# EFFECT ON MICRO-HARDNESS OF ALUMINIUM 6061 USING PM ELECTRODE DURING EDM

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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 resulted in higher values of micro-hardness. 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 work piece 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 micro-hardness 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).*

***Keywords -*** *Electric, discharge, machining, Powder metallurgy, Surface finish, ANOVA, Taguchi Method, Green Compact.*

## 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 work piece 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, work piece and process for making of tool electrode controls the composition and state of this layer. Ahsan et al. (2012) 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) 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) 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) 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) 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) 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 work piece. Shunmugam and Philip (1994) observed that electro discharge machining using tungsten powder green compact electrode modifies the wear resistance of work piece surface. Simao et al. (2002) 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) obtained composite layers of 100μm thickness on the aluminium work piece using titanium green compact electrode and through deposition of decomposed carbon from hydrocarbon dielectric. Wang et al. (2002) concluded that almost three times harder layer is formed on the work piece 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 work piece, 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 work piece and electrode weight was recorded using Contech Instruments weighing balance with least count of 0.0001.

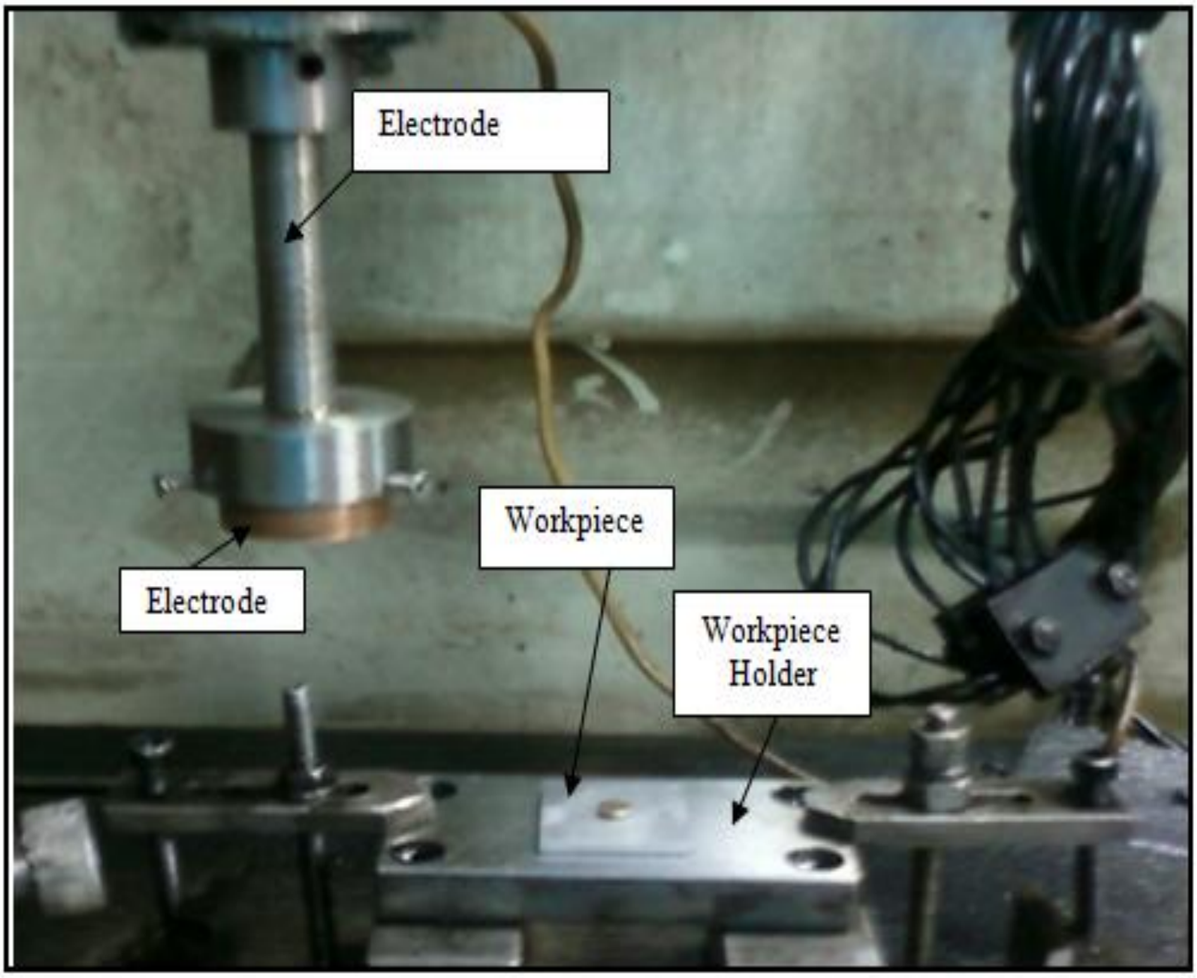



**Figure 1: View of the experimental set-up of EDM machine**

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.

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

Where W, t, ρ are reduction in weight of work piece or electrode (gm), machining time (min) and density of work piece or electrode (gm/mm$^3$) respectively.

## 2.1 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 *MR*R and better hardness 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 $(T_{on})$ µs | 100 | 200 | 400 |
| Pulse OFF-time $(T_{off})$ µs | 100 | 200 | 400 |
| Compacting pressure $(P_c)$ MPa | 7.85 | - | - |
| Flushing pressure $(F_p)$ bar | 0.15 | - | - |
| Sintering Temperature $(T_s)$ °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**

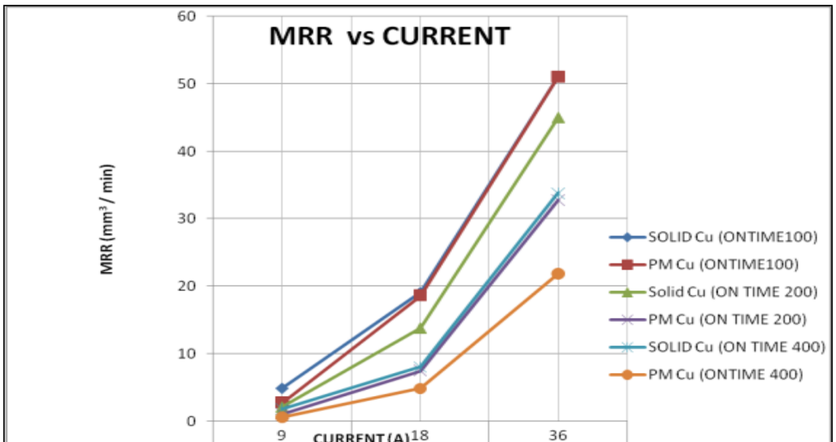
| S No. | Control Parameters | | Output Values conventional copper electrode | | |
|---|---|---|---|---|---|
| | Current *(I)* | ON & Off-Time $(T_{on} / T_{off})$ | *MRR* $mm^3/min$ | *EWR* $mm^3/min$ | Hard-ness (Hv) |
| 1 | 9 | 100 | 4.95 | 0.06 | 144 |
| 2 | 18 | 100 | 19.11 | 0.22 | 139.3 |
| 3 | 36 | 100 | 51.07 | 0.39 | 190.2 |
| 4 | 9 | 200 | 2.2 | 0.06 | 189.0 |
| 5 | 18 | 200 | 13.86 | 0.18 | 192.7 |
| 6 | 36 | 200 | 44.99 | 0.25 | 231.5 |
| 7 | 9 | 400 | 1.79 | 0.05 | 235.0 |
| 8 | 18 | 400 | 8.06 | 0.12 | 204.7 |
| 9 | 36 | 400 | 33.84 | 0.14 | 265.2 |

**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 ($T_{on}$ / $T_{off}$) | *MRR* $mm^3/min$ | *EWR* $mm^3/min$ | Hard-ness (Hv) |
| 1 | 9 | 100 | 2.77 | 9.56 | 182.3 |
| 2 | 18 | 100 | 18.64 | 14.66 | 172.5 |
| 3 | 36 | 100 | 51.04 | 24.18 | 206 |
| 4 | 9 | 200 | 1.11 | 8.36 | 241.3 |
| 5 | 18 | 200 | 7.54 | 16.4 | 207.8 |
| 6 | 36 | 200 | 32.78 | 26.3 | 251.7 |
| 7 | 9 | 400 | 0.62 | 8.47 | 268.2 |
| 8 | 18 | 400 | 4.87 | 11.98 | 221.5 |
| 9 | 36 | 400 | 21.89 | 24.32 | 367 |

## 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.

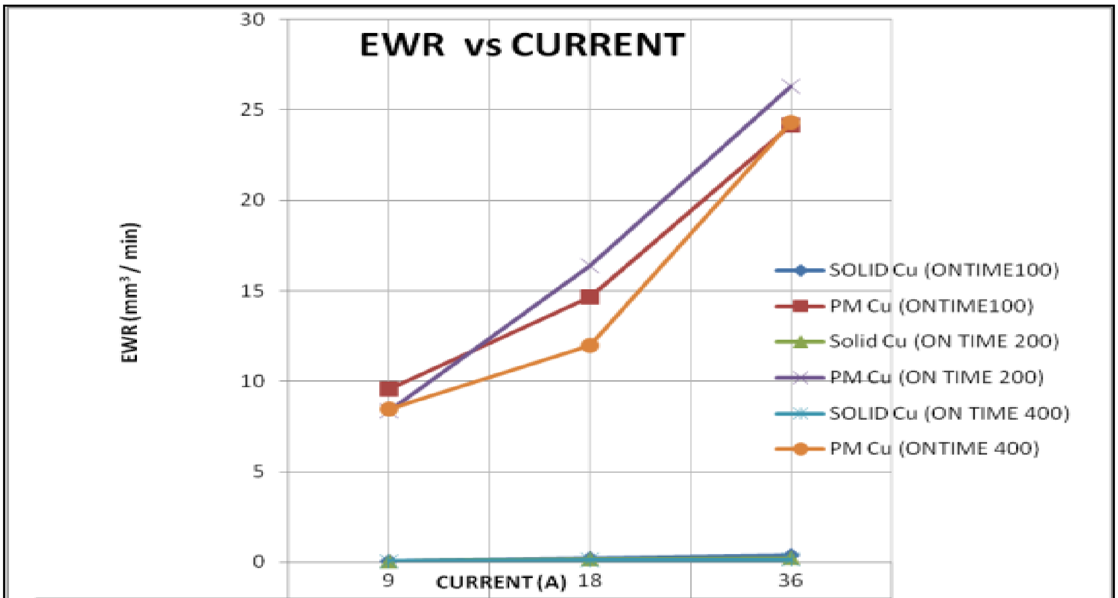



| | 9 | 18 | 36 |
|---|---|---|---|
| SOLID Cu (ONTIME100) | 4.95 | 19.11 | 51.07 |
| PM Cu (ONTIME100) | 2.77 | 18.64 | 51.04 |
| Solid Cu (ON TIME 200) | 2.2 | 13.86 | 44.99 |
| PM Cu (ON TIME 200) | 1.11 | 7.54 | 32.78 |
| SOLID Cu (ON TIME 400) | 1.79 | 8.06 | 33.84 |
| PM Cu (ONTIME 400) | 0.62 | 4.87 | 21.89 |

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

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 100μs pulse ON-time. The PM electrode also has maximum *MRR* at same conditions.

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.




| | 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**

Figure 4 shows the micro-hardness (Hv) values at different values of pulse ON-time and current for conventional and PM copper semi sintered electrode. It was found that Hv value increased as current & pulse ON-time increased with both conventional & PM electrode. It is attributed to the fact that at higher values of pulse energy at higher value of current, more heat is generated and this increases the work piece temperature & due to quenching effect hardness increases.

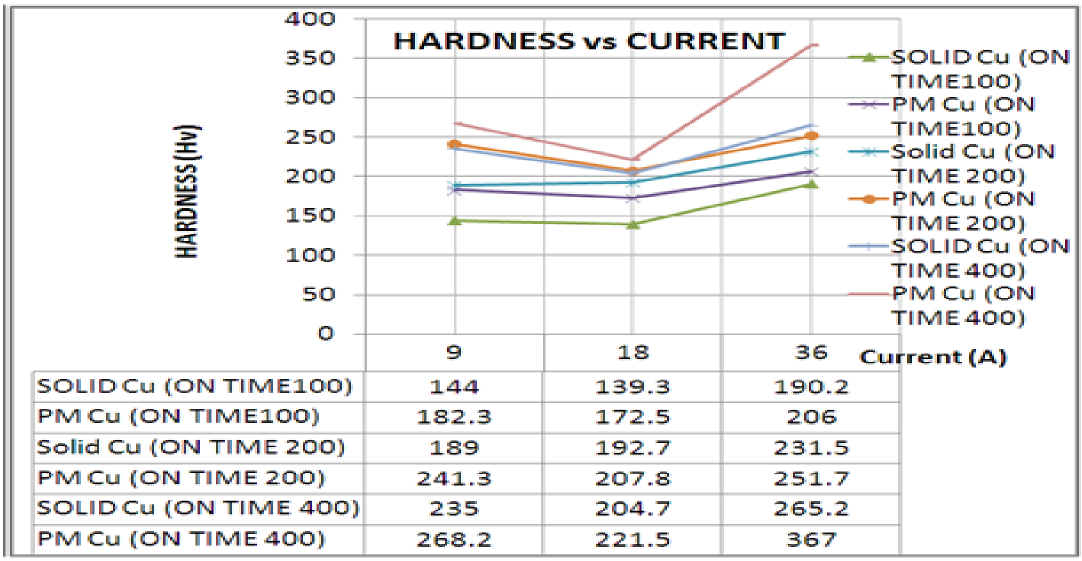



**Figure 4: Hardness (Hv) vs Current for Solid and PM Copper Electrode at different Pulse On-time**

Also, due to higher EWR for PM copper electrode, more copper particles gets transferred on the work piece surface. The PM copper electrode gives higher Hv values as compared to conventional electrode for same set of conditions. Hv value is maximum for PM copper electrode at 36A and 400 μs.

## 3.1 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 Micro-Hardness (Hv) 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 Micro-Hardness (Hv) with PM electrode | | | | | |
|---|---|---|---|---|---|---|
| Parameter | df | SSA | MSSA | F ratio | P value | Remarks |
| Current *(I)* | 2 | 2609 | 1304.5 | 16.6 | 0.057 | Significant |
| OFF-Time $(T_{off})$ | 2 | 15776.8 | 7888.4 | 100.6 | 0.0098 | Significant |
| ON-Time $(T_{on})$ | 2 | 668.7 | 334. 4 | 4.3 | 0.189 | |

| | | | | |
|---|---|---|---|---|
| Residual | 2 | 156.7 | 78.4 | |
| Total | 8 | 19211.3 | | |

### 3.2 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 work piece surface when machined with PM semi sintered electrode. Recast layer can also be seen on the work piece. The electrical discharge machined surface becomes rough due to deposition of debris which were not removed by flushing from the machining gap.

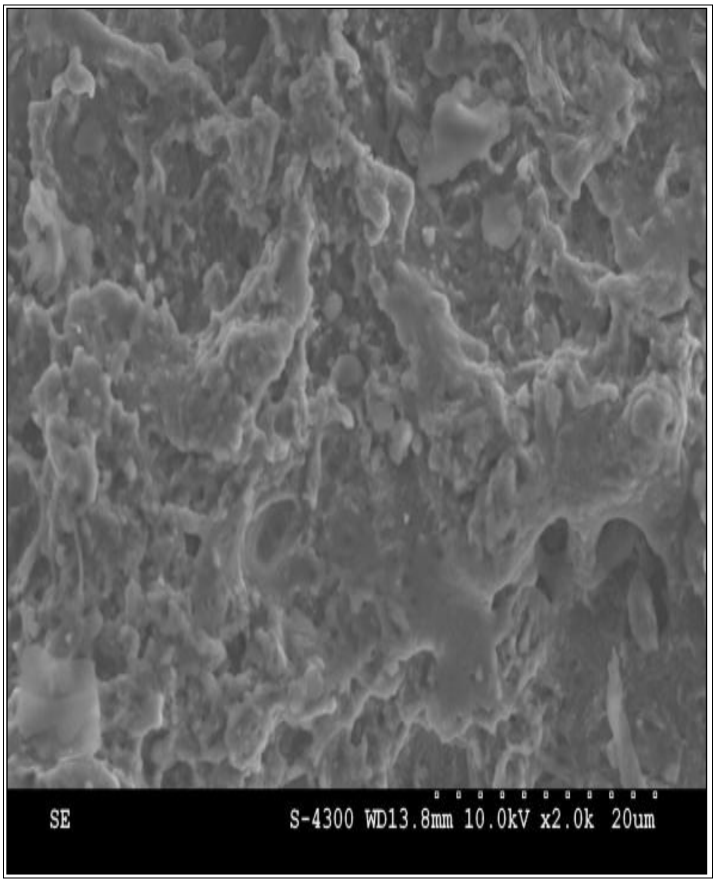



**Figure 5: SEM micrograph at 2000× of Al 6061 machined with solid copper electrode (I 9Amp, pulse on time 100μs)**

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.

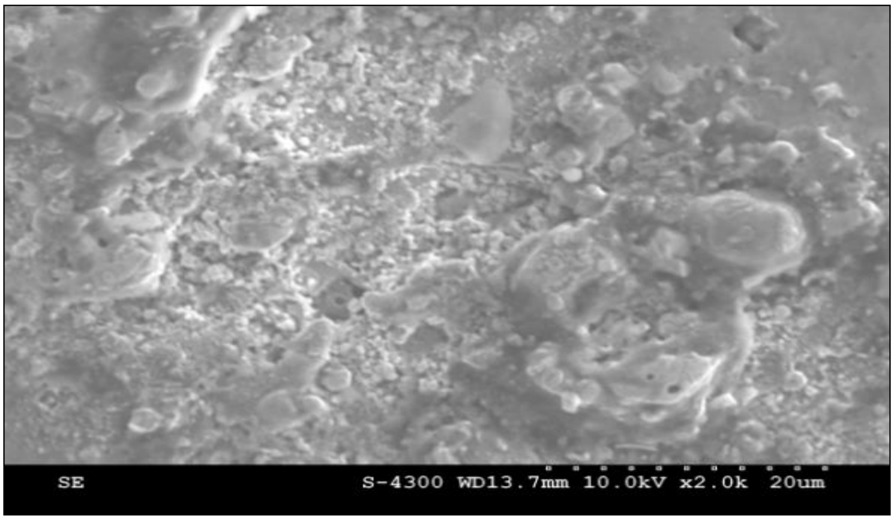
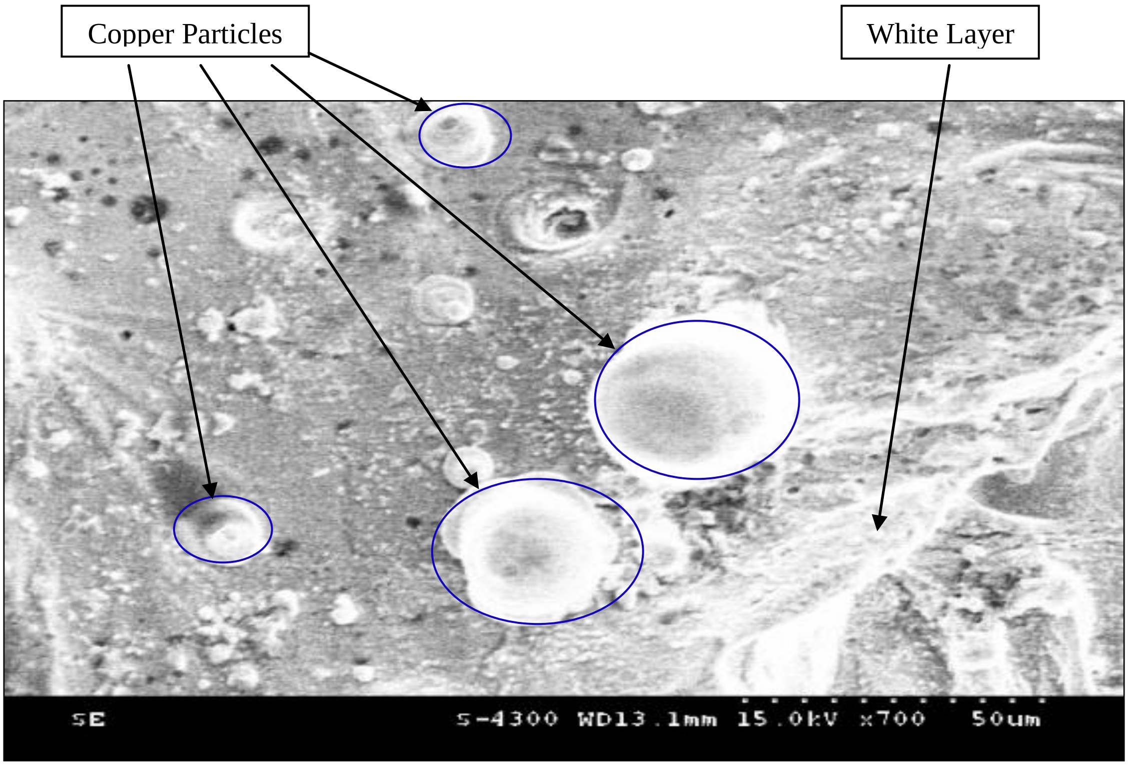



**Figure 6: SEM micrograph at 2000× of Al 6061 machined with green compact copper electrode (I 9Amp, pulse on time 100µs)**

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. White layer with free copper particles is also visible in the micrograph. Micrograph in Figure 7 shows an increase in the presence of copper particles on the work piece surface machined with PM copper electrode which results in increase in micro hardness. Only few copper particles were observed on the work piece surface after machining with conventional copper electrode.



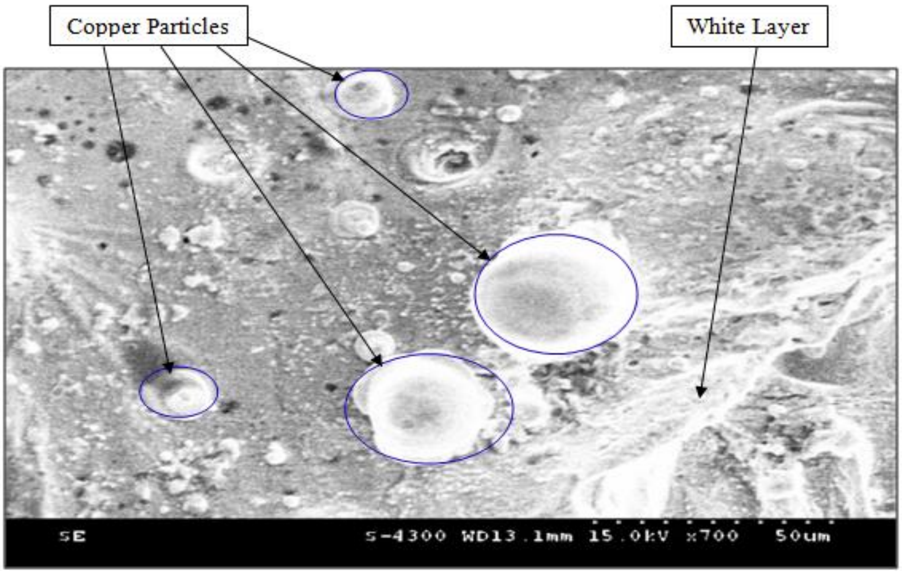



**Figure 7: SEM micrograph at 700× of Al 6061 machined with green compact copper electrode (I 36 Amp, pulse on time 400μs)**

## 3.3 Empirical Model of the Process

The empirical expressions between output parameter (Z) such as Micro-Hardness (Hv) with the input parameters as current *(I)*, ON-time $(T_{ON})$ and OFF-time $(T_{OFF})$ while machining using PM electrode, could be hypothesized as equation 2.

$$Z = a_1 + a_2*I + a_3*I^2 + a_4*T_{ON} + a_5*T^2_{ON} + a_6*T_{OFF} + a_7*T^2_{OFF} + a_8*I*T_{ON}*T_{OFF} \quad ...2$$

where $a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8$ are constants.

*A multiple linear regression model for Micro-hardness is given in equation 3.*

$$\textbf{Micro-hardness (Hv)} = 127.96 - 4.406*I + 1.155*T_{OFF} - 0.188*T_{ON} + 0.133*I\text{^}2 - 0.0015*T_{OFF}\text{^}2 + 0.00032*T_{ON}\text{^}2 - 0.000012*It*T_{OFF}*T_{ON} \quad ...3$$

$R^2$ = 99.78, $R^2$ adj = 98.26, Mean absolute error = 1.76

The $R^2$ value signifies that the regression model developed explicate 99.78% of the unpredictability. The $R^2$ adjusted value is 98.26% and is more appropriate to evaluate models with several independent parameters. Average magnitude of error is 1.76. The model can be simplified by removing ON-time^2 term as its P-value is greater than 0.1.

## IV. CONCLUSION

The present work assesses the machining of Aluminium-6061 with PM copper electrode. Empirical expressions are proposed to simplify the evaluation of Micro-Hardness (Hv) 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. It is found that the machining with PM electrode results in increased micro-hardness in comparison with 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.

5. Empirical expressions have been successfully developed to predict the evaluation of the Hv values.

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