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Surface alloying of aluminium by W-Cu-Cr powder metallurgy tool electrodes in EDM

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ABSTRACT: Aluminium alloys are used extensively due to their high strength-to-weight ratio. On the other hand, pure aluminium metal is much too soft for such uses and it does not have the high tensile strength that is needed. In this study, Electric Discharge Alloying (EDA) is used to modify the surface of aluminium with the help of tool electrodes manufactured by powder metallurgy (P/M) process. Surface alloying by material transfer during Electric Discharge Machining (EDM) has emerged as a key research area in the last decade. Though EDM is basically a material removal process, efforts have been made to use it as a surface treatment method to enhance the resistance to abrasion by depositing a thin layer. Electrodes have been made of W-Cu-Cr metal powders of 325 and 200 mesh sizes. The investigated process parameters are composition, compaction load, pulse on-time and peak current settings. Measurements of Material Transfer Rate (MTR), Tool Wear Rate (TWR) and Surface Roughness (Ra) were undertaken on the EDM-ed specimens. Taguchi's design of experiments and ANOVA has been used to find the effect of various process parameters on the output responses Overall Evaluation Criterion (OEC) was carried to find suitable process parameters aiding surface alloying in EDM.

KEYWORDS -Electric Discharge Alloying (EDA), Material Transfer Rate (MTR), Powder Metallurgy (P/M) electrodes, surface treatment, Overall Evaluation Criterion (OEC).

I. INTRODUCTION

Surface alloying is a process of adding elements to influence the apparent physical characteristics of the substrate by the formation of alloys, meta-stable alloys or phases or amorphous layers. Because of the intermittent isolated discharges, an Electric Discharge Machined (EDMed) specimen will have a satin or matt appearance. Electric Discharge Machining (EDM) is basically a negative process, but efforts have been made to use it as a positive and/or additive process. The transfer of materials in the substrate was found to be a function of several electrical parameters of the circuit. Desired surface modifications have been successfully carried out by using conventional solid electrode material, by machining with powder metallurgy (P/M) electrodes and by mixing fine powders in the dielectric medium.

The kind of powders used in P/M electrode is diverse and includes C (graphite), SiC, Cr, Al_2O_3, Al, Cu, Si and Ni of varying sizes. Compared to conventional solid electrodes, P/M electrodes were found to be highly sensitive to changes in EDM process parameters like pulse current and pulse duration. The functional performance of a component is directly dependent on the quality of the surface that is being produced on the component by various manufacturing processes. Therefore, the surface integrity that is being produced in the manufactured surfaces is very important [1]. The examination of a section of the surface layer produced by EDM revels that there is a top white layer which crystallizes from the liquid cooled at high speed [2, 3]. The depth of this top melted zone depends on the pulse energy and duration. Below the top layer is a chemically affected layer with changes in the average chemical composition and possible phase changes. After this, there is a plastically deformed zone with micro and macro strains characterized by the presence of twinning slip and phase changes. The EDM process changes not only the surface of the work-piece metal, but also the subsurface.

Surface modification may be necessary to improve resistance to wear, erosion and indentation, reduce friction, increase lubrication, improve resistance to corrosion and oxidation and improve fatigue resistance. Wang et al [2] suggested method to surface repairing and strengthening of cutting tools and moulds and have called it 'Electric Discharge Coating (EDC)'. Experiments were conducted on carbon steel with Ti powder compact electrodes using negative polarity of the tool and a machining time of 18 minutes. It gave a concentration of TiC as high as 51% and more than three times increase in hardness. Kumar S., Batra U., [4] has investigated the response of die steel materials to surface modification by EDM method with tungsten powder mixed in the dielectric medium. Peak current, pulse on-time and pulse off-time were taken as variable factors and micro-hardness of the machined surface was taken as the response parameter. It was possible to achieve a maximum amount of 3.25% tungsten in the machined surface of H13 die steel. Tasi H. C. et al [5] proposes a new method of blending the Cu powders contained resin with Cr powders to form tool electrodes. Electrodes were made at 20 MPa pressure and 200°C temperature in a hot mounting machine. The results showed that using such electrodes facilitated the formation of a modified surface layer on the work-piece after EDM, with remarkable corrosion resistance properties. Ho S. K. et al [6] gives details of experimental results when alloying Ti-6Al-4V using both solid and powder compacted Cu electrodes with commercial water based dielectric fluid. Glow discharge optical emission spectroscopy showed that the percentage of Cu transferred from the solid electrodes to the work-piece was up to 29%, while for the powder compact electrodes the level was significantly higher, with the 32 MPa pressed pellets giving 78% at the surface. Hwang Y. L. et al [7] proposed multi-layer electrodes (MLEs) to coat Titanium carbide (TiC) layer on the surface of a nickel work-piece by Electric Discharge Coating (EDC). The experimental results indicate that the graphite (Gr) layers enhance the concentration of carbon element locally. Also, carbon with high concentration increases the combination of Ti and C to become TiC which enhances the surface hardness of the coated layer. Comparison of the performance of powder metallurgy (P/M) tool electrodes with conventional electrodes in normal EDM (using straight polarity and not in machining conditions favouring surface modification) was done by Samuel and Philip [8]. This study established that P/M electrodes were technically viable for EDM machining and their related properties could be controlled by varying compaction and sintering parameters. It was also found that under certain processing and operating conditions, P/M electrodes could cause net material addition instead of material removal. Patowari et al. [9] machined C-40 grade steel with WC/Cu P/M electrodes. Surface examination on SEM revealed relatively few micro-cracks and an increase in hardness from 200-220 HV to 1200-1632 HV.

The objective of the present work is to conduct an experimental study on surface alloying during EDM by depositing a layer over the work surface of aluminium using specially prepared P/M green compact tools. Taguchi's design of experiment and ANOVA has been used to investigate the different working ranges and levels of the EDM process parameters which aids in deposition of a layer with acceptable surface finish.

II.EXPERIMENTATION

The experiments have been conducted on EDM model F25 series of Sparkonix available at the Advanced Manufacturing Laboratory, Mechanical Engineering Department, NITSilchar. It is a die sinking vertical EDM machine. The x-axis and y-axis movements are given to the work table and the z-axis movement is on the tool holder. Hydrocarbon oil is used as the dielectric medium. The P/M electrodes were prepared using W, Cu and Cr metal powders of 325 mesh size using 25 tons manual pellet press. The schematic diagram of EDM machine for surface alloying along with the EDM machine is shown in Fig. 1.

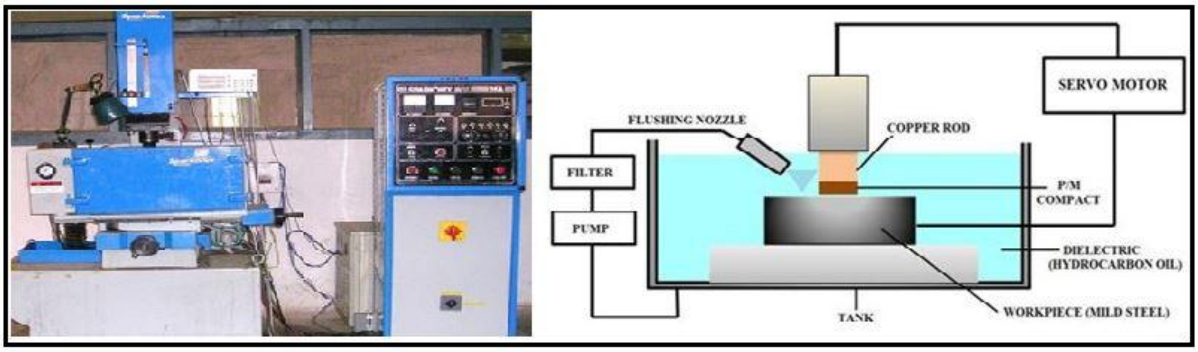

Figure 1 EDM set up and schematic diagram of EDM machine for surface alloying

The work-piece selected for experimentation is aluminium of dimension 25mm×25 mm×5mm. Emery papers of grades 80, 160, 180, 210 and 260 were used to polish the work surface to eliminate the problem due to inclination. The process parameters along with their levels and values are shown in Table 1.

Table 1 Process parameters with their levels and values

Parameters	**Levels**			
	Level 1	**Level 2**	**Level 3**	**Level 4**
Composition	C1	C2	C3	C4
Compaction Load (Tons)	5	10	15	20
On Time (μs)	25	106	463	1010
Current (A)	4	6	8	10
Polarity	Normal (N)	Reverse (R)	-	-

The P/M electrodes prepared are designated as C1 (W 50%, Cu 25%, Cr 25%), C2 (W 55%, Cu 25%, Cr 20%), C3 (W 60%, Cu 25%, Cr 15%) and C4 (W 65%, Cu 25%, Cr 10%). Composition and compaction load have been chosen such that the compacts can retain their shape and can be handled without the fear of disintegration. Peak current (I_p) settings impose some restrictions because at very low I_p settings, the sparking phenomenon is feeble and does not produce desired results. At higher value of I_p settings, arcing takes place which leads to undesirable effect on tool and work-piece. So the $I_p$setting has been chosen so that for all T_{on} settings, it leads to the desired effect. Each specimen has been EDM-ed for 5 minutes. Gap control has been so adjusted that average gap voltage remained around 55-75 V. The pulse off-time values are selected by keeping the duty factor 0.6 to 0.7 and the values are 17 μs, 76 μs, 222 μs and 392 μs respectively corresponding to the pulse on-time values. The flushing pressure was kept constant at 5 kg/cm^2.

III. RESULTS AND DISCUSSIONS

Material Transfer Rate (MTR), Tool Wear Rate (TWR) and surface roughness (R_a) are selected as response parameters. Based on the levels of the input parameters, Taguchi’s L-16 orthogonal array has been selected for conducting 16 numbers of experiments. The MTR and TWR values for the 16 set of experiments are shown in Table 2.

Table 2 MTR and TWR value for first set of experiments

Exp. No.	**Composition**	**CL (tons)**	**Polarity**	**T_{on} (μs)**	**Current (A)**	**FP (kg/cm^2)**	**M.T.R (mg/min)**	**T.W.R (mg/min)**
01.	C11	5	N	25	4	5	-0.50	2.78
02.	C12	10	N	106	6	5	-0.06	2.84
03.	C13	15	R	463	8	5	0.30	1.50
04.	C14	20	R	1010	10	5	-0.24	4.28
05.	C21	5	N	1010	8	5	-1.94	7.56
06.	C22	10	N	463	10	5	-2.52	2.62
07.	C23	15	R	106	4	5	0.66	3.54
08.	C24	20	R	25	6	5	1.02	4.76
09.	C31	5	R	106	10	5	1.88	13.08
10.	C32	10	R	25	8	5	0.76	1.82
11.	C33	15	N	1010	6	5	-1.02	5.34
12.	C34	20	N	463	4	5	-0.16	1.84
13.	C41	5	R	463	6	5	3.08	2.76

14.	C42	10	R	1010	4	5	1.58	5.28
15.	C43	15	N	25	10	5	-2.76	4.5
16.	C44	20	N	106	8	5	-2.04	3.08

The negative MTR indicates that there is no net addition of material from the tool to the work-piece, but material removal has taken place. This is because machining is more dominant than addition in these cases. Analysis of variance (ANOVA) of the experimental data was performed to obtain the percentage contribution of the factors and their significance as shown in Table 3. The results show that the parameters polarity and current contribute more percentage in the MTR. The average effects of each parameter are shown in Fig. 2.

Table 3 ANOVA for the first set of experimental data

SL. NO.	FACTOR	SUM OF SQUARES	VARIENCE	F-RATIO	PURE SUM	PERCENTAGE
1.	COMPOSITION	2.292	0.764	7.576	1.989	4.889
2.	COMP.LOAD(Tons)	3.854	1.284	12.738	3.551	8.728
3.	POLARITY	25.1	25.1	248.875	24.999	61.437
4.	ON-TIME (μs)	1.134	0.378	3.749	0.831	2.044
5.	CURRENT (amp)	8.108	2.702	26.797	7.805	19.182
	Other	0.201	0.1			3.72

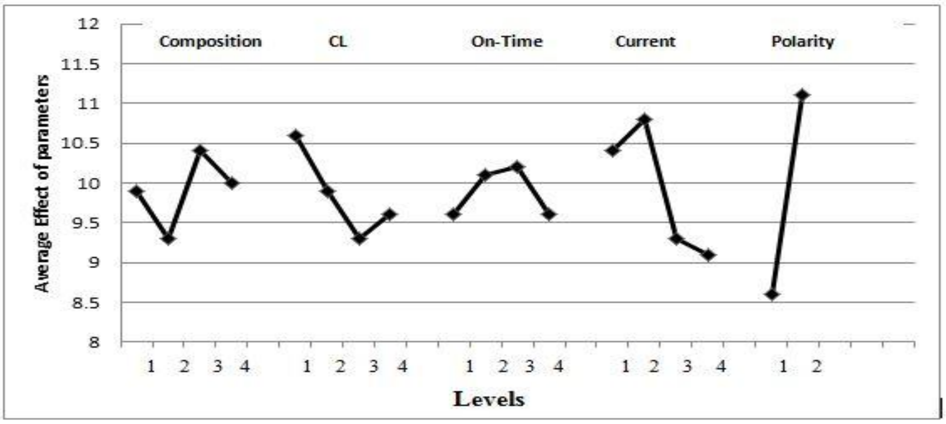

Figure 2 Average effects of parameters for first set of experiments

As seen from the first phase of experiments that reverse polarity is giving good layer deposition while the normal polarity doesn't favor the deposition in so many cases and it leads to arching in some cases. In the next phase of experimentation, only reverse polarity is considered which will help to explore more range of conditions which favor the MTR. The MTR, TWR and R_a value for the next phase of experiments are shown in Table 4.

Table 4 MTR, TWR and R_a value for second set of experiments

Exp. No.	Composition	CL (Tons)	T_{on} (μs)	T_{off}(μs)	Current (A)	MTR (mg/min)	TWR (mg/min)	Ra (μm)
01.	C11	5	25	17	4	-0.06	1.70	5.15
02.	C12	10	106	76	6	-0.22	12.92	6.22
03.	C13	15	463	222	8	-0.72	7.6	6.25
04.	C14	20	1010	392	10	-1.92	14.38	7.4
05.	C21	5	106	76	8	1.26	11.08	9.3
06.	C22	10	25	17	10	1.44	24.12	9.56
07.	C23	15	1010	392	4	0.54	3.18	7.22
08.	C24	20	463	222	6	1.96	12.12	6.26
09.	C31	5	463	222	10	3.34	11.44	6.83
10.	C32	10	1010	392	8	2.24	26.6	8.45
11.	C33	15	25	17	6	-0.76	13.02	9.47
12.	C34	20	106	76	4	0.26	13.3	8.6
13.	C41	5	1010	392	6	6.36	40.44	13.32
14.	C42	10	463	222	4	3.10	22.16	7.25
15.	C43	15	106	76	10	8.6	38.14	10.76
16.	C44	20	25	17	8	3.32	26.42	8.3

ANOVA analysis of the experimental data was carried out by considering only MTR and is shown in Table 5. The result shows that the parameter composition of the P/M electrode solely contributes for MTR. The average effect of parameters is shown in Fig. 3.

Table 5 ANOVA for the second set of experimental data

SL. NO.	FACTOR	SUM OF SQUARES	VARIENCE	F-RATIO	PURE SUM	PERCENTAGE
1.	COMPOSITION	77.995	25.998	5.095	62.688	55.828
2.	COMP.LOAD(Tons)	6.781	2.26	0.443	0	0
3.	ON-TIME (μs)	4.536	1.512	0.296	0	0
4.	CURRENT (amp)	7.666	2.555	0.5	0	0
	Other	15.306	5.102			44.172

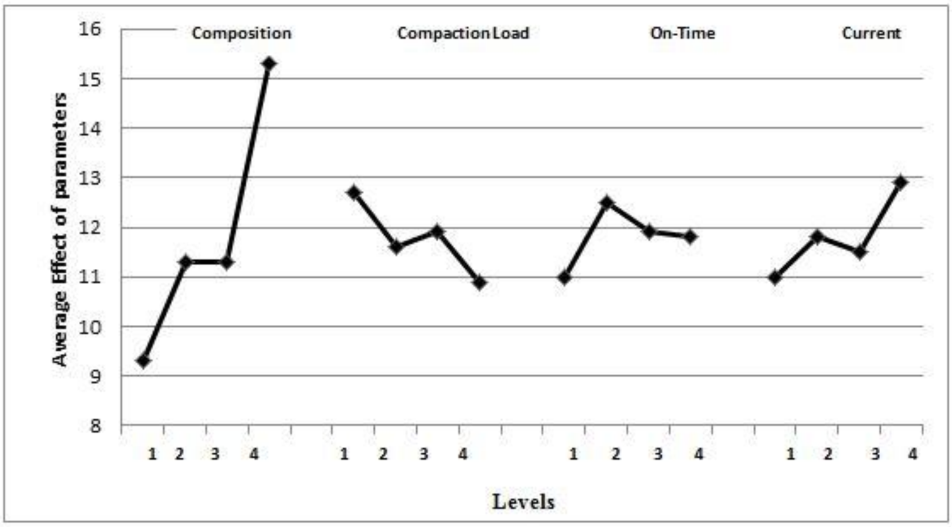

Figure 3 Average effects of parameters for second set of experiments

Based on the average effects the optimum condition and performance for MTR is as shown in Table 6. Confirmation experiments have been conducted using the suggested optimum conditions and the result is shown in Table 7.

Table 6 Optimum conditions and performance

Sl. No.	Factor	Level Description	Level	Contribution
1.	Composition	C4	4	23.548
2.	Comp. Load (Tons)	5	1	0.928
3.	On-Time (µs)	106	2	0.678
4.	Current (amp)	10	4	11.068
Total contribution from all factors				36.221
Current grand average of performance				61.796
Expected result at optimum condition				88.018

Table 7 Results of the confirmation experiment

Sl. No.	Response Variable	Value
1.	Material Transfer Rate (mg/min)	80.92
2.	Tool Wear Rate (mg/min)	208.98
3.	Roughness (µm)	13.20

It has been found that the deposited surface is uniform throughout. There is no indication of any lump deposition and any damage due to arcing. The tool electrode is also uniformly consumed. It is evident from the confirmation experiment that the surface roughness increased with increase in current. The surface of the coated work-piece and the tool after the confirmation experiment along with the surface roughness profile is shown in Fig. 4.

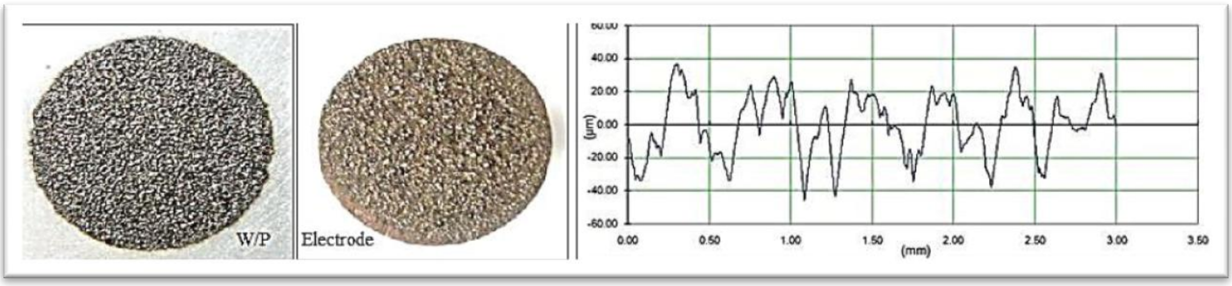

Figure 4 Work-piece, electrode and surface roughness profile

In actual machining operation, it is difficult to simultaneously optimize a single output performance. In such cases, when it has to satisfy more than one objective, performance of samples tested are evaluated by multiple criteria of evaluation, where it can be combined into a single quantity, the overall evaluation criteria (OEC). The evaluation of each criterion may have different units of measure, quality characteristics and relative weighting. To combine the different criterion, they must first be normalized and weighted accordingly.

An OEC is constructed such that it not only forces each criteria reading to have compatible units of measure but also reflects proper relative weighing of each individual criterion. The calculation of OEC for two outputs X and Y with weighing W_x and W_y respectively is given by (1).

$$OEC = \left[\frac{x_1 - x_{\min}}{x_{\max} - x_{\min}} \right] \times W_x + \left[\frac{y_1 - y_{\min}}{y_{\max} - y_{\min}} \right] \times W_y \qquad (1)$$

To obtain the OEC, each criteria or output measure is first normalized, weighted accordingly using the above formulae and then assigned with Quality Characteristics (QC), like the bigger is best (QC=B), the nominal is the best (QC=N) or the smaller is the best (QC=S).

OEC has been conducted by assigning weightage i.e. giving importance to both MTR and R_a. Two conditions are considered which are: Condition 1 (75% weightage to MTR and 25% weightage to R_a) i.e. giving more importance to MTR than roughness and Condition 2 (50% weightage to MTR and 50% weightage to R_a) i.e. giving equal importance to MTR and roughness. The OEC is calculated using the details given in Table 8.

Table 8 Overall Evaluation Criteria

Sl. No.	Parameter	Worst	Best	QC	Condition 1 (weights)	Condition 2 (weights)
1.	MTR	-1.92	8.6	B	75	50
2.	Roughness	13.3	5.1	S	25	50

The OEC values for the two set of conditions is shown in Table 9 for the 16 set of experimental data. The analysis is done for the bigger is the best of OEC, i.e., to maximize OEC.

Table 9 OEC values for condition 1 and 2

Exp. No.	Composition	CL (Tons)	T_{on} (μs)	T_{off}(μs)	Current (A)	MTR (mg/min)	TWR (mg/min)	Ra (μm)	OEC 1	OEC 2
01.	C11	5	25	17	4	-0.06	1.70	5.15	38.26	58.84
02.	C12	10	106	76	6	-0.22	12.92	6.22	33.83	51.5
03.	C13	15	463	222	8	-0.72	7.6	6.25	30.26	49.12
04.	C14	20	1010	392	10	-1.92	14.38	7.4	18.11	36.23

05.	C21	5	106	76	8	1.26	11.08	9.3	34.97	39.73
06.	C22	10	25	17	10	1.44	24.12	9.56	35.44	38.95
07.	C23	15	1010	392	4	0.54	3.18	7.22	36.19	49.00
08.	C24	20	463	222	6	1.96	12.12	6.26	49.24	61.6
09.	C31	5	463	222	10	3.34	11.44	6.83	57.35	64.7
10.	C32	10	1010	392	8	2.24	26.6	8.45	44.56	49.58
11.	C33	15	25	17	6	-0.76	13.02	9.47	20.04	29.06
12.	C34	20	106	76	4	0.26	13.3	8.6	29.99	39.26
13.	C41	5	1010	392	6	6.36	40.44	13.32	59.03	39.35
14.	C42	10	463	222	4	3.10	22.16	7.25	54.36	61.01
15.	C43	15	106	76	10	8.6	38.14	10.76	82.82	65.64
16.	C44	20	25	17	8	3.32	26.42	8.3	52.72	55.63

The ANOVA analysis for the two set of conditions were carried out and is shown in Table 10.

Table 10 ANOVA analysis for condition 1 and 2

SL. NO.	FACTOR	SUM OF SQUARES	VARIENCE	F-RATIO	PURE SUM	PERCENTAGE
1.	COMPOSITION	2302.205	767.401	2.216	1263.342	31.125
2.	COMP.LOAD(Tons)	195.974	65.324	0.188	0	0
3.	ON-TIME (µs)	320.859	106.953	0.308	0	0
4.	CURRENT (amp)	200.989	66.996	0.193	0	0
	Other	1038.862	346.287			68.875

(a) ANOVA for MTR 75% and Ra 25%

SL. NO.	FACTOR	SUM OF SQUARES	VARIENCE	F RATIO	PURE SUM	PERCENTAGE
1.	COMPOSITION	2733.122	911.04	3.619	1977.926	38.939
2.	COMP.LOAD(Tons)	256.915	85.638	0.34	0	0
3.	ON-TIME (µs)	970.743	323.581	1.285	215.547	5.916
4.	CURRENT (amp)	787.536	262.512	1.042	32.34	0.587
	Other	755.195	251.731			54.558

(b) ANOVA for MTR 50% and Ra 50%

From Table 10, it is evident that, composition of the P/M electrode is the sole criterion for effecting higher MTR in the work-piece substrate for having higher importance to MTR w.r.t roughness while for equal importance of MTR and roughness, composition along with pulse on-time are the process parameters. Based on the ANOVA analysis, confirmation experiments have been conducted using the optimum solutions as suggested in Table 11.

Table 11 Optimum conditions and performance

Sl. No.	Factor	Level Description	Level	Contribution
1.	Composition	C4	4	19.909
2.	Comp. Load (Tons)	5	1	5.079
3.	On-Time (µs)	463	3	5.479
4.	Current (amp)	10	4	6.106
Total contribution from all factors				36.573
Current grand average of performance				42.323
Expected result at optimum condition				78.896

(a) Optimum conditions for MTR 75% and Ra 25%

Sl. No.	Factor	Level Description	Level	Contribution
1.	Composition	C4	4	20.756
2.	Comp. Load (Tons)	5	1	4.993
3.	On-Time (µs)	463	3	12.296
4.	Current (amp)	10	3	6.783
Total contribution from all factors				44.828
Current grand average of performance				37.133
Expected result at optimum condition				69.22

(b) Optimum conditions for MTR 50% and Ra 50%

Based on the optimum conditions, confirmation experiments were conducted and the results are tabulated in Table 12.

Table 12 Results of the confirmation experiment for condition 1 and 2

Sl. No.	Response Variable	Value in condition1	Value in condition 2
1	Material Transfer Rate (mg/min)	75.6	65.88
2	Tool Wear Rate (mg/min)	182.94	163.72
3	Roughness (μm)	12.17	10.22

IV. CONCLUSIONS

Powder Metallurgy (P/M) compact electrodes have been successfully used to modify the surface characteristics of the work-piece by transfer of tool material to the work surface. The following conclusions can be drawn from the current investigation of surface alloying of aluminium using W-Cu-Cr P/M electrodes in EDM.

- From the ANOVA analysis after the first phase of experimentation, it is found that polarity and current plays a significant role in MTR. Reverse polarity is giving good layer deposition while normal polarity doesn't favor deposition and sometimes it leads to arching.
- ANOVA analysis after the second phase of experimentation, gives emphasis to the composition of the P/M electrodes as the sole criteria for MTR. Optimum conditions suggest that C4 (W 65%, Cu 25%, Cr 10%) is the best combination of the P/M electrodes.
- Taguchi method of design of experiments has been used successfully to conduct the experiments. OEC have been formulated for achieving multi objective output of MTR along with good roughness. The details of the OEC results is tabulated in Table 13

Table 13 Overall details of the confirmation experiment

Sl. No.	Response Variables	CNF EXP for only MTR	OEC CNF EXP (75% MTR & 25% Ra)	OEC CNF EXP (50% MTR & 50% Ra)
1	MTR (mg/min)	80.92	75.6	65.88
2	TWR (mg/min)	208.98	182.94	163.72
3	Ra (μm)	13.20	12.17	10.22

- It is evident from table 13 that, as we assign higher weights to a particular process output, the value drastically improves. The MTR value is maximum (80.92 mg/min) when the sole objective was to have a good MTR to the work surface. While the MTR comes down to 65.88 mg/min when equal weights were assigned to both MTR and roughness of the work part.
- The P/M electrode composition W 65%, Cu 25%, Cr 10% helps in net mass transfer which further opens up new areas to explore the other EDM process parameters and to find the optimum conditions aiding maximum MTR.

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