Volume : 4 | Issue : 10 | Special Issue Oct- 2015 • ISSN No 2277 - 8179

SURFACE MODIFICATION OF ALUMINIUM USING PM ELECTRODE ON EDM

Engineering

KEYWORDS: Electric, discharge, machining, Powder metallurgy, Surface finish, ANOVA, Taguchi Method, Green Compactnd I(Pulse current), Revolutions per minute (RPM)

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ABSTRACT

Electric discharge machining (EDM) is one of the most popular machining methods to produce complicated shapes and machine hard materials. Present work attempts to correlate the usefulness of green compact copper electrode made using powder metallurgy (PM) in comparison with conventional copper electrode during EDM of Aluminium. It was observed that machining with green compact PM copper electrode improved surface finish. Conventional copper electrode is suitable when higher material removal rate and lower electrode wear rate is desired. The microstructure study revealed significant material transfer from the PM electrode to the workpiece surface at higher current and higher pulse ON-time. Significant input parameters were identified using Taguchi method and ANOVA. Empirical expression was proposed to predict the surface roughness value. Surface modification of Aluminium by electrical discharge machining is feasible and the technique is being referred as EDM using Powder Metallurgy Copper Electrode (EDM-PME).

I. Introduction

Non-conventional manufacturing processes provide attractive alternative for difficult-to-machine materials. Among these, EDM has become one of the most successful processes for machining economically high strength steels with high level of accuracy. The behaviour of machined surface is an important factor in extending its useful life. Thus, a surface modification process is essentially required to improve the surface properties. Surface improvement methods such physical vapour deposition, chemical vapour deposition, thermal spraying, etc. have been proposed to augment the machined surface performance. These methods need special apparatus and have difficulties in process control. Researchers have proposed several new surface modification methods, to increase the working life and wear resistance, based on electrical discharge phenomena. During EDM, the workpiece upper region comprises of recast layer which is subjected to surface tensile stresses, local hardening, micro cracking, porosity and minor alloying due to transfer of metal from the tool electrode or carbon from the dielectric fluid. Electrical discharge energy along with non-electrical parameters such as dielectric fluid, workpiece and process for making of tool electrode controls the composition and state of this layer. Ahsan et al. (2012) [1] examined the use of cobalt and chromium powder mixed sintered electrode while EDM and confirmed the migration of electrode materials onto the mild steel surface resulting in the improved hardness. Bhattacharya et al. (2013) [2] found that significant migration of material from the suspended silicon, tungsten, graphite powder and electrode to the machined surface results in higher micro-hardness of die steel surface during EDM. Chen et al. (2008) [3] observed that the constituents of the semi-sintered electrode get deposited on the work piece surface to form a modified layer on low-carbon steel during EDM. Kumar and Batra (2012) [4] found significant migration of tungsten and carbon to the various die steel work piece surface and an improvement in micro-hardness while EDM. Lee et al. (2004) [5] used partially sintered powder metallurgical electrodes for machining chromium steel mill roll and found some textured and alloyed layers of hardness over 900 HK on the work piece surface. Patowari et al. (2011) [6] used tungsten carbide mixed copper powder green sintered electrodes while EDM and established that the deposition of a hard layer of tungsten carbide and copper changes the surface integrity of the C-40 steel workpiece. Shunmugam and Philip (1994) [7] observed that electro discharge machining using tungsten powder green compact electrode modifies the wear resistance of workpiece surface. Simao et al. (2002) [8] indicated an increase in micro-hardness on the surface of hardened AISI D2 Sendzimir rolls using green sintered powder metallurgy electrodes of titanium carbide mixed with tungsten carbide and cobalt while electrical discharge texturing. Tsunekawa et al. (1994) [9] obtained composite layers of 100μm thickness on the aluminium workpiece using titanium green compact electrode and through deposition of decomposed carbon from hydrocarbon dielectric. Wang et al. (2002) [10] concluded that almost three times harder layer is formed on the workpiece surface while EDM with titanium powder green compact electrode.

Hardened alloy steel is most commonly used in industrial applications like automobiles, mould making and die casting industries. But the limitation of using alloy steel is their poor corrosion resistance, higher machining time and higher weight. Aluminium alloy is getting popularity in the automobile and aeronautical industries due to its light weight and excellent strength to weight ratio, but it cannot withstand surface wear under higher load circumstances. It becomes gradually more important to expand the technique to improve surface characteristics of machined aluminium surface at lesser costs and with minimal setup procedures. Therefore, the present study is focused on using PM copper electrode to affect modifications on Aluminium surface through EDM.

II. Experimental Methodology

The experimental set-up, as illustrated in Figure 1, comprises of a Charmilles-D20 EDM machine having ISOPULSE generator, powder metallurgy and conventional copper electrodes, Aluminium workpiece, electrode holder and work holding device. Surface roughness (Ra), Metal removal rate (MRR) and Electrode wear rate (EWR)) were recorded after each trial of fixed time period. Ra values ware recorded on TALYSURF surface roughness tester on 8 mm tracing length. Change in the workpiece and electrode weight was recorded using Contech Instruments weighing balance with least count of 0.0001.

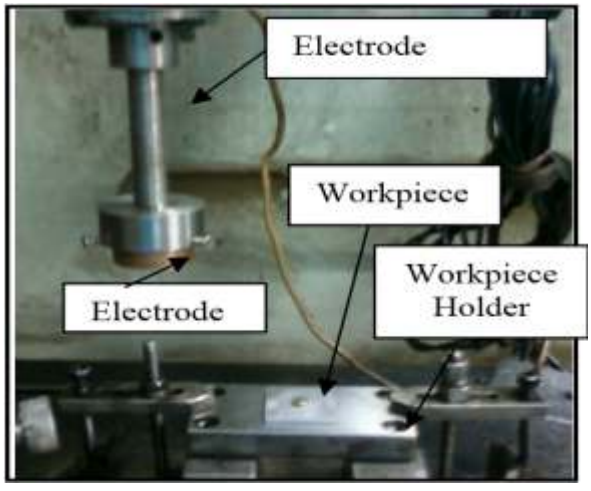


Figure 1: View of the experimental set-up of EDM machine

Microstructure analysis was done on some samples using Hitachi's S-4300SE scanning electron microscope. Material specifications used to perform investigations are given in Table 1. MRR and EWR are calculated as in equation 1.

$$\text{MRR or EWR } (mm^3/min) = \frac{W \quad mm^3/min}{\rho \, X \, t} \quad \ldots.1$$

Where W, t, ρ are reduction in weight of workpiece or electrode (gm), machining time (min) and density of workpiece or electrode (gm/mm3) respectively.

A. Development of Powder Metallurgy Electrode

The PM copper electrodes were formed using 40-45 µm grain size copper powder. The powder was blended with binder polyvinyl alcohol for 1 hour and then placed in a cylindrical die and punch. It was then compacted at a pressure of 7.85 MPa and sintered at 280°C for 120 minutes in the electric furnace. Proper experimental design methodology is required for precise characterization of the machining procedure. The criterion for research is to achieve high MRR and better surface finish along with reduction in EWR. Controllable parameters i.e. pulse ON-time, pulse OFF-time and peak current along with their levels are given in Table 1.

Table 1 : Controllable parameters with their levels and Material specifications used to perform investigations

Control Parameters	Levels		
	1	2	3
Electrode Polarity	+ve		
Peak current (I) A	9	18	36
Pulse ON-time (Ton) µs	100	200	400
Pulse OFF-time (Toff) µs	100	200	400
Compacting pressure (Pc) MPa	7.85	-	-
Flushing pressure (Fp) bar	0.15	-	-
Sintering Temperature (Ts) °C	280	-	-
Work piece material – Aluminium 6061	Mg 0.85%, Si 0.60%, Fe 0.40%, Cu 0.25%, Zn 0.25%, Cr 0.14%, Mn 0.12%, Ti 0.10% ; Size : 30mm(L) x 30mm (W) x 3mm(H); Vickers Hardness (Hv) : 90		
Electrode material - Copper	Electrode Shape: Disc type, Outside Dia. = 29mm, Inside Dia. = 17.5 mm, Thickness = 15 mm; Vickers Hardness (Hv) : 140; Electrical Resistivity : 16.78 nΩ.m; Granule size 40-45 µm		
Dielectric Oil	Kerosene (commercial grade) and hydraulic oil in 1:1 ratio		

Taguchi recommended L9 orthogonal array for three controllable parameters along with the observed values of response is given in Table 2 and Table 3. Each trial was repeated thrice to reduce the effect of noise factors.

Table 2 : L9 Matrix of levels and observed values with conventional copper electrode

S. No.	Control Parameters	Output Values conventional copper electrode			
	Current (I)	ON & Off-Time (Ton / Toff)	MRR mm^3/ min	EWR mm^3/ min	Surface Roughness (Ra)
1	9	100	4.95	0.06	3.19
2	18	100	19.11	0.22	6.8
3	36	100	51.07	0.39	12.6
4	9	200	2.2	0.06	3.34
5	18	200	13.86	0.18	6.16
6	36	200	44.99	0.25	11.67
7	9	400	1.79	0.05	3.42
8	18	400	8.06	0.12	5.54
9	36	400	33.84	0.14	11.3

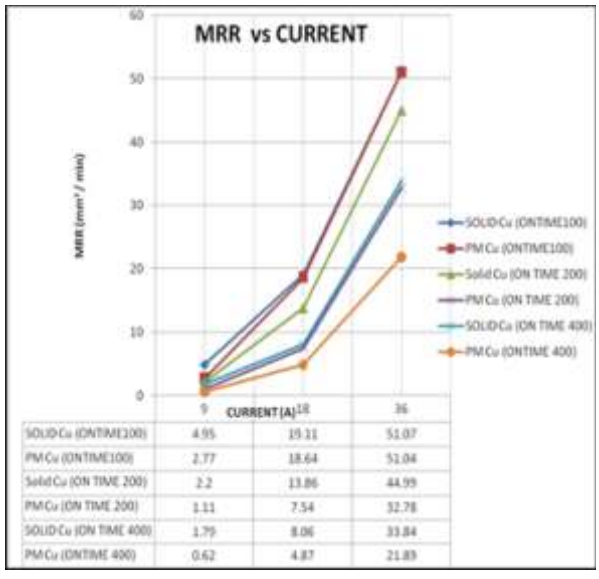
Table 3 : Matrix of levels and observed values with PM copper electrode

S. No.	Control Parameters	Output Values PM copper electrode			
	Current (I)	ON & Off-Time (Ton / Toff)	MRR mm^3 /min	EWR mm^3/ min	Surface Roughness (Ra)
1	9	100	2.77	9.56	2.2
2	18	100	18.64	14.66	3.4
3	36	100	51.04	24.18	3.46
4	9	200	1.11	8.36	2.17
5	18	200	7.54	16.4	3.16
6	36	200	32.78	26.3	4
7	9	400	0.62	8.47	2.12
8	18	400	4.87	11.98	3.44
9	36	400	21.89	24.32	4.43

III. Results and Discussion

It can be seen from the Figure 2 that MRR increases as current increases for particular value of pulse ON-time, for conventional and PM copper electrode at 50% duty factor. This is owing to higher energy available per spark discharge resulting in higher temperature conditions at higher current. The material eroded in the form of granules is removed instantly by flushing, thereby increasing MRR. But as pulse ON-time increases, the MRR reduces at particular value of current. Increased pulse ON-time leads to reduction in the frequency of pulses and this result in expansion of plasma channel. This causes reduction in spark density, which reduces metal removal. It was found that metal removal rate is inferior for all values of current and pulse ON-time for PM electrode as compared to conventional electrode. MRR is maximum for conventional electrode at 36A current and 100 s pulse ON-time. The PM electrode also has maximum MRR at same conditions.

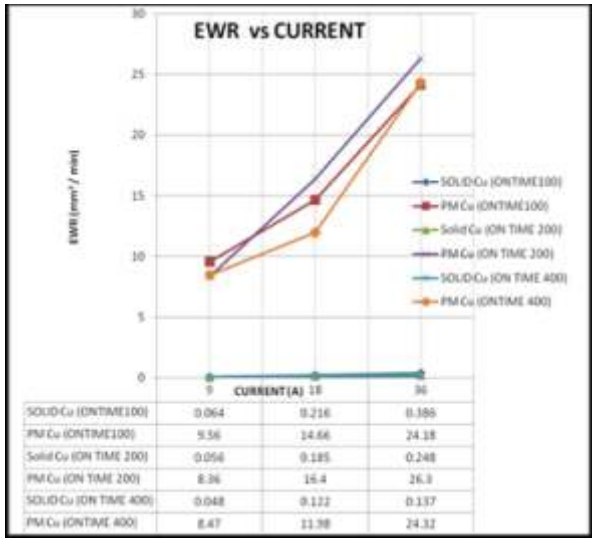
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	9	18	36
SOLID Cu (ONTIME100)	4.95	19.11	51.07
PM Cu (ONTIME100)	2.77	18.64	51.04
Solid Cu (ON TIME 200)	2.2	13.86	44.99
PM Cu (ON TIME 200)	1.11	7.54	32.78
SOLID Cu (ON TIME 400)	1.79	8.06	33.84
PM Cu (ONTIME 400)	0.62	4.87	21.83

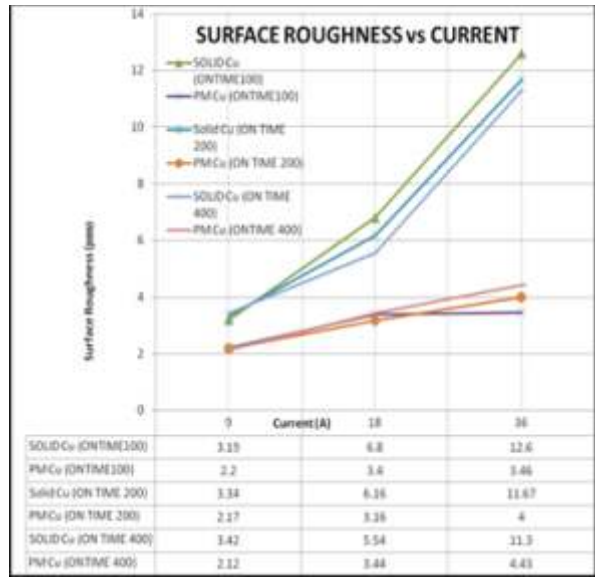
Figure 2 : MRR vs Current for Solid and PM Cu Electrode at different Pulse ON Time

Figure 3 shows EWR at different values of pulse ON-time and current for conventional and PM copper semi sintered electrode at 50% duty factor. For all levels of pulse ON-time, EWR varies in direct proportion to the current and follows the same variation as MRR. This increase in the electrode wear is attributed to increase of electron impingement on electrode at higher current. Also, at particular value of current, EWR is higher at lower values of Pulse ON-time i.e. at higher frequency. This is owing to the plasma channel expansion at higher values of pulse ON-time. This results in lower spark density and reduces EWR. It is observed that the EWR is very high in PM electrode. This is due to loose bonding of atoms in PM electrode due to which more electrode wear occurs. Figure 2 illustrates that EWR is very low as compared to MRR at all values of current for conventional electrode, and it is higher or comparable to MRR for PM electrode.
Figure 4 shows Ra values at different values of pulse ON-time and current for conventional and PM copper semi sintered electrode at 50% duty factor. It was observed that Ra value increases as the current increases for all values of pulse ON-time. Ra value is maximum at 36A and pulse ON-time 100s & 400s for conventional and PM copper electrode respectively. It is attributed to the fact that at higher values of pulse energy, larger size craters are formed and thus surface finish deteriorates.



	9	18	36
SOLID Cu (ONTIME100)	0.064	0.216	0.386
PM Cu (ONTIME100)	9.56	14.66	24.18
Solid Cu (ON TIME 200)	0.056	0.185	0.248
PM Cu (ON TIME 200)	8.36	16.4	26.3
SOLID Cu (ON TIME 400)	0.048	0.122	0.137
PM Cu (ONTIME 400)	8.47	11.98	24.32

Figure 3: EWR vs Current for Solid and PM Cu Electrode at different Pulse On-time



	9	18	36
SOLID Cu (ONTIME100)	3.19	6.8	12.6
PM Cu (ONTIME100)	2.2	3.4	3.46
Solid Cu (ON TIME 200)	3.34	6.16	11.67
PM Cu (ON TIME 200)	2.17	3.16	4
SOLID Cu (ON TIME 400)	3.42	5.54	11.3
PM Cu (ONTIME 400)	2.12	3.44	4.41

Figure 4 : Surface Roughness vs Current for Solid and PM Copper Electrode at different Pulse On- time

Also at a particular value of current, Ra value reduces with rise in pulse ON-time for conventional as well as PM copper electrode. Due to the growth of plasma channel at higher values of pulse ON-time, eroded workpiece and electrode particles gets redeposited on the machined surface which results in lower Ra value. The surface finish improved in comparison to the conventional electrode when PM electrode was used. This is due to higher deposition of electrode particles on the machined surface due to higher EWR, which resulted in better surface finish on the workpiece. The minimum value of Ra has been achieved with PM electrode at 9A and 400 s.

A. Analysis of variance (ANOVA)

The analysis of variance (ANOVA) table decomposes the variance in the investigations into its components, and then assesses their importance. F-ratio compares the variation due to the effect of every parameter with the variations due to uncertainties. Table 4 shows ANOVA done using StatGraphics software for Surface Roughness (Ra) using PM electrode. Since P-value for current is less than 0.1 for surface roughness at the 90 % confidence level.

Table 4: Analysis of Variance table

	ANOVA and F-test for Surface Roughness (Ra) with PM electrode					
Parameter	**df**	**SSA**	**MSSA**	**F ratio**	**P value**	**Remarks**
Current (I)	2	5.69	2.85	33.46	0.029	Significant
OFF-Time (Toff)	2	0.154	0.077	0.90	0.525	
ON-Time (Ton)	2	0.217	0.108	1.28	0.439	
Residual	2	0.170	0.085			
Total	8	6.24				

B. Microstructure analysis

Microstructure analysis was carried out on few samples to study the surface of Aluminium after EDM using PM electrodes. As seen from the SEM micrographs in Figure 5, machining with conventional electrode results in bigger craters in comparison to the semi sintered electrodes. The uniform distribution of the electrode material was seen on the workpiece surface when machined with PM semi sintered elec-

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trode. Recast layer can also be seen on the workpiece. The electrical discharge machined surface becomes rough due to deposition of debris which were not removed by flushing from the machining gap.

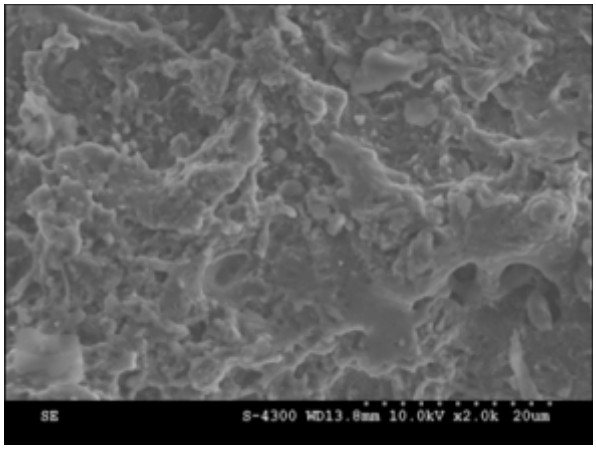


Figure 5: SEM micrograph at 2000× of Al 6061 machined with solid copper electrode (I 9Amp, pulse on time 100μs)

Figure 6 shows a smooth and crack-free surface without the typical craters of EDM. The copper particles from green compact electrode can also be seen here. The low bonding strength of electrode helps in rapid dielectric breakdown. Due to this the current flow gets established easily for the same applied voltage..

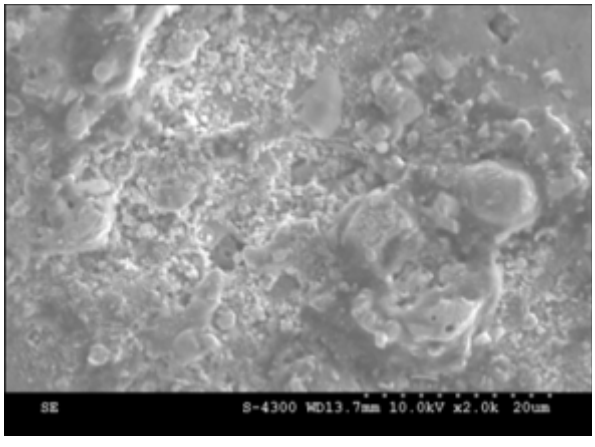


Figure 6: SEM micrograph at 2000× of Al 6061 machined with green compact copper electrode (I 9Amp, pulse on time 100μs)

The sparking gets evenly dispersed among the particles broken down from the PM electrode, which thus decreases the electric density of the sparks. Due to this crater size and depth diminishes and surface finish is improved. White layer with free copper particles is also visible in the micrograph.

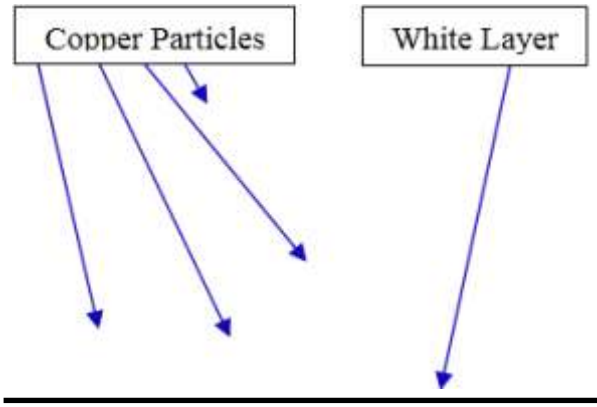




Figure 7: SEM micrograph at 700× of Al 6061 machined with green compact copper electrode (I 36 Amp, pulse on time 400μs)

Micrograph in Figure 7 shows an increase in the presence of copper particles on the work piece surface machined with PM copper electrode. Only few copper particles were observed on the work piece surface after machining with conventional copper electrode.

C. Empirical Model of the Process

The empirical expressions between output parameter (Z) such as Surface roughness (Ra) with the input parameters as current (I), ON-time (TON) and OFF-time (TOFF) while machining using PM electrode, could be hypothesized as equation 2.

$$Z = a1 + a2*I + a3*I2 + a4*TON + a5*T2ON + a6*TOFF + a7*T2OFF + a8*I*TON*TOFF \quad ...2$$

where a1, a2, a3, a4, a5, a6, a7, a8 are constants.

A multiple linear regression model for surface roughness is given in equation 3.

Surface roughness (Ra) = 1.24 + 0.126*current - 0.00077*OFF time + 0.00027*ON time - 0.0016*current^2 - 0.0000023*OFF time^2 - 0.00000135*ON time^2 + 4.63E-7*current*OFF time*ON time 3

R2 = 99.99, R2 adj = 99.98, Mean absolute error = 0.003

The R2 value signifies that the regression model developed explicate 99.99% of the unpredictability. The R2 adjusted value is 99.98% and is more appropriate to evaluate models with several independent parameters. Average magnitude of error is 0.003. The model can be simplified by removing the ON-time term, since its P-value is greater than 0.1.

IV. CONCLUSIONS

The present work assesses the machining of Aluminium-6061 with PM copper electrode. Empirical expressions are proposed to simplify the evaluation of Surface roughness at different values of pulse ON-time, pulse OFF-time and current. Based on the results and discussion, following can be concluded:

1. The results confirmed that the MRR is lower at all levels of pulse ON-time and current for PM copper electrode in comparison with conventional electrode.

2. The results also confirmed that the EWR is very low for conventional copper electrode as compared to PM copper electrode.

3. Experimental results also show that the surface finish has improved with PM copper electrode as compared to conventional copper electrode.

4. The electrical parameters more significantly affect the EDM

machining process but fabrication method of electrode (in this study powder metallurgy) also affect the EDM process output and gives better results for surface finish.

6. Empirical expressions have been successfully developed to predict the evaluation of the Ra values.

It can be stated that modification of the work piece surface is possible while electric discharge machining using PM copper electrode and it gives better surface finish than a conventional copper electrode.

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