International Journal of Mechanical and Materials Engineering (IJMME), Vol. 7 (2012), No. 2, 136-145.

AN EXPERIMENTAL INVESTIGATION AND PARAMETRIC OPTIMIZATION FOR WIRE EDM OF Al-5%ZrO_2 PARTICULATE REINFORCED METAL MATRIX COMPOSITE

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Received 18 February 2012, Accepted 06 July 2012

ABSTRACT
This paper presents an experimental investigation for the wire electrical discharge machining (Wire EDM) of newly developed Al-5%ZrO_2 particulate reinforced metal matrix composite (PRMMC). Experiments have been carried out in order to investigate the effects of input parameters such as dielectric conductivity, pulse width, time between pulses, maximum feed rate, servo control mean reference voltage, short pulse time, wire feed rate, wire mechanical tension and dielectric injection pressure on the performance measures such as spark gap and material removal rate. L_{36} mixed orthogonal array ($2^1 \times 3^8$) has been selected to plan, conduct and analyse the experiments. The significant parameters have also been identified and their effect on performance measures has been studied. The results obtained have been validated by conducting the confirmation experiments. Comparison of results using different wire electrode has also been presented in this paper. The newly developed metal matrix composite can be used in aerospace industries

Keywords: Metal Matrix Composite, Spark gap, Material removal rate, Taguchi method, Wire-EDM.

Nomenclature

Symbol	Abbreviation
A, DC	Dielectric conductivity
B, PW	Pulse Width
C, TBP	Time between pulses
D, MFR	Maximum feed rate
E, SCMRV	Servo control mean reference voltage
F, SPT	Short pulse time
G, WFR	Wire feed rate
H, WMT	Wire mechanical tension
I, IP	Injection pressure
SG	Spark gap
MRR	Material removal rate
Wire EDM	Wire electrical discharge machine
ANOVA	Analysis of variance
Vc	Mean cutting speed
t	Thickness of work piece
b	Width of cut
PRMMC	Particulate reinforced metal matrix composite

1. INTRODUCTION
A composite can simply be defined as a combination of two or more dissimilar materials having a distinct interface between them such that the properties of the resulting material are superior to the individual constituting components. Metal Matrix Composites (MMC) have been so intensely researched over the past years that many new high strength to weight ratio materials have been prepared. In these MMCs, the good ductility of the metallic alloys as matrix material is retained while the modulus and strength of the composites are increased as a result of the reinforcement phases (Murmu, 2011). Most of these materials have been developed for the aerospace industries, storage battery plates, satellite structures, antenna structure and high temperature structures. Zamri et al. (2011) investigated the potential of palm oil clinker as reinforcement in aluminium matrix composites for tribological applications. In particulate reinforced composites, discrete, uniformly dispersed particles of a hard brittle material are surrounded by a softer more ductile matrix. Small particles of uniform size with proper orientation exhibit more strengthening effects. Many researchers have tried modern machining methods to machine the MMC and out of which wire electrical discharge machining (WEDM) emerged as an effective machining method. WEDM is a machining process controlled by a large number of process parameters. The setting of the various process parameters required in the WEDM process, play a crucial role in producing an optimal machining performance. Parameters setting for advanced materials have to be optimized experimentally because parameters setting given by the manufacturers are only valid for the common steel grades. Hewidy et al. (2005) developed the model for the WEDM parameters for Inconel 601 using response surface methodology for the performance characteristics such as Metal Removal rate, Wear Ratio, Surface Roughness using brass wire as wire electrode. Chiang and Chang (2006) investigated an effective approach for the optimization of the WEDM process of Al_2O_3 particle reinforced in Al 6061 alloy with multiple performance characteristics using pure copper as wire electrode. Surface removal rate and Surface roughness were investigated using grey relational analysis. Ramakrishnan and Karunamoorthy (2006) used zinc coated brass wire for WEDM of heat treated tool steel work piece and obtained multi response optimization using Taguchi's robust design approach. Manna and Bhattacharyya (2006) used Taguchi L_{18} orthogonal array and Gauss elimination method for the parametric optimization of aluminium reinforced silicon

carbide metal matrix composite. Effect of machining parameters on machining performance criteria such as metal removal rate, surface roughness, gap current, and spark gap were studied and used brass wire in WEDM. Saha et al. (2008) analyzed the wire electrical discharge machining of tungsten carbide cobalt composite using brass wire in WEDM and optimization method such as back propagation neural network (4-11-2) and multivariable regression model were used. Patil and Brahmankar (2010a) experimentally analyzed the effect of electrical as well as non-electrical machining parameters on performance characteristics during WEDM of metal matrix composite (Al/ Al_2O_{3p}). Reinforcement percentage, current and on-time was found to have significant effect on cutting rate, surface finish and kerf width separately. Garg et al. (2010) reviewed the research work in sinking EDM and WEDM on metal matrix composite materials. Most of the published work belongs to SiC reinforced metal matrix composites. Not so much work has been reported on Al_2O_3 reinforced and other MMC types. Patil and Brahmankar (2010b) analyzed the material removal rate in wire electro-discharge machining of silicon carbide particulate reinforced aluminium matrix composites and model was developed by using dimension analysis and non-linear estimation technique such as quasi-newton and simplex. In addition, an empirical model, based on response surface was also developed. Jangra et al. (2011) studied a digraph and matrix method to evaluate the machinability of tungsten carbide composite with WEDM. A methodology based on digraph and matrix method was proposed to evaluate the machinability of tungsten carbide in terms of material removal rate. Shah et al. (2011) investigated the effect of all critical WEDM parameters for the machining of tungsten carbide cobalt composites using Taguchi L_{27} orthogonal array. It was found that the material thickness has little effect on the material removal rate and kerf but was significant factor in terms of surface roughness. Ali et al. (2011) investigated the influence of silicon carbide powder concentration in dielectric fluid and electrical discharge energy in micro electro discharge machining of titanium alloys using design of expert software. Ndaliman et al. (2011) modified the surface of titanium through electric discharge machining. Taguchi L_{18} orthogonal array was used by Kuriakose and Shunmugam (2005) for the WEDM of Titanium alloy (Ti-6Al-4V) and considered cutting velocity and surface finish as performance measures. Taguchi L_{16} orthogonal array was used by Ramarishnan and Karunamoorthy (2006) for the WEDM of heat treated tool steel and considered material removal rate, surface roughness and wire wear ratio as performance measures. Taguchi L_{27} orthogonal array was also used by Mahapatra and Patnaik (2006) for the WEDM of D2 tool steel and considered material removal rate, surface finish and kerf as performance measures. Taguchi L_{32} orthogonal array was used by Parashar et al. (2009) for the WEDM of SS 304 L and considered surface finish as performance measure.

Literature survey on the WEDM of metal matrix composites reveals that no work has been reported on Al-5%ZrO_2-PRMMC so far. In the present work Al-5%ZrO_2-PRMMC has been prepared using Stir Casting technique and 5 % of ZrO_2 particulates by weight have been added to prepare Al-5%ZrO_2-PRMMC. The stir casting method is widely used among the different processing techniques available (Anilkumar et al., 2011). The optimal settings of parameters have been determined through experiments planned, conducted and analyzed using Taguchi method. L_{36} mixed orthogonal array ($2^1 \times 3^8$) was selected to design the experiments as no author has used this array to analyze the WEDM machining process so far. Literature survey also reveals that diffused wire was not used for the WEDM of composites so in present work diffused wire has been used as wire electrode in experimentation and the result obtained were compared with the results obtained by using brass wire electrode.

2. FABRICATION & MECHANICAL PROPERTIES OF Al-5%ZrO_2-PRMMC

Zirconia (ZrO_2) reinforced particles of 20 µm average particle size (APS) have been used for casting of Al-5%ZrO_2- Particulate Reinforced Metal Matrix Composite (PRMMC) by liquid stir casting technique.

Table 1 Chemical composition of 2024 Al alloy matrix

Al-Matrix	%Cu	%Si	%Mg	%Zn	%Mn	%Fe	%Pb	Al
2024 Al	3.13	0.52	0.84	0.15	0.48	0.02	0.01	Bal

Table 1 and Table 2 represent the chemical composition of Al-matrix and mechanical properties of ZrO_2 used for manufacturing of PRMMC. Number of samples with 5 wt% ZrO_2 reinforced particles – aluminium metal matrix composite has been fabricated.

Figure 1 Specimen placed in UTM

These fabricated samples have been utilized for testing of mechanical properties. Tensile test has been performed using Universal Testing Machine (H 25 K-S make). Figure 1 shows the fabricated specimen under UTS in ultimate tensile machine (UTM). The average test results have been reported in the paper and represented in tabular form (Table 3).

Table 2 Properties of Zirconia (ZrO_2) reinforced particulates

Reinfor-cement	Density	Hardness	Modulus of Elasticity	Fracture Toughness
ZrO_2	4.15 gcm^{-3}	1600 (HV)	380 (GPa)	12 (MPa $m^{-1/2}$)

Brinell hardness tester of capacity 35 KN has been utilized to measure the hardness of the fabricated composite samples shown in Figure 2.

Figure 2 Specimen placed in Brinell Hardness Tester.

From Table 3 it is clear that strength to weight ratio of the fabricated PRMMC is higher than the monolithic steel. Hence it is a very good material recommended for applications where high strength to weight ratio is important for fuel economy e.g. aerospace, automotive and defence applications related components.

Table 3 Properties of 2024 Al alloy matrix and Al-5%ZrO_2 PRMMC

Material	Density gcm^{-3}	Hardness (BHN)	Yield strength (MPa)
2024 Al alloy matrix	2.71	85	67
Al-5% ZrO_2-PRMMC APS: 20μm	2.77	91.2	75.7

3. EXPERIMENTAL SET-UP

Robofil-290 CNC wire EDM shown in Figure 3 with diffused coated (half hard) wire having 250 μm diameter has been used for experimentation.

Performance of WEDM has been evaluated on the basis of material removal rate (MRR) and spark gap (SG). Heat treated stir cast Al/5%wt. ZrO_2-PRMMC is used for machining by WEDM. The mean cutting speed has been calculated by the following relation:

Mean cutting speed = length of travel/ machining time. Machining time is obtained from the computer, which is attached to the machine tool.

The MRR is calculated utilizing the relation:
MRR = Mean cutting speed × thickness of the material in mm × width of cut (mm)

$$= V_c \times t \times b \, mm^3/\min \qquad (1)$$

Figure 3 Wire EDM Robofil-290
(Courtesy by Charmilles Technologies)

Width of cut is measured using profile projector PV-600A (make) having least count 0.001 mm. Straight cut of 8mm has been made by WEDM in the work piece. After the WEDM, width of cut has been measured using profile projector at three different locations. Spark gap has been calculated using equation 2.

Width of cut = Diameter of wire + 2× spark gap (2)

Figure 4 WEDM of workpiece

Average of three values of spark gap has been shown in Appendix (Table A2). Figure 4 shows the photograph of the Wire EDM of the workpiece. This paper makes use of Taguchi's method for designing the experiments. L_{36} mixed orthogonal array ($2^1 \times 3^8$) has been selected for the present investigation. Using this design, process parameter dielectric conductivity has two levels where as all other 8 parameters have three level. The process parameters and their levels selected for final experimentation has been depicted in Table 4.

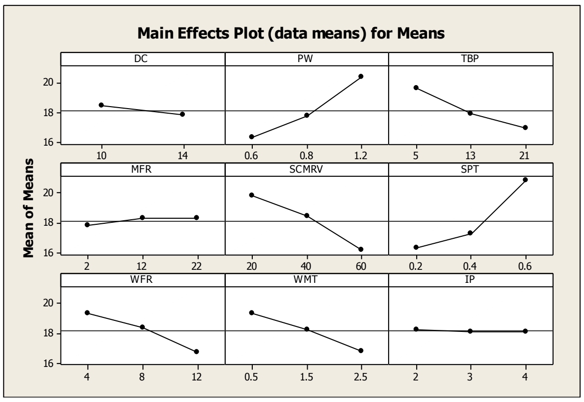
Table 4 Process parameters and their values at different levels

Symbols	Parameters	Units	Level 1	Level 2	Level 3
DC	Dielectric conductivity	mho	10	14	
PW	Pulse width	μs	0.6	0.8	1.2
TBP	Time between pulses	μs	5	13	21
MFR	Maximum feed rate	micron/min.	2 units*	12 units**	22 Units***
SCMRV	Servo Control Mean Reference Voltage	volts	20	40	60
SPT	Short pulse time	μs	0.2	0.4	0.6
WFR	Wire Feed Rate	m/min	4	8	12
WMT	Wire Mechanical Tension	Deca Newton	0.5	1.5	2.5
IP	Injection Pressure	bars	2	3	4
Constant Parameters					
Workpiece Height	10.1 mm				
Machining Voltage	80 volts				
Ignition Pulse Current	8 units (1/2 A)				

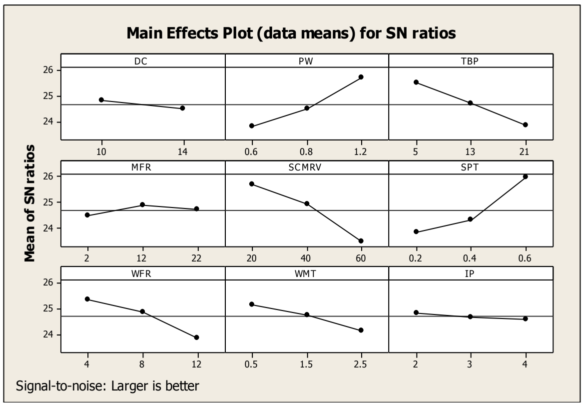
*2units=14.64 micron/min.; **12 units=87.84 micron/min.; ***22 units=161.04 micron/min.

4. RESULTS AND DISCUSSIONS

Process performance characteristics such as material removal rate (MRR) and spark gap (SG) have been used to analyse the effect of process parameters. Parameter setting as per L_{36} mixed orthogonal array has been shown in appendix (Table A1). Each trial has replicated for three times; hence 108 trial runs were executed in completely randomized fashion to reduce the effect of experimental noise to the maximum possible extent. In the Taguchi method, a loss function has been defined to gauge the deviation between the experimental and desired value of a performance characteristics. The loss function is further transformed into a signal-to-noise (S/N) ratio. Three categories of performance characteristics are usually used in the analysis of the S/N ratio, i.e. lower-the-better, higher-the-better and nominal-the-best. Here the desirable objective is larger value of MRR and smaller value of SG. Appendix (Table A2) represents the experimental results and S/N ratio for MRR and SG. The peak value of these plots corresponds to the optimum conditions.



(a) Experimental obtained data graph

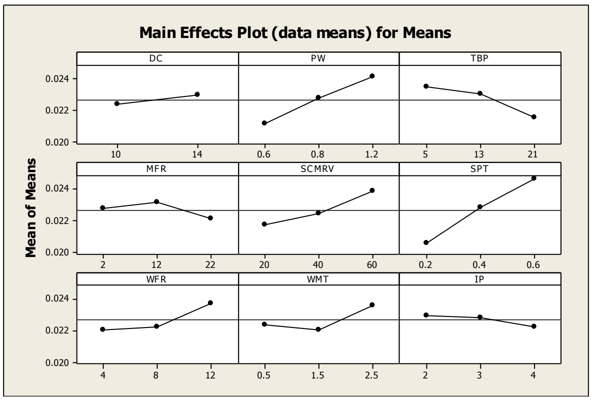


(b) S/N ratio graph

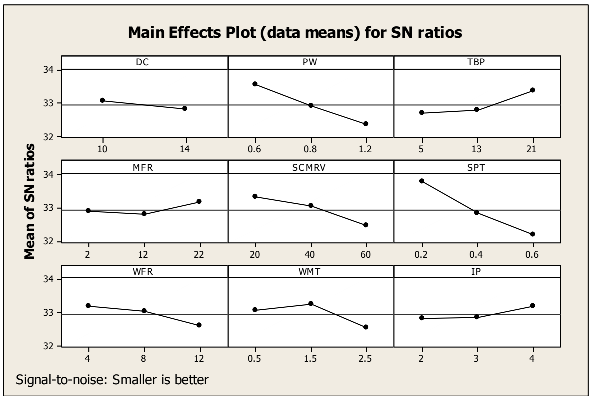
Figure 5 Effect of process parameters on Material Removal Rate

The main effect has been studied by the level average response analysis of experimentally obtained data and S/N ratio and the analysis has been done by averaging the experimentally obtained data and S/N ratio at each level of each parameter and plotting the value in graphical form. The main effect plots for experimental obtained data and S/N ratio for material removal rate have been shown in Figure 5. The main effect plots for experimental obtained data and S/N ratio for spark gap have been shown in Figure 6.

Figure 5(a) and 5(b) show that the material removal rate increases with the increase in pulse width and short pulse time. The MRR decreases with increase in time between pulses, servo control mean reference voltage, wire feed rate and wire mechanical tension. This is because the discharge energy increases with the pulse width and short pulse time leading to more material removal rate. As the time between pulses increases, the number of discharges within a given period becomes less which leads to a lower material removal rate.



(a) Experimental obtained data graph



(b) S/N ratio graph

Figure 6 Effect of process parameters on spark gap – (a) experimental obtained data and (b) S/N ratio

With increase in servo control mean reference voltage, the average discharge gap gets widened resulting into a lower material removal rate. With increases of wire feed rate, the discharge energy decreases and causes of low material removal rate. Dielectric conductivity, maximum feed rate and injection pressure has no significant effect on MRR (Table 5). The average values of spark gap for each parameter at levels 1, 2 and 3 for experimental obtained data and S/N ratio are plotted in Figure 6(a) and 6(b) respectively. Figure 6(a) and 6(b) show that the spark gap increases with increase in pulse width, servo control mean reference voltage and short pulse time. The spark gap decreases with increase in time between pulses. This is because the discharge energy increases with the pulse width and short pulse time leading to a more spark gap. As the time between pulses increases, the number of discharges within a given period becomes less which leads to a lower spark gap. With increase in servo control mean reference voltage, the average discharge gap gets widened resulting into a higher spark gap. Dielectric conductivity, maximum feed rate and injection pressure have no significant effect on spark gap (Table 6).

4.1 Selection of Optimum Levels.

An ANOVA technique was used to identify the significant parameters and to quantify their effects on the performance characteristics. The ANOVA results for MRR and SG are given in Table 5 and Table 6 respectively The response table (Table 7) show the average of each response characteristic (experimentally obtained data) for each level of each factor for material removal rate. The tables include ranks based on delta statistics, which compare the relative magnitude of effects. The delta statistic is the highest minus the lowest average for each factor. Ranks based on delta values have been identified using Minitab, version 14.0. The ranks indicate the relative importance of each factor to the response.

Table 5 Pooled analysis of variance (ANOVA) results for material removal rate (experimental obtained data)

Source	DF	Seq. SS	Adj.MS	F	P
DC	Pooled				
PW	2	305.85	152.93	16.96	0.000
TBP	2	135.46	67.73	7.51	0.001
MFR	Pooled				
SCMRV	2	243.90	121.95	13.52	0.000
SPT	2	409.20	204.60	22.69	0.000
WFR	2	124.26	62.13	6.89	0.002
WMT	2	118.17	59.09	6.55	0.002
IP	Pooled				
Error	95	856.69	9.02		
Total	107	2193.53			

DF - degrees of freedom, SS - sum of squares, MS - mean squares(Variance), F-ratio of variance of a source to variance of error, $P < 0.05$ - determines significance of a factor at 95% confidence level

Table 6 Pooled analysis of variance (ANOVA) results for spark gap (experimental obtained data)

Source	DF	Seq. SS	Adj. MS	F	P
DC	pooled				
PW	2	0.000162	0.000081	14.15	0.000
TBP	2	0.000071	0.000035	6.26	0.003
MFR	Pooled				
SCMRV	2	0.000088	0.000044	7.69	0.001
SPT	2	0.000293	0.000146	25.58	0.000
WFR	2	0.000059	0.000029	5.21	0.007
WMT	2	0.000049	0.000024	4.32	0.016
IP	Pooled				
Error	95	0.000544	0.0000057		
Total	107	0.001269			

From Table 7, the ranks and the delta values show that short pulse time has the greatest effect on material removal rate followed by pulse width, servo control mean reference voltage, time between pluses, wire feed rate, wire mechanical tension, dielectric conductivity, maximum feed rate and injection pressure. As material removal rate has “higher the better” type quality characteristic, so from Table 7, the optimal parametric combination for higher MRR is $B_3C_1E_1F_3G_1H_1$.The response table (Table 8) shows the average of each response characteristic for each level of each factor for spark gap. As spark gap has "lower the better" type quality characteristic, so from Table 8 the optimal parametric confirmation for minimum SG is $B_1C_3E_1F_1G_1H_2$.

4.2 Estimation of Optimum Response Characteristics

In this section, the optimal values of the response characteristics e.g. material removal rate and spark gap along with their respective confidence intervals have been predicted. Considering the effect of the significant parameters, the optimal value of each response characteristic has been predicted. The estimated mean of the material removal rate has been determined utilizing the relation described by Kumar (1993) and Roy (1990) and is shown in Equation 3.

$$\mu_{MRR} = \bar{B}_3 + \bar{C}_1 + \bar{E}_1 + \bar{F}_3 + \bar{G}_1 + \bar{H}_1 - 5\bar{T} \tag{3}$$

$$\bar{T} = overall\ mean\ of\ Material\ removal\ rate$$
$$= \left[\sum MRR_1 + \sum MRR_2 + \sum MRR_3\right]/108$$
$$= 18.14638\ mm^3/\min$$

Where, MRR_1, MRR_2, and MRR_3 values are taken from the Appendix (Table A2) and the optimum values of the significant parameter i.e. $\bar{B}_3\bar{C}_1\bar{E}_1\bar{F}_3\bar{G}_1\bar{H}_1$ have been taken from the Table 7.

μ_{MRR} =20.37 + 19.62 + 19.83 + 20.85 + 19.31 + 19.37 – 5 (18.14638) = 28.6181 mm^3/min

The 95 % confidence intervals of confirmation experiments (CI_{CE}) and population (CI_{POP}) have been calculated by using the eqns 4 and 5.

$$CI_{CE} = \sqrt{f_\alpha(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \tag{4}$$

$$CI_{POP} = \sqrt{\frac{f_\alpha(1, f_e)V_e}{n_{eff}}} \tag{5}$$

Where, $F\alpha$ (1, f_e) = The F ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom f_e.

$$n_{eff} = \frac{N}{1 + \left[\begin{matrix} DOF\ associated\ in\ the \\ estimate\ of\ mean\ response \end{matrix}\right]} = 8.30769$$

N = Total number of experiments =108; R = Sample size for confirmation experiments = 3; V_e = Error variance = 9.02 (Table 5); f_e = error DOF = 95 (Table 5); $F_{0.05}$ (1, 95) = 3.9412 (Tabulated F value); So CI_{CE} = ± 4.0160, and CI_{POP} = ± 2.068

Therefore, the predicted confidence interval for confirmation experiments is:

Mean μ_{MRR} - CI_{CE} < μ_{MRR} < Mean μ_{MRR} + CI_{CE}; 24.6021 < μ_{MRR} < 32.6341

The 95% confidence interval of the population is:

Mean μ_{MRR} - CI_{POP} < μ_{MRR} < Mean μ_{MRR} + CI_{POP}; 26.5501< μ_{MRR} < 30.6861

Table 7 Response Table for Experimentally obtained data for MRR

Level	DC	PW	TBP	MFR	SCMRV	SPT	WFR	WMT	IP
1	18.45	16.31	19.62	17.85	19.83	16.33	19.31	19.37	18.23
2	17.84	17.76	17.92	18.29	18.43	17.26	18.40	18.25	18.13
3		20.37	16.90	18.29	16.18	20.85	16.72	16.82	18.08
Delta	0.62	4.07	2.71	0.44	3.65	4.52	2.59	2.56	0.15
Rank	7	2	4	8	3	1	5	6	9

Table 8 Response Table for Experimentally obtained data for SG

Level	DC	PW	TBP	MFR	SCMRV	SPT	WFR	WMT	IP
1	0.02239	0.02114	0.02347	0.02275	0.02172	0.02058	0.02206	0.02239	0.02297
2	0.02296	0.02275	0.02300	0.02317	0.02242	0.02283	0.02225	0.02203	0.02281
3		0.02414	0.02156	0.02211	0.02389	0.02461	0.02372	0.02361	0.02225
Delta	0.00057	0.00300	0.00192	0.00106	0.00217	0.00403	0.00167	0.00158	0.00072
Rank	9	2	4	7	3	1	5	6	8

The estimated mean of the Spark Gap can be determined by using the Equation 6.

$$\mu_{SG} = \bar{B}_1 + \bar{C}_3 + \bar{E}_1 + \bar{F}_1 + \bar{G}_1 + \bar{H}_2 - 5\bar{T} \quad (6)$$

$$\bar{T}_G = overall\ mean\ of\ Spark\ gap$$
$$= \left[\sum SG_1 + \sum SG_2 + \sum SG_3\right]/108 = 0.02267 mm$$

Where, SG_1, SG_2, and SG_3 values are taken from the Appendix (Table A2) and the optimum values of the significant parameters i.e. $\bar{B}_1 \bar{C}_3 \bar{E}_1 \bar{F}_1 \bar{G}_1 \bar{H}_2$ are taken from the Table 8.

μ_{SG} = 0.02114 + 0.02156 + 0.02172 + 0.02058 + 0.02206 + 0.02203– 5(0.02267) = 0.015715 mm
η_{eff} = 6.307; N = 108; R = 3; V_e = 0.0000057;
f_e = DOF = 95 (From Table 6); $F_{0.05}$ (1, 95) = 3.9412;
So, CI_{CE} = ± 0.003192, and CI_{POP} = ± 0.001644.

Therefore, the predicted confidence interval for confirmation experiments is:
Mean μ_{SG} - CI_{CE} < μ_{SG} < Mean μ_{SG} + CI_{CE};
0.0125 < μ_{SG} < 0.0189

The 95% confidence interval of the population is:
Mean μ_{SG} - CI_{POP} < μ_{SG} < Mean μ_{SG} + CI_{POP};
0.0140 < μ_{SG} < 0.01735

5. CONFIRMATION EXPERIMENT

In order to validate the results obtained, three confirmation experiments have been conducted for each of the response characteristics (MRR and SG) at optimal levels of the process variables. The average values of the characteristics have been obtained and compared with the predicted values. The results have been represented in Table 9.

The values of MRR and SG obtained through confirmation experiments are within the 95% of CI_{CE} of respective response characteristic. The maximum material removal rate is 27.556 by using diffused wire electrode whereas maximum material removal rate by using brass wire electrode is equal to 25.347. The minimum value of spark gap is 0.014 by using diffused wire electrode whereas minimum spark gap by using brass wire electrode is equal to 0.010.

6. CONCLUSIONS

Based on experimental investigation on fabrication of Al-5%ZrO_2 PRMMC and thereafter machining of fabricated MMC by WEDM, the following points are concluded and listed below:

- The developed Al-5%ZrO_2 PRMMC has low density (2.77 gcm^{-3}), high yield strength (75.7 MPa) and high hardness (91.2 BHN) which proves that the composite has high strength to weight ratio. Hence Al-5%ZrO_2 PRMMC may be utilized for application in the aerospace and automotive industry.
- The newly developed Al-5%ZrO_2 PRMMC can be machined effectively by WEDM as high material removal rate (27.556 mm^3/min) and low spark gap (0.014 mm) is identified during machining.
- The significant parameters for material removal rate and spark gap are pulse width, time between pulses, servo control mean reference voltage, short pulse time, wire feed rate and wire mechanical tension.
- Optimal parametric combination for material removal rate is $B_3C_1E_1F_3G_1H_1$ and for spark gap is $B_1C_3E_1F_1G_1H_2$. The optimal machining conditions for maximum material removal rate are pulse width of 1.2 µs, time between pulses of 5 µs, servo control mean reference voltage of 20 volts, short pulse time of 0.6 µs, wire feed rate of 4 m/min and wire mechanical tension of 0.5 daN and the optimal machining conditions for minimum spark gap are pulse width of 0.6 µs, time between pulses of 21 µs, servo control mean reference voltage of 20 volts, short pulse time of 0.2 µs, wire feed rate of 4 m/min and wire mechanical tension of 1.5 daN.
- The predicted optimal range for material removal rate at 95% confidence level is CI_{CE} : 24.6021 < μ_{MRR} < 32.6341; CI_{POP} : 26.5501< μ_{MRR} < 30.6861 and for spark gap is CI_{CE} : 0.0125 < μ_{SG} < 0.0189; CI_{POP} : 0.0140 < μ_{SG} < 0.01735 respectively.
- The optimum value of maximum material removal rate is more while using diffused wire as compared to brass wire electrode whereas the optimum value of minimum spark gap is less while using brass wire electrode as compared to diffused wire electrode.

Table 9 Predicted optimal values, confidence intervals, results of confirmation experiments and percentage change.

Type of wire electrode	Response	Optimal set of parameters	Predicted optimal value	Predicted confidence interval at 95% confidence level	Parameters selected for trials	Actual value (avg. of three exps.)	% change
Diffused	MRR	$B_3C_1E_1F_3G_1H_1$	26.373	CI_{CE} : 24.6021 < μ_{MRR} < 32.6341 CI_{POP} : 26.5501< μ_{MRR} < 30.6861	$A_1B_3C_1D_2E_1$ $F_3G_1H_1$ I_2	27.556	4.48
	SG	$B_1C_3E_1F_1G_1$ H_2	0.01515	CI_{CE} : 0.0125 < μ_{SG} < 0.0189 CI_{POP} : 0.0140 < μ_{SG} < 0.01735	$A_1B_1C_3D_2E_1$ F_1G_1 H_2I_2	0.014	7.59
Brass	MRR	$B_3C_1E_1F_3G_1H_1$	27.079	CI_{CE} : 24.4774 < μ_{MRR}< 32.4826 CI_{POP} : 26.419 < μ_{MRR} < 30.541	$A_1B_3C_1D_2E_1$ $F_3G_1H_1$ I_2	25.347	6.39
	SG	$B_1C_3E_1F_1G_2H_1$	0.01106	CI_{CE} : 0.01082 < μ_{SG} < 0.01853 CI_{POP} : 0.01269 < μ_{SG} < 0.01666	$A_1B_1C_3D_2E_1$ F_1G_2 H_1I_2	0.010	9.58

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Appendix

Table A1 Experimental control log as per L_{36} mixed orthogonal array ($2^1 \times 3^8$)

Exp. No.	DC	PW	TBP	MFR	SCMRV	SPT	WFR	WMT	IP
1	10	0.6	5	2	20	0.2	4	0.5	2
2	10	0.8	13	12	40	0.4	8	1.5	3
3	10	1.2	21	22	60	0.6	12	2.5	4
4	10	0.6	5	2	20	0.4	8	1.5	3
5	10	0.8	13	12	40	0.6	12	2.5	4
6	10	1.2	21	22	60	0.2	4	0.5	2
7	10	0.6	5	12	60	0.2	8	2.5	4
8	10	0.8	13	22	20	0.4	12	0.5	2
9	10	1.2	21	2	40	0.6	4	1.5	3
10	10	0.6	5	22	40	0.2	12	1.5	4
11	10	0.8	13	2	60	0.4	4	2.5	2
12	10	1.2	21	12	20	0.6	8	0.5	3
13	10	0.6	13	22	20	0.6	8	0.5	4
14	10	0.8	21	2	40	0.2	12	1.5	2
15	10	1.2	5	12	60	0.4	4	2.5	3
16	10	0.6	13	22	40	0.2	4	2.5	3
17	10	0.8	21	2	60	0.4	8	0.5	4
18	10	1.2	5	12	20	0.6	12	1.5	2
19	14	0.6	13	2	60	0.6	12	0.5	3
20	14	0.8	21	12	20	0.2	4	1.5	4
21	14	1.2	5	22	40	0.4	8	2.5	2
22	14	0.6	13	12	60	0.6	4	1.5	2
23	14	0.8	21	22	20	0.2	8	2.5	3
24	14	1.2	5	2	40	0.4	12	0.5	4
25	14	0.6	21	12	20	0.4	12	2.5	2
26	14	0.8	5	22	40	0.6	4	0.5	3
27	14	1.2	13	2	60	0.2	8	1.5	4
28	14	0.6	21	12	40	0.4	4	0.5	4
29	14	0.8	5	22	60	0.6	8	1.5	2
30	14	1.2	13	2	20	0.2	12	2.5	3
31	14	0.6	21	22	60	0.4	12	1.5	3
32	14	0.8	5	2	20	0.6	4	2.5	4
33	14	1.2	13	12	40	0.2	8	0.5	2
34	14	0.6	21	2	40	0.6	8	2.5	2
35	14	0.8	5	12	60	0.2	12	0.5	3
36	14	1.2	13	22	20	0.4	4	1.5	4

Table A2 Experimental results for Material Removal Rate (MRR) and Spark Gap (SG)

Trial No.	MRR (mm^3/min)			Average MRR (mm^3/min)	S/N ratio (dB) for MRR	SG (mm)			Average SG (mm)	S/N ratio (dB) for SG
	MRR_1	MRR_2	MRR_3			SG_1	SG_2	SG_3		
1	21.29	22.63	19.1	21.0062	26.3823	0.017	0.019	0.02	0.0187	34.5593
2	17.89	19.72	15.47	17.6967	24.8279	0.026	0.021	0.022	0.023	32.7273
3	16.47	16.22	12.32	15.0037	23.2863	0.024	0.027	0.03	0.027	31.3371
4	20.31	20.26	19.92	20.1651	26.0910	0.02	0.02	0.024	0.0213	33.385
5	17.63	20.51	16.85	18.3262	25.1710	0.03	0.026	0.026	0.0273	31.2455
6	15.85	15.12	13.75	14.9065	23.4219	0.027	0.027	0.029	0.0277	31.1558
7	13.91	14.5	11.36	13.2559	22.2970	0.024	0.027	0.026	0.0257	31.8024
8	21.65	19.65	17.04	19.4467	25.6505	0.022	0.024	0.023	0.023	32.76
9	22.34	24.67	24.94	23.9832	27.5657	0.024	0.02	0.025	0.023	32.7273
10	19.09	13.94	14.7	15.9106	23.7967	0.022	0.021	0.023	0.022	33.1456
11	16.64	13.15	13.16	14.3191	22.9631	0.024	0.022	0.022	0.0227	32.8847
12	18.71	23.8	24.74	22.4156	26.8083	0.024	0.02	0.024	0.0227	32.8623
13	21.44	17.83	22.57	20.6106	26.1461	0.02	0.019	0.018	0.019	34.4169
14	13.93	12.63	11.02	12.5284	21.8373	0.021	0.02	0.02	0.0203	33.8335

15	20.33	17.67	19.53	19.1782	25.6106	0.027	0.024	0.023	0.0247	32.1372
16	21.76	18.84	16.7	19.1014	25.4702	0.026	0.024	0.022	0.024	32.3757
17	24.63	11.86	13.83	16.7747	23.3161	0.023	0.021	0.02	0.0213	33.404
18	27.45	20.4	21.41	23.0857	27.0538	0.029	0.023	0.022	0.0247	32.0901
19	17.6	16.35	11.34	15.0972	23.0843	0.023	0.024	0.025	0.024	32.3908
20	17.32	17.44	20.7	18.4873	25.2510	0.021	0.016	0.015	0.0173	35.1239
21	16.08	18.91	20.39	18.4584	25.1951	0.027	0.026	0.023	0.0253	31.9066
22	17.44	14.23	18.78	16.8144	24.3316	0.02	0.021	0.02	0.0203	33.8335
23	16.33	15.58	18.68	16.8673	24.4651	0.016	0.023	0.024	0.021	33.4326
24	18.6	23.4	20.84	20.9446	26.3072	0.025	0.029	0.026	0.0267	31.463
25	16.49	13.25	16.1	15.2815	23.5559	0.021	0.023	0.022	0.022	33.1456
26	21.9	22.57	27.12	23.8629	27.4410	0.023	0.024	0.023	0.0233	32.6387
27	13.38	16.24	12.24	13.9543	22.7164	0.026	0.023	0.022	0.0237	32.4949
28	15.28	18.14	10.86	14.7588	22.7828	0.019	0.02	0.019	0.0193	34.2713
29	19.28	20.21	15.91	18.4628	25.1841	0.028	0.03	0.026	0.028	31.0421
30	16.24	17.75	11.66	15.2173	23.2126	0.023	0.026	0.022	0.0237	32.4949
31	11.37	11.75	9.466	10.8629	20.5989	0.021	0.02	0.02	0.0203	33.8335
32	22.65	24.07	18.31	21.6781	26.5379	0.023	0.027	0.026	0.0253	31.9066
33	22.22	22.67	21.71	22.2015	26.9236	0.024	0.024	0.022	0.0233	32.6334
34	17.14	17.97	12.85	15.9896	23.7842	0.02	0.025	0.026	0.0237	32.4642
35	16.89	12.6	13.32	14.2705	22.8844	0.027	0.027	0.026	0.0267	31.4793
36	20.63	22.27	19.5	20.7956	26.3210	0.021	0.025	0.025	0.0237	32.4898