFF) process is done on the prepared machine setup in Precision engineering laboratory, that will produce highly finished surface as compared to traditional machining process applied earlier that included drilling, boring and reaming. The large number of workpieces of brass material were obtained, out of this lot, selection of nearly equal surface roughness value pieces are selected for AFM experimentation. In the present experimental work, 18 workpieces are selected on which hybrid AFM has to be performed, their initial surface roughness value tested on roughness tester machine was found to be in the range 1.65 µm to 1.99 µm, the initial weight measured were in the range 3.7684 gm to 3.949 gm. After performing machining, the roughness values obtained were in the range 0.90 µm to 1.92 µm, while the final reduce weight obtained was in the range 3.6921 gm to 3.7491 gm. The maximum and minimum material removal obtained was 0.1999 gm and 0.1142 gm whereas maximum and minimum percentage reduction in surface roughness was found to be 37.96 and 3.33 respectively.

2.6. Pilot experimentation:

After relevant acquisition process of workpiece, the undertaking of surface roughness and initial weight of al the workpieces was done, followed by sampling i.e. closest reading pieces were selected for experimentation. The machining was simple two-way AFM process using two vertically opposed piston-cylinder arrangement.*2.5.2. Response characteristics:*
The effect of selected process parameters were studied on the following response characteristic of AFM process: Material removal (MR) = (Initial weight – final weight).

2.7. Procedure:

The alternating current that reverses direction periodically is converted into direct current flowing in only one direction using rectifier device. In motor generated set the AC motor shaft is coupled to DC generator. The multi phase alternating current is produced in armature windings, commutator on the armature converts it into direct output current. A transformer contains two magnetically coupled windings, the primary winding is driven by input AC supply, while the secondary winding give supply to AC-DC converter. Firstly, we fill the media into one of the cylinders of the two way AFM. Placing the workpiece between the two-piece fixture, we fix both the fixtures on the upper and lower jig such that they fit into the groove of the jig. We then fix this jig onto the AFM setup such that the cylinders are in line with the pistons with the help of the nut and bolt provision given. Subsequently, we set the pressure manually by using the handle for both the upper and lower side. After the pressure has been set, we manually operate the pistons with the help of the operating levers in accordance with the number of cycles required. After the machining is done, we unclamp and dismantle the fixture. We then remove the workpiece, clean it with cloth and in a toluene bath and the surface roughness and weight is measured. The difference in weight gives us the material removal. Clean setup after experimentation. Tabulate and analyse observations to get results.

fixes into the media cylinder. The output results in terms of material removal is explained below. In table 1, the three experimental runs of material removal of each workpiece is shown alongwith 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.

Table 1: Mean and variance of output results

S.No.	R-1	R-2	R-3	Mean	Variance	Sum of Squares of Reciprocals
1	0.17	0.18	0.17	0.173	3.33E-05	33.356
2	2.44	1.94	1.77	2.05	0.121	0.250
3	3.33	3.67	4.54	3.846	0.389	0.070
4	0.45	0.54	0.26	0.416	0.020	7.720
5	2.9	2.77	2.53	2.733	0.035	0.135
6	1.36	1.81	1.49	1.553	0.053	0.432
7	0.65	0.71	0.63	0.663	0.001	2.290
8	1.39	1.46	1.53	1.46	0.004	0.471

9	5	6.57	6.96	6.176	1.076	0.027
Sum	17.69	19.65	19.88			
Total Sum (T)		57.22				
Average		2.1193				

The main effects of S/N ration i.e. sound to noise ratio alongwith levels and iterations is shown in table 2. 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.

Table 2: Response table for S/N ratio

Level	Magnet	ECM Rod	ECM volt
L1	0.753	-9.235	-2.773
L2	1.153	5.987	4.222
L3	5.068	10.223	5.527
L2-L1	0.399	15.223	6.995
L3-L2	3.915	4.236	1.305
Difference	3.516	-10.987	-5.690

Table 3: ANOVA Raw Data:

Source	SS	DOF	V	P	F-Ratio	F-Ratio	Pooling
Magnet	6.592	2	3.296	7.198	4.223	19	No (Significant)
ECM rod	53.305	2	26.652	58.211	34.147	19	No (Significant)
ECM volt	16.063	2	8.031	17.542	10.29	19	No (Significant)
Error	15.61	20	0.78	17.046			
T	91.571	26		100			

3. Modelling and Simulation of Experimentation

3.1. Introduction to RSM:

RSM is amalgamation of statistical methods in which desired values are to be controlled. Here we forecast the properties of product, find out the factor level, relationships between variables and designation of individual and combined effect of input variables is done.

3.2. Procedure of RSM:

It 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 and then optimization is done using central composite design (CCD). Optimal factor levels are identified and then experiments are performed. We find the optimum spot where response is maximised or minimised. The two models used are screening response and steepest ascent model. The steepest ascent model tells where to take new experiments and the response at those points are noted. It is a second order model that includes linear, cross product terms and second order term. The linear terms have one subscript and quadratic have two subscripts.

Table 4: Input variables

Type of media	Pressure (bar)	Volume of media	Number of cycle
1	10	175	4
2	15	200	6
3	20	225	8
4	25	250	10
5	30	275	12

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. The table 1 shows the different input variables and their five levels.

Table 5: 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

Table 6: Values of factors and different points of cube:

Readings	Factors	Replicas	Runs	Base blocks	Blocks	Cube points	Center points	Axial points	Center points (axial)	alpha
Value	4	1	30	1	1	8	6	6	0	1

The design was set and graphs were obtained between different values as shown in table 7.

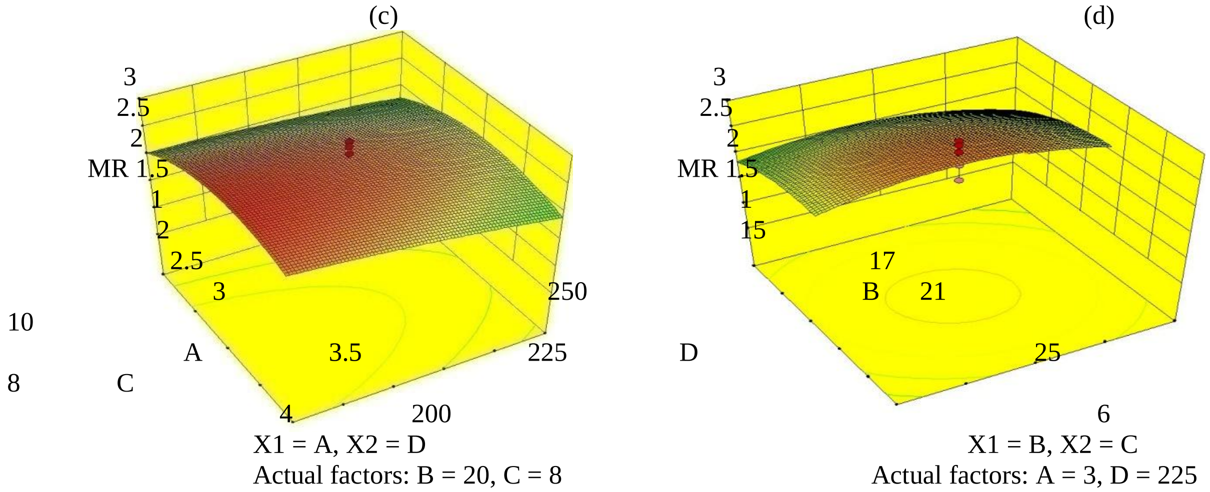
Table 7: Design table in terms of actual factors

Run	Type of media	Pressure	No. of cycle	Volume of media	Material removal
1	4	25	6	200	1.9543
2	3	20	8	225	2.6532
3	4	15	10	200	1.5329
4	2	25	10	200	1.3932
5	1	20	8	225	0.8032
6	4	15	6	200	1.8578
7	3	10	8	225	0.7593
8	3	30	8	225	0.8029
9	4	25	10	200	2.2076
10	2	25	6	250	1.1029
11	2	25	6	200	1.4191
12	3	20	4	225	1.1529
13	4	25	6	250	0.9043
14	4	15	10	250	1.2866
15	2	15	6	200	2.0546
16	3	20	12	225	1.2874
17	2	15	10	250	0.8031
18	3	20	8	225	2.0021
19	4	25	10	250	0.9041
20	3	20	8	225	2.5234
21	3	20	8	225	2.2872
22	3	20	8	275	2.3987
23	2	15	6	250	0.8155
24	2	25	10	250	1.1027
25	5	20	8	225	1.2874
26	3	20	8	175	2.0832
27	2	15	10	200	1.0571
28	3	20	8	225	2.7352
29	3	20	8	225	2.5229
30	4	15	6	250	1.2876

Table 8: Statics control terminology

Readings	**Std. Dev.**	**Mean**	**CV%**	**Press**	**R-Sq**	**Adj R-Sq**	**Pred R-Sq**	**Adeq R-Sq**
Value	0.36	1.57	22.74	9.40	0.8814	0.6934	0.2163	7.458

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.



A: Type of media, B: Extrusion pressure, C: No. of cycles, D: Vol. of media

Fig.2: 3D Surface model (c) Extrusion pressure (surface view from top), (d)) Extrusion pressure (surface view from front)

4. Results and Discussion:

4.1. Effect of electrolytic force and magnetic assisted AFM on material removal:

The voltage supplied to the anode and cathode is in the range 6-18 V, and it affects the removal of material from the workpiece during AFM process. The conventional AFM is made hybrid with the help of attachment of electrochemical electrodes and prepared electrolyte. For electrochemical action to occur, both anode (workpiece) and tool (ECM rod) must be conducting in nature and flow of current should be easy through the prepared electrolyte.

4.2. Effect of ECM voltage and rod size on material removal:

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 (fig.3).

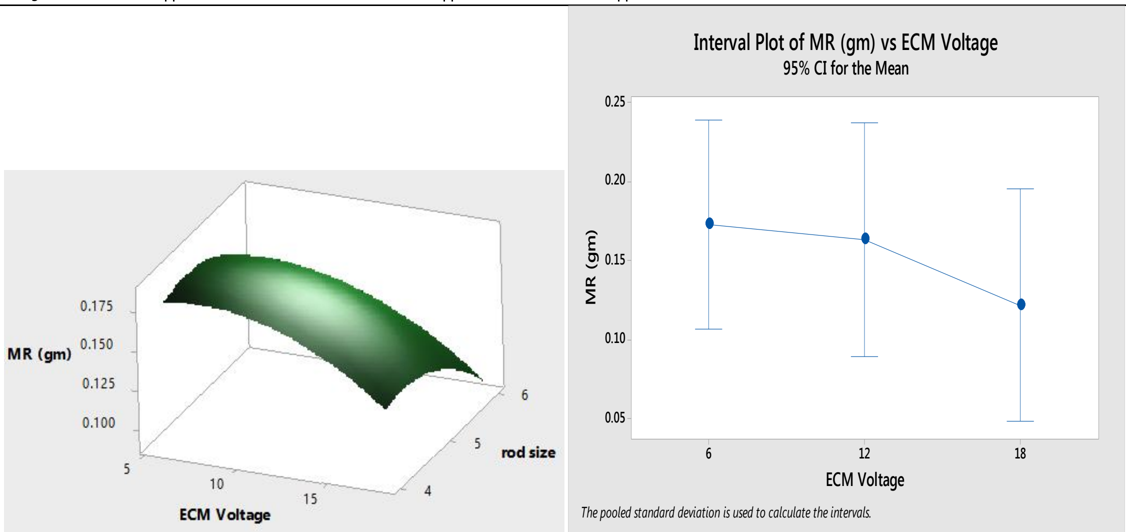


Fig.3. Surface and fited line plot of MR vs ECM voltage

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. The another method of analysis of the effect of input parameters on the output results is the technique of fitted line having scattered points on the graphic line obtained and the points are above, on or below the line at the pre-decided three levels of the input parameter taken at the x-axis. If the rod size is increased from 4 to 6 mm, then the material removal gradually decreases from about 0.167 gm to 0.135 gm and standard value ranges from 0.2397-0.01794 gm for rod size.

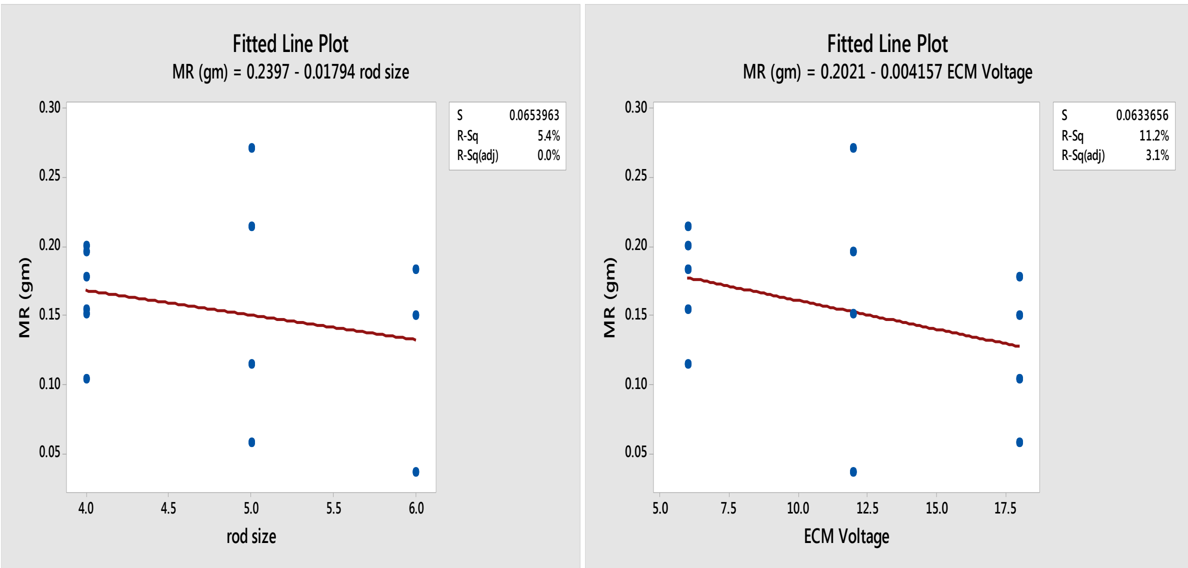


Fig.4. Fitted line plot of (a) MR vs rod size, (b) MR vs ECM voltage

The S value is 0.0653963, R-Sq is 5.4 % and R-Sq (adj) is 0.0 %. In case of supplied ECM voltage the fitted line plot is explained in figure 16, where material removal decreases from 0.175 gm to 0.12 gm as we increase voltage from 6 to 18 V. The standard MR values ranges from 0.2021 to 0.004157 gm for ECM voltage parameter, the S value is 0.0683666, the R-Sq is 11.2 % and R-Sq (adj) is 3.1 % in this case.

4.3. Pareto and contour chart detailed explanation

In figure 5(a), the Pareto chart analysis of the effect of input parameters i.e. ECM voltage and ECM rod size on the output response i.e. MR (gm) is done.

(a) (b)

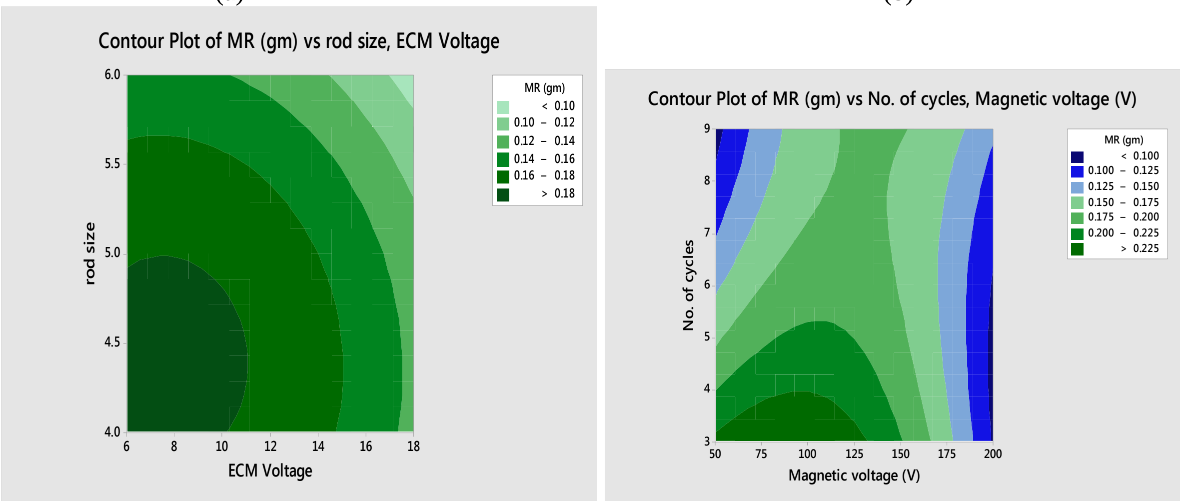


Fig.5. (a) Pareto Chart of standardized effects, (b) Contour plot of MR vs rod size and voltage

The value of sensitivity α is 0.05, A is ECM voltage while B is rod size and the terms A, B, AA, BB, AB values are 1.0, 0.8, 0.4, 0.39 and 0.07 respectively.

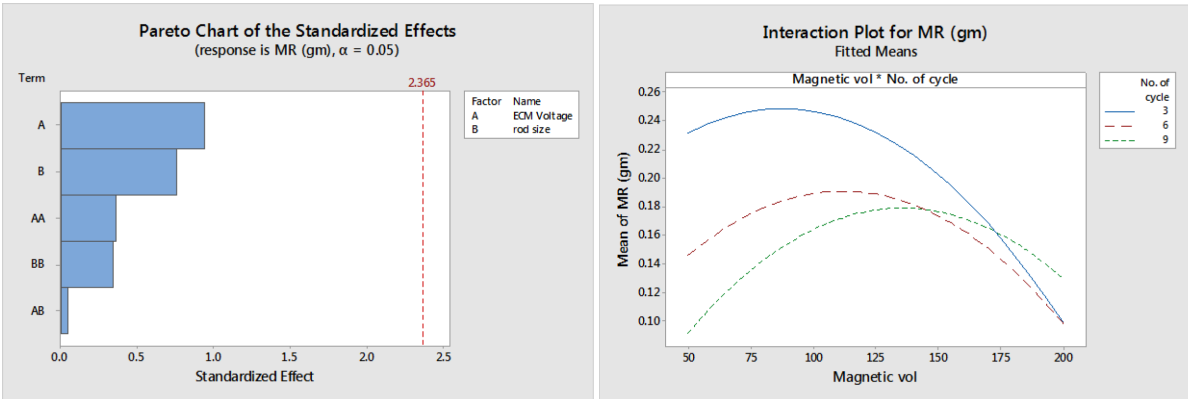


Fig.6 (a) pareto chart of standardized effects, (b) interaction plot for material removal

These standard effect values ranges from 0 to 2.5 and the dashed vertical line is shown at the standardized effect value of 2.365. The contour plot of MR vs rod size, ECM voltage is shown in figure 6 where voltage is taken at x-axis and rod size at y-axis and the output response are shown in terms of curves that are viewed moving away from the origin. If the MR values less than 0.1 it is lightest green in colour at the outermost distance from the origin. If the value ranges between 0.1-0.12, 0.12-0.14, 0.14-0.16, 0.16-0.18, the colour becomes dark green which indicates that more material removal occurs as we go towards the origin, if MR is greater than 0.18, the black shaded region enclosing the origin is shown in the contour plot. The interaction plot is as shown in figure 6(b).

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 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. In abrasive flow machining process, it is important to obtain higher material removal and for that a newly developed fixture and polymer combination was utilized and media flow was analysed using solidworks software to know the effect of magnetic field on pressure, shear rate and velocity of media. The hybrid attachments of electromagnet and anode and cathode setting of workpiece and ECM rod resulted in increased force on abrasive particle onto the work surface and high material removal resulted. The rod is fixed inside the workpiece and the magnetic poles at the outer periphery.

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