AN EXPERIMENTAL INVESTIGATION ON ECG PROCESS DURING GRINDING OF HYBRID AL/ (5WT. % AL_2O_3+5WT. %ZRO_2)-MMC

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ABSTRACT

This paper presents the experimentally investigated results during grinding of hybrid Al/ (Al_2O_3+ZrO_2) MMC. An electrochemical grinding set up has been designed and fabricated for conducting the experimentation. A resinoid copper impregnated diamond grinding wheel (average mesh size of diamond particles: 1000 µm) is used to grind the inner surface of cylindrical workpiece. Taguchi method based design of experiment, an orthogonal L_{27} (3^{13}) array and analysis of variance (ANOVA) are employed to identify the most significant electrochemical grinding (ECG) process parameters during finishing of hybrid Al/ (Al_2O_3+ZrO_2) MMC. A comprehensive mathematical model for correlating the interactive and higher-order influences of ECG process parameters such as grinding wheel speed, work piece speed, electrolyte concentration, DC supply voltage and DC current on MRR has been developed for effective grinding of such composite. Test results reveals MRR 0.88 g/min and surface roughness height, R_a 0.14µm at 12000 rpm grinding wheel rotational speed, DC voltage 10V, DC supply current 5A parameter setting. Whereas test results reveal MRR 1.22g/min and surface roughness height, R_a 0.55µm at parameters setting 6000 rpm grinding wheel rotational speed, 15V DC supply, 15A DC supply current.

Keywords: Electrochemical Grinding, Hybrid-Mmc, Material Removal Rate, Surface Roughness Height.

1. Introduction

Particulate reinforced hybrid matrices composites are attracting greater degree of interest to numbers of researchers due to its wide spread applications in the field of aviation, automotive medical etc due to their better unidirectional strength to weight ratio, higher strength and better wear resistance properties at adverse operating condition**.** Finishing of particulate reinforced hybrid matrices composites through conventional machining produces parts with higher surface roughness with burrs and are having heat affected zone (HAZ) which resists its wide spread engineering applications as stated by Manna and Bhattacharyya [1]. A number of research work reported by different researchers on various hybrid machining processes such as WEDM, EDM, ECG etc. have proven their applications on the machining of particulate reinforced metal matrix composites. These processes have their own limitations based on predominance of selected processes used during for machining. Thus problems of low MRR, high surface roughness, poor dimensional accuracy with (HAZ) during machining on particulates reinforced MMC remains to be resolved. A cost effective manufacturing of mini and micro dimensional part of hybrid Al/ (Al_2O_3+ZrO_2) MMC with satisfactory tolerance by any known machining processes is still very difficult to choose. Hence, an attempt is made to investigate and find out optimum ECG machining process parameter condition to produce cost effective parts made of stir casted Al/(Al_2O_3+ZrO_2)- MMC.

Allison and Cole [2] stated that the aluminium alloy reinforced with discontinuous ceramic reinforcement is rapidly replacing conventional materials in various automotive, aerospace and automobile industries. But machining of ceramic reinforced metal matrix composite poses one of the major problems, which resist its wide spread engineering applications stated by Manna and Bhattacharyya, [2]; Cronjager and Meister, [3]. Manna and Bhattacharyya [4] concluded that the hard reinforced particles of MMC, which intermittently come into contact with the hard surface, act as small cutting edges like those of grinding wheel on the cutting tool edge, which in due course becomes worn out by abrasion, resulting in the formation of a poor surface finish during conventional machining of MMC. Various nonconventional machining processes such as ECM, EDM, WEDM, etc. are also not effectively used for the machining of particulate reinforced metal matrix composites for their inherent limitation of process capabilities. Hocheng et al. [5] concluded that machining of Al/SiC-MMC by EDM requires a huge amount of current and discharge of SiC/Al is more irregular. Thus machining problems associated with low material removal rate, high surface roughness, (HAZ) and poor dimensional accuracy etc on finished parts remains unresolved. Advance nontraditional machining techniques such as abrasive jet machining, water jet machining, laser beam machining etc can be applied for the machining of Al/SiC-MMC but cost effective manufacturing of mini and micro dimensional part of slurry casted hybrid Al/ (Al_2O_3+ZrO_2)-MMC with satisfactory tolerance by any well known machining processes is still very difficult as concluded by Manna and Bhattacharyya [6]. Hence, an attempt is made for an applied research investigation to identify the optimum ECG machining process condition to produce cost effective parts of stir casted Al/(Al_2O_3+ZrO_2)-MMC. Jain [7] opined that conventional grinding produces components with good surface finish and dimensional tolerances but such components are also associated with burrs, heat affected zone (HAZ) and thermal residual stresses , where as these defects are not found in parts produced by electrochemical grinding process. Surface integrity of parts produced by hybrid machining process can be improved considerably by enhancing the advantages and minimizing the potential disadvantages of individual technique applied as explained by Lauwers [8]. Author concluded that by lowering process force and tool wear, surface integrity can be enhance with increase in productivity but it needs good understanding of the process-material interaction and process parameters must be selected in a suitable way to eradicate strong negative effect generated during hybrid machining. Brinksmeier et al. [9] stated that ultra precision grinding is primarily used to generate high quality functional parts usually made from hard and diffcult to machine materials.

2. Planning and design for experimental investigation.

Table 1 represents the chemical composition of Aluminum ingot A6061 is used as a matrix material. Table 2 and Table 3 represent the chemical composition of Al_2O_3 particles with 38 µm average particle size (APS) and ZrO_2 particles with 25 µm APS respectively used as reinforced particulates. Liquid stir casting technique is used to fabricate the MMC round shape ingot. The workpiece samples are prepared from the stir cast MMC ingot. The conventional machining methods (i.e. turning, drilling and reaming) are utilized to prepare the workpiece sample of outside diameter (OD) 25 ± 0.2mm, inside diameter (ID) of 15 ± 0.2mm and length of 20 ± 0.1mm each for further experimental investigation i.e. electrochemical grinding operation. Mitutoyo Surf test SJ-400 a surface measuring instrument is used to measure the inner surface roughness of the prepared sample by conventional machining process. The measured average surface roughness heights, R_a, (µm) and R_t (µm) are found 1.55 µm and 9.2 µm respectively.

Table 1 Composition of Aluminium

Grade	UNS No.	Si (%)	Fe (%)	Cu (%)	Ma (%)	Ti (%)	Mg (%)	Cr (%)	Zn (%)	Un-specified elements (%)	Aluminum
6061	A96061	0.4-0.80	0.70	0.15-0.40	0.15	0.15	0.8-1.20	0.04-0.35	0.25	0.15	Remaining

Table 2 Composition of Alumina

Grade	Mesh size Avg (APS)	Heavy metals (Pb) %	Na2O %	Cl %	SO4 %	Al2O3
Puriss	400 (38µm)	≤ 0.005	≤ 0.2	0.1	0.1	Remaining

Table 3 Composition of ZrO2

Metal	Mesh size Avg (APS)	SiO2 %	Fe2O3 %	TiO2 %	Na2O %	ZrO2
ZrO2	600 (25µm)	0.02	0.003	0.003	0.005	Remaining

Figure1 Prepared workpiece samples from stir cast MMC ingot

Fig.2 shows a schematic diagram of fabricated ECG setup is utilized for experimental investigation. Two stepper motors are used to control and maintain the grinding wheel and workpiece rotational speed. Linear motion in X and Z axis are controlled by two

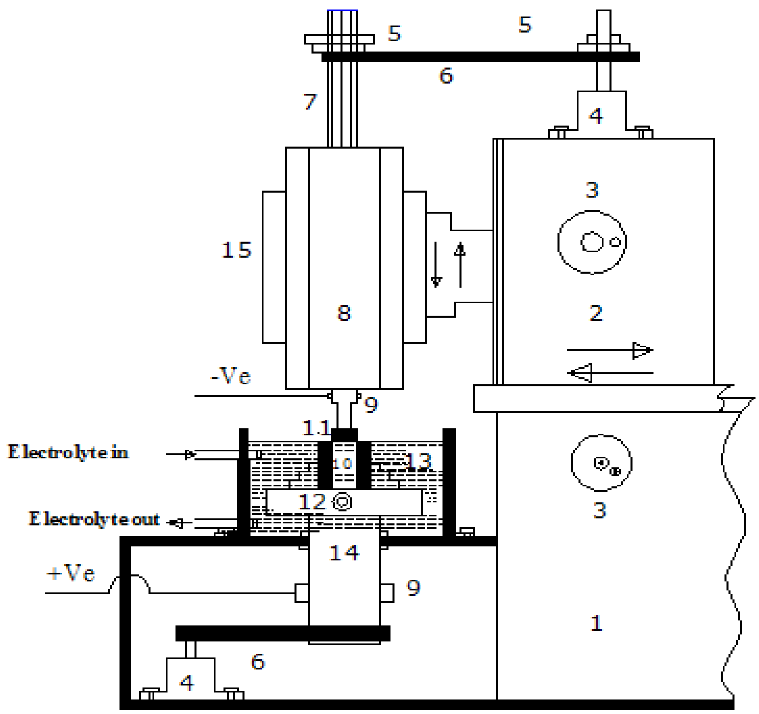

Figure 2 Schematic diagram of developed ECG setup

Components details: 1: Base, 2: Upper housing, 3: Control Knob, 4: Motor, 5: Pulley, 6: Belt, 7: Quill spindle, 8: Quill, 9: Carbon contact bush subassembly, 10: Workpiece, 11: Grinding wheel, 12: 4jaw chuck, 13: Machining chamber, 14: Workpiece rotational spindle micronic dial mounted on control knob, fitted on base and upper housing respectively. Circulations of electrolyte and flow rate are maintained by a small pump and are controlled by control valves. Negative terminal of DC supply is connected to grinding wheel spindle and +Ve terminal to the workpiece rotating spindle through carbon contact bush subassembly respectively and are properly insulated from the base of machine. Liquid stir casted workpiece surfaces are thoroughly cleaned before used.

3. ECG process parameters and their levels.

A set of experiments has been designed based on Taguchi's robust design [10]. The five controllable ECG process parameters such as A (Grinding wheel rotational speed, rpm), B (Electrolyte concentration), C (DC voltage), D (DC current) E (Workpiece rotational speed, rpm) with three levels each have been considered for investigation of material removal rate and surface roughness height, R_a, (μm). Table 4 represents the various parameters and their levels are considered for experimental investigation. An orthogonal L_{27} (3^{13}) array is used for factorial design to select run at random for investigation of material removal rate and surface roughness height, R_a, (μm) during electrochemical grinding of hybrid Al/(Al_2O_3+ZrO_2)-MMC. The sodium nitrate ($NaNO_3$) with dematerialized and deionizer water is used as electrolyte for experimentation.

Table 4 Machining parameters and their levels

Sl.No	Symbol	Machining parameters	Level			units
			1	2	3	
1.	A	Grinding wheel rotational speed	6000	9000	12000	rpm
2.	B	Electrolyte concentration	10	20	30	g/*l*
3.	C	DC supply voltage	5	10	15	Volts
4.	D	DC current	5	10	15	A
5.	E	Workpiece rotational speed	100	125	150	rpm

4. Results and discussion

The main purpose of the Analysis of Variance (ANOVA) is to investigate the design parameters and to indicate which parameters are significantly affecting the quality characteristic. In the analysis, the sum of the square deviation is calculated from the value of S/N ratio by separating the total variability of S/N ratio for each control parameter. This analysis helps to find out the relative contribution of machining parameter in controlling the response e.g. MRR (g/min) and R_a (μm) of the ECG process. Table 5 represents the L_{27} (3^{13}) array, investigated results and S/N ratio (dB). Table 6 represents the ANOVA and 'F' test values with percentage of contribution, i.e. effectiveness of the individual ECG process parameters on material removal rate (MRR, g/min).

Table 5 an orthogonal L_{27} (3^{13}) array, experimental results MRR and R_a for Al/ (5wt. % Al_2O_3+ 5wt. % ZrO_2)-MMC

Exp Sl.	A (1)	B (2)	C (3)	D (4)	E (5)	1 G/W (rpm)	2 Electrolyte concentration	3 (V)	4 (A)	5 W/P (rpm)	MRR			MRR (g/min) (Avg)	S/N ratio (dB), MRR	R_a (μm) (Avg)
											MRR 1	MRR 2	MRR 3			
1	1	1	1	1	1	6000	10	5	5	100	0.62	0.68	0.71	0.670	-3.520	0.343
2	1	1	1	1	2	6000	10	5	5	125	0.69	0.73	0.69	0.703	-3.066	0.357
3	1	1	1	1	3	6000	10	5	5	150	0.72	0.7	0.85	0.757	-2.515	0.320
4	1	2	2	2	1	6000	20	10	10	100	0.75	0.72	0.85	0.773	-2.297	0.487
5	1	2	2	2	2	6000	20	10	10	125	0.88	0.84	0.83	0.850	-1.420	0.457
6	1	2	2	2	3	6000	20	10	10	150	0.85	0.9	0.92	0.890	-1.027	0.467
7	1	3	3	3	1	6000	30	15	15	100	1.12	1.32	1.41	1.283	2.043	0.570
8	1	3	3	3	2	6000	30	15	15	125	1.35	1.31	1.32	1.327	2.453	0.567

9	1	3	3	3	3	6000	30	15	15	150	1.35	1.36	1.39	1.367	2.711	0.550
10	2	1	2	3	1	9000	10	10	15	100	0.81	0.82	0.81	0.813	-1.795	0.387
11	2	1	2	3	2	9000	10	10	15	125	0.84	0.86	0.88	0.860	-1.315	0.383
12	2	1	2	3	3	9000	10	10	15	150	0.85	0.92	0.88	0.883	-1.091	0.353
13	2	2	3	1	1	9000	20	15	5	100	0.76	0.77	0.75	0.760	-2.385	0.217
14	2	2	3	1	2	9000	20	15	5	125	0.78	0.73	0.83	0.780	-2.194	0.197
15	2	2	3	1	3	9000	20	15	5	150	0.75	0.87	0.76	0.793	-2.068	0.155
16	2	3	1	2	1	9000	30	5	10	100	0.81	0.85	0.77	0.810	-1.852	0.383
17	2	3	1	2	2	9000	30	5	10	125	0.79	0.96	0.8	0.850	-1.513	0.383
18	2	3	1	2	3	9000	30	5	10	150	0.83	0.92	0.78	0.843	-1.540	0.350
19	3	1	3	2	1	12000	10	15	10	100	1.35	1.29	1.25	1.297	2.244	0.450
20	3	1	3	2	2	12000	10	15	10	125	1.35	1.39	1.35	1.363	2.690	0.430
21	3	1	3	2	3	12000	10	15	10	150	1.01	1.36	1.15	1.173	1.197	0.393
22	3	2	1	3	1	12000	20	5	15	100	1.29	1.2	1.27	1.253	1.949	0.377
23	3	2	1	3	2	12000	20	5	15	125	1.13	1.19	1.21	1.177	1.402	0.347
24	3	2	1	3	3	12000	20	5	15	150	1.27	1.18	1.27	1.240	1.853	0.347
25	3	3	2	1	1	12000	30	10	5	100	0.85	0.87	0.91	0.877	-1.154	0.140
26	3	3	2	1	2	12000	30	10	5	125	0.84	0.97	0.91	0.907	-0.896	0.096
27	3	3	2	1	3	12000	30	10	5	150	0.94	0.91	0.94	0.930	-0.633	0.081

Table 6 ANOVA for MRR of Al/ (5 wt % Al_2O_3+5 wt % ZrO_2)-MMC

Sl.No.	Control factor	Sum of square 'SS'	DOF	Variance	'F' Test	% Contribution
1	A	33.790	2	16.8948	453.0635	33.303
2	B	2.994	2	1.49703	40.14565	2.951
3	C	21.614	2	10.807	289.8081	21.303
4	D	39.624	2	19.812	531.2944	39.054
5	E	0.828	2	0.41408	11.10431	0.816
	Error	2.610	70	0.03729	----	2.573
	Total	101.460	80	----	----	100.000

From Table 6, it is concluded that the DC supply current (parameter, D) is the most significant process parameter with 39.05% contribution. Grinding wheel rotational speed (parameter, A) and DC supply voltage (parameter, C) are significant parameters for material removal rate with 33.3% and 21.3% contribution respectively. Experimental results reveals MRR 0.877 g/min and surface roughness height, R_a 0.14µm at 12000 rpm grinding wheel rotational speed, 10 V DC supply voltage, 5 A DC supply current parameter setting. Whereas experimental result reveals MRR (1.28g/min) at parameters setting 6000 rpm grinding wheel rotational speed, 15 V DC supply voltage, 15 A DC supply current. The corresponding measured surface roughness height, R_a is 0.55µm. Fig. 3 shows interaction graph between grinding wheel rotational speed and DC supply voltage on MRR. From interaction graph Fig.3, it is clear that at parameter 12000 grinding wheel rotational speed, 10 V DC supply voltage and 10 A DC supply current MRR is 1.0 to 1.20 g/min. Fig. 4 and Fig. 5 show the SEM of workpiece inner surface texture before (i.e. after reaming) and after electrochemical grinding respectively. From Fig. 4, it is clear that the generated surface has number of ploughing action and breakages of lines at peaks where as no such grooving or ploughing on the workpiece inner surface are observed after ECG as observed in Fig. 5.

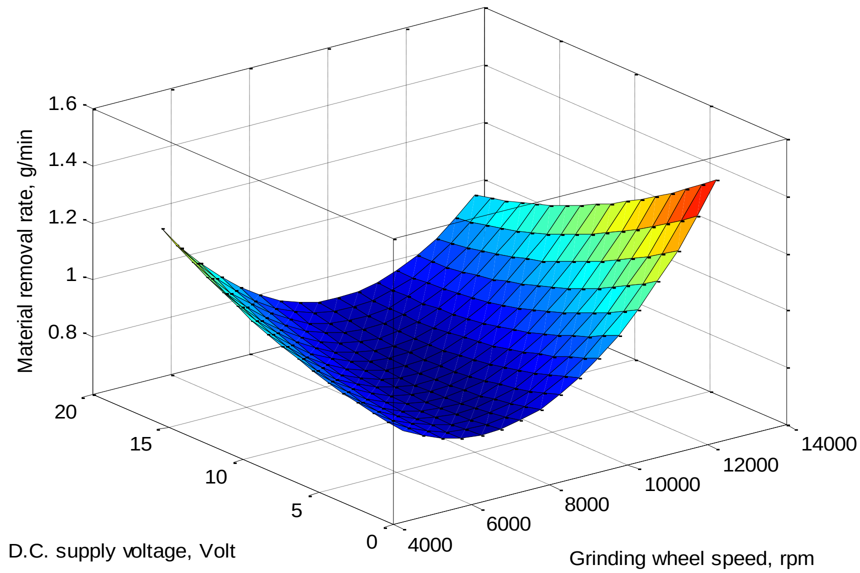

Figure 3 Interaction graph between grinding wheel rotational speed and D.C. supply voltage on MRR

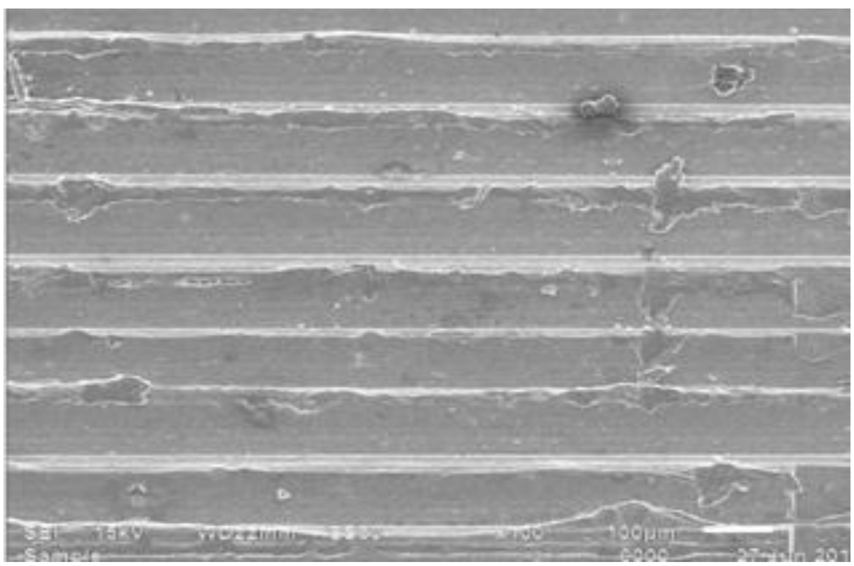

Figure 4 SEM of the inner surface of prepared workpiece before ECG

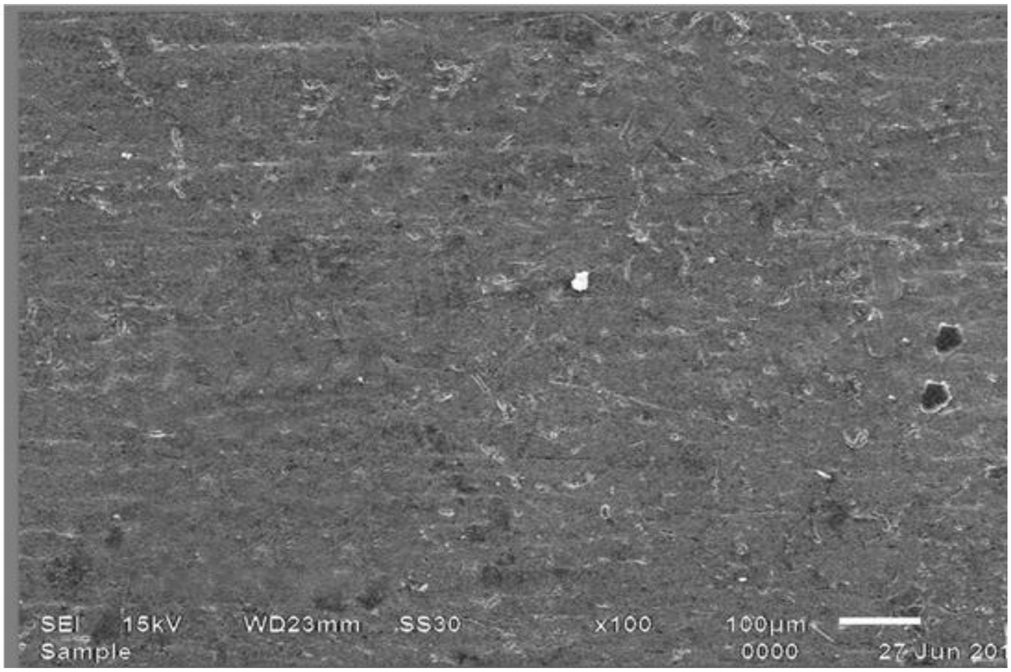

Figure 5 SEM of the inner surface of workpiece after ECG

5. Development of mathematical models.

The mathematical models for material removal rate (g/min) and surface roughness height R_a, (µm) during electrochemical grinding is developed based on the general format of second order equation as given below.

MRR= $a + bx_1 + cx_2 + dx_3 + ex_4 + fx_5 + gx_1x_2 + hx_1x_3 + ix_1x_4 + jx_1x_5 + kx_2x_3 + lx_2x_4 + mx_2x_5 + nx_3x_4 + px_3x_5 + qx_4x_5 + rx_1^2 + sx_2^2 + tx_3^3 + ux_4^2 + vx_5^2$……………… (1).

The mathematical models are developed considering all the parameters considered for experimental investigation such as A: Grinding wheel rotational speed (x_1); B: Electrolyte concentration (x_2); C: DC supply voltage (x_3); D: DC supply current (x_4); E: Workpiece rotational speed (x_5) is

$Y_{MRR} = 0.01\times10^{-4} - 0.04675\times10^{-3}x_1 + 0.0141x_2 + 0.0112\times10^{-5}x_3 - 0.0105\times10^{-6}x_4 + 0.01007x_5 - 0.0856\times10^{-4}x_1x_2 - 0.05939\times10^{-4}x_1x_3 - 0.021693\times10^{-4}x_1x_4 – 0.02296\times10^{-5}x_1x_5 +$

$0.00133x_2x_3 + 0.0525\times10^{-7}x_2x_4 - 0.0106\times10^{-6}x_2x_5 + 0.051\times10^{-7}x_3x_4 + 0.0444\times10^{-3}x_3x_5 + 0.01222\times10^{-2}x_4x_5 + 0.019695\times10^{-6}x_1^2 + 0.00124x_2^2 + 0.09388\times10^{-2}x_3^2 + 0.0255\times10^{-2}x_4^2 - 0.032\times10^{-3}x_5^2$….(2)

$Y_{Ra} = 0.012\times10^{-4} - 0.0298\times10^{-4}x_1 + 0.07901373x_2 + 0.0135\times10^{-3}x_3 - 0.0122680\text{x}10^{-2}x_4 - 0.00508x_5 - 0.05876\times10^{-4}x_1x_2 - 0.02025\times10^{-4}x_1x_3 - 0.05483\times10^{-4}x_1x_4 - 0.0493\times10^{-5}x_1x_5 + 0.0012734x_2x_3 + 0.056\times10^{-6}x_2x_4 - 0.01091\times10^{-4}x_2x_5 + 0.061\times10^{-6}x_3x_4 - 0.01489\times10^{-2}x_3x_5 + 0.03071\times10^{-2}x_4x_5 + 0.01348\times10^{-6}x_1^2 + 0.0484\times10^{-2}x_2^2 - 0.08782\times10^{-2}x_3^2 + 0.030\times10^{-7}x_4^2 + 0.03964\times10^{-3}x_{5.}^{2}$……….(3)

These developed mathematical models can be utilized to set the parameters for machining of hybrid Al/ (Al_2O_3+ZrO_2) MMC effectively by developed electrochemical grinding process.

6. ADDIRIVITY TEST.

Table 7 & 8 represents the parametric condition utilized for additivity test to validate the developed mathematical models for MRR and Ra respectively during electrochemical grinding of hybrid Al/ (5 wt % Al_2O_3+5 wt % ZrO_2)-MMC on developed ECG setup. These tables also represent the % of error of the calculated values utilizing developed models with respect to the experimental results.

Table 7 Additivity test condition, results and percentage of error, MRR

Sl.No.	ECG Parameters					Material Removal Rate (MRR, g/min)		
	x_1	x_2	x_3	x_4	x_5	Experimental value	Developed Equation value	% of error
1	6000	10	5	5	150	0.757	0.74	2.36
2	9000	30	5	10	100	0.81	0.79	1.69
3	12000	20	5	15	125	1.17	1.09	6.91

Table 8 Additivity test condition, results and percentage of error, Ra

Sl.No.	ECG Parameters	Surface roughness height R_a, (μm)

	x_1	x_2	x_3	x_4	x_5	Experimental value	Developed Equation value	% of error
1	6000	10	5	5	150	0.32	0.313	2.07
2	9000	30	5	10	100	0.323	0.307	3.88
3	12000	20	5	15	125	0.36	0.33	8.07

Parameter, x_1: Grinding wheel rotational speed, Parameter, x_2: Electrolyte concentration, Parameter, x_3: DC Voltage, Parameter, x4: DC current and Parameter, x5: Workpiece rotational speed.

6. Conclusion

Based on the experimental results obtained during electrochemical grinding of hybrid Al/(Al_2O_3+ZrO_2)-MMC on developed electrochemical grinding setup and thereafter discussion, the calculated S/N ratio (dB), the analysis of ANOVA and 'F' test values the following conclusions are drawn as listed below.

(i) For material removal rate, the parameter DC supply current (parameter, D) is identified as the most significant process parameter.

(ii) Grinding wheel rotational speed (parameter, A) and DC supply voltage (parameter, C) both are significant parameters for the material removal rate.

(ii) The developed mathematical models for performance characteristics e.g. material removal rate and surface roughness height, R_a of electrochemical grinding process is successfully proposed for proper selection of machining parameters and evaluation of MRR and R_a under various parametric combinations during finishing of hybrid Al/(5wt.% Al_2O_3+5wt.% ZrO_2)- MMC by electrochemical grinding process.

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