Electrode wear investigation on sinking-electrical discharge machining of Cu-electroplated Al: Discharge current and pulse-on time effect

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Abstract. Sinking-EDM is a non-conventional machine that utilizes electrical energy that is converted to thermal energy which can produce spark on gap between electrode and workpiece with flowed by dielectric fluid. The spark will produce an erosion and then transform to a crater that is effecting electrode and workpiece melt. It will decrease the mass of electrode during EDM machining until cause it worn down. The materials processed on EDM machine are Al and Cu-electroplated Al using CuCr electrodes. Cu-electroplated Al is a materials obtained from aluminium coated by Cu using electroplating in order to increase its electrical conductivity. Experimental method are used to pull up data, the parameter set are discharge current of 4, 7, 10 A and pulse-on time of 50, 75, 100 µs, while the result to be analyzed were electrode wear rate (EWR) and then did a comparison EWR by workpiece material Al and Cu-electroplated Al in accordance set parameter are discharge current with value 7 A and pulse-on time with values 50 µs, 75 µs, 100 µs. An EWR value can be calculated by measuring the electrode weight loss during the EDM process with a digital scale. SEM test is carried out on the electrode that produces the lowest and highest EWR to clarify the phenomenon that occurs, and SEM test equipment are used to access electrode morphology of EWR results. The result showed that the higher the value of the discharge current used EWR would also be increase, while the higher pulse-on time value used EWR were decrease. The highest EWR occurs at parameter discharge current 10 A and pulse-on time 50 µs with a value of 0.478 mm³ min⁻¹, while the lowest EWR occurs at parameter discharge current 4 A and pulse-on time 100 µs with a value of 0.008 mm³ min⁻¹. The highest value in Cu-electroplated Al workpiece material with parameter discharge current 7 A and pulse-on time 50 µs is 0.119 mm³ min⁻¹, while the highest EWR value in Al workpiece material with same cutting parameter is 0.068 mm³ min⁻¹.

Keyword: Sinking-EDM, discharge current, pulse-on time, Cu-electroplated Al, EWR.

1. Introduction
Sinking-electrical discharge machining (EDM) is one of the non-conventional machining techniques for cutting the metal workpiece by utilizing thermal energy obtained from electric sparks in the narrow gap between the electrode and workpiece. Due to its unique features, such as the capability to process any electrically conductive material, independent to its strength and hardness, along with the ability to achieve complex geometry with high dimensional accuracy, this
machining is considered as one of the most competitive non-conventional machining processes and widely used in modern industries (aerospace, automotive, mold, microelectronics, and biomedical industry). The cutting process involves an erosion occurring due to a high frequency electric spark occurred periodically in the narrow gap between workpiece and the electrode in the dielectric fluid. This spark represents discharge energy transformed into high temperature, and absorbed by the workpiece material resulting material melting and evaporation. A portion of melted and evaporated material particle located at workpiece-electrode gap, called debris, is then flushed and removed away by dielectric fluid during pulse-off time [1].

There are many studies regarding EDM application for metals and alloys cutting, but, for soft metal, such as aluminium (Al) is rarely found in literature. Due to its relatively lower strength compared with common ferrous metals, it is sufficiently processed by conventional machining, however, for modern automotive and aerospace industry, this conductive and lightweight material is extensively used for complex and precision parts, in the form of monolithic or composite, therefore, EDM is suitable to meet the geometrical requirements. In his study, Khan compared the machinability between mild steel and Al using brass and copper (Cu) electrode on EDM. The results showed that the MRR and EWR were increased with the use of higher current and voltage. By using similar electrode, the higher MRR was reached at Al compared with that on mild steel cutting [2]. On the other hand, surface finish, geometrical and dimensional accuracy of Al2219, Al7050, and Al7075 using EDM were evaluated by Gatto et al [3]. Similarly, the study of EDM performance on Al6061 cutting was conducted by Imran et al. using graphite electrode under paraffin oil and distilled water as dielectric fluid with pulse-on time and current variation [4].

The electrical conductivity on both electrode and workpiece material becomes one of determining parameters of EDM performance. Several efforts were carried out to improve the machinability of less-conductive materials where some of them is achieved by modification on the workpiece materials. Hanzel et al. have been successfully developed SiC with GNPs and GO conducting filler to enhance its EDM machinability and the results showed the higher MRR was found on the machining of SiC with 15 GNP (most conductive material developed) [5]. In paralel, by adding high content of TiN on zirconia ceramic matrix, both of electrical conductivity and surface quality of the materials was improved under EDM process [6]. These studies indicate that the EDM productivity and product quality can be increased by enhancing the electrical conductivity. Unfortunately, the effect on electrode wear mechanism was seldomly discussed in the existed studies.

In EDM, electrode wear is generated by high generation of spark inducing electrode material melting and vaporization, as similarly occurred on the workpiece material. Due to this wear, the electrode lose its volume inducing dimensional change, therefore, the cavity formed becomes innacurate [7]. This issue leads to the need of additional cost on the machining, thus, the electrode wear should be minimized. Preparing non-commercial electrode with special composition is costly and not always effective. Process parameter modification has been reported to be effective and efficient way to control the electrode wear during EDM. The most determining process parameter on EDM performance, involving electrode wear rate (EWR), were polarity, discharge current, and pulse-on time, as mentioned by Muthuramalingam and Mohan [8]. Kumar and Laxminarayana [9] have examined the effect of discharge current, pulse-on time and pulse-off time on the EDM die sinker process with SS316 material on EWR. The study used copper electrode. The result showed that the variables used affect the EWR value. Prayoga [10] using some parameters process on EDM for surface roughness, MRR and EWR. The conclusion obtained from the study is that the higher value of discharge current will increase the value of EWR. Mohal and Harmesh [11] investigated the coating on Al-SiCP causing an increase in EWR in the EDM machining process.
In the present study, the commercial CuCr electrode wear rate was investigated under discharge current and pulse-on time variation for cutting Cu-electroplated Al alloy material using Sinking EDM. The results were then compared with untreated Al alloy EDM. To observe the electrode surface after EDM process, SEM analysis was conducted at selected samples.

2. Material and methods

The experimental sequence is described as follows and refers to work done by Pradana [12]. Various of discharge current and pulse-on time combinations were applied to investigate the EWR on the Cu-electroplated Al alloy sample. The results of prescribed experiment were then compared with those of untreated Al alloy sample. From the results, the highest and lowest value of EWR were selected and SEM observation was performed to determine the morphological differences on the surface of the electrodes at the lowest and highest EWR.

2.1 Workpiece preparation

Workpiece specimen material used in this research work is Cu-copperplated Al alloy and untreated counterpart. The cylindrical Al specimen was firstly processed by electroplating under the voltage and current of 1.2 V and 0.05 A, respectively, for 15 minutes inside the CuSO₄ solution. The workpiece specimen was prepared with the surface size diameter of 10 mm and the length of 20 mm. The appearance of workpiece specimens were shown in Figure 1.

![Figure 1. Cu-electroplated Al workpiece material](image)

2.2 Electrode material

Cylindrical copper chromium (CuCr) having the density of 9.3 x 10⁻³ g mm⁻³ with the diameter and length of 25.4 mm and 50 mm, respectively, was flattened and polished using centrifugal sand paper machine to ensure the flat surface condition with the similar level of surface roughness in each machining step. The compositions of electrode material (in at.%) are listed in Table 1.

| Element | Cu | Si  | Cr  | Mn  | Fe  |
|---------|----|-----|-----|-----|-----|
| At. %   |    | 13.27 | 0.56 | 0.19 | 0.57 |

2.3 Sinking EDM and analysis

All the machining operations were conducted on C-TEK ZNC 320 EDM under Chevron HONIL0 409 dielectric insulation by using discharge current and pulse-on time. The digital scale instrument OPTIMA OPD-E204 was used to measure the electrode weight difference between before and after machining. Electrode wear rate (EWR) is determined by the calculation electrode mass before and after machining process divide by its density and machining time expressed in mm³ min⁻¹. The formula is shown below.
Where $\Delta w_{el}$ is the lost electrode mass (g), $\rho$ is the specific gravity (g mm$^{-3}$), and $t$ is time used for EDM-sinking process. The machining condition including process parameter were set constatly as listed on Table 2.

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\text{EWR} = \frac{\Delta w_{el}}{\rho \times t}
\]

As shown on Table 2, the experiment was conducted using nine different combinations of current and pulse-on time. The discharge current variations used were 4, 7, and 10 A, while the pulse-on time was varied in range of 50, 75, and 100 $\mu$s. The EDM process was also done on untreated Al specimen with the similar pulse-on time variation but only at the current of 7 A for reference. Subsequently, the comparison of the EWR between Cu-electroplated Al specimen and untreated Al specimen were conducted at similar level of discharge current adjustment to simplify the experiment. At last, to analyze the electrode wear phenomenon intensively, the surface morphology of selected CuCr electrode after EDM process was captured using SEM with the magnification of 2000 times.

3. Results and discussion

3.1 CuCr EWR on the Cu-electroplated Al workpiece EDM

The EWR calculation results were obtained by measuring the electrode mass before and after the EDM sinking machining process first by using a digital scale. The EWR calculation results on the Cu-electroplated Al workpiece EDM are provided in Table 3.

Table 2. EDM parameters set in experiment

| Cutting Parameters       | Value     | Unit   |
|--------------------------|-----------|--------|
| Depth                    | 0.25      | mm     |
| Current (I)              | 4, 7, 10  | A      |
| pulse-on time ($T_{on}$) | 50, 75, 100 | $\mu$s |
| pulse-off time ($T_{off}$)| 4         | $\mu$s |
| Gap voltage (V)          | 40        | V      |
| Jumping distance         | 8         | mm     |
| Work time                | 4         | s      |
| Polarity                 | Electrode + |      |
| High voltage             | 1         | V      |
| Dielectric Fluid         | Chevron HONILO 409 |      |

Table 3. CuCr EWR on the Cu-electroplated Al workpiece EDM

| No | Current (A) | Pulse-on time (µs) | Weight before machining (g) | Machining time (min) | Weight after machining (g) | EWR (mm$^3$ min$^{-1}$) |
|----|-------------|--------------------|-----------------------------|---------------------|---------------------------|------------------------|
| 1  | 4           | 50                 | 93.669                      | 21.55               | 93.662                    | 0.032                  |
| 2  | 4           | 75                 | 91.700                      | 16.25               | 91.696                    | 0.024                  |
| 3  | 4           | 100                | 91.697                      | 16.46               | 91.695                    | 0.008                  |
The result of the EDM sinking are strongly influenced by the process parameter used. Based on Table 3, the different EWR is resulted by EDM with the respective parameter combination, where the higher current applied induced the higher EWR. On the other hand, EWR value shifts to the lower level when the longer period of pulse-on time is used. In overall, the highest EWR was resulted at the combination of 10 A current and 50 \( \mu \)s pulse-on time 0.478 mm\(^3\) min\(^{-1}\). Contrary, the lowest EWR of 0.008 mm\(^3\) min\(^{-1}\) was calculated from the the current and pulse-on time combination of 4 A and 100 \( \mu \)s, respectively. To simplify the discussion, the EWR curves made from discharge currents under different pulse-on time are then shown on Figure 2.

![Figure 2. EWR curves on Cu-electroplated Al workpiece under different current and pulse on-time](image)

From Figure 2, it can be observed that the EWR becomes greater when the higher discharge current was applied during machining in all pulse-on time levels. The increase of EWR was induced by the higher discharge energy generation represented by higher current, irrespective with the other parameter. This phenomenon was also similar with the study reported by Wang et al [13]. The higher current generated higher energy spark which induced larger region undergoing melting, evaporation, and separately solidified by dielectric on both workpiece and electrode. This phenomena resulted a group of particle (debris) located at workpiece-electrode gap then flushed away by dielectric fluid during pulse-off time inducing higher MRR and EWR [1]. Since the increase of MRR (with the more erosion than EWR) by the use of higher discharge energy, the debris composed from eroded conductive metallic particles along with the dielectric decomposition product is also multiplied and submerged at the electrode – workpiece gap. These conductive particles promote the significant impact on the characteristics of hydrocarbon dielectric
breakdown [14], which thermally spall the electrode material and subsequently increase the tool wear amount [15,16]. The results of work done by Pandey, et al. [17] revealed the similar situation that the higher the value of discharge current will accelerate the electrode wear rate because the erosion process will occur faster.

On the other hand, from Figure 2, the pulse on time is also has a significant effect to control the EWR during machining with the inverse relation compared with discharge current. From the figure, the EWR curve is higher than the other when the shorter period of pulse-on time is utilized. This relation may caused by the heat resulted during the machining was removed easily because of the Cu- and Al-based material applied on both electrode and workpiece having higher thermal conductivity. The rapid heat transfer facilitated by highly conductive material inducing a temperature reduction around the CuCr tool surface for a longer pulse-on time resulting less melting and vaporization. On the other hand, the longer pulse-on time can expand the plasma channel due to the presence of high amount of debris at electrode – workpiece gap, thus decreasing the energy density in the machining process [13,14]. Moreover, the more amount of dielectric flushing for each period when shorter pulse-on time is applied.

3.2 EWR comparison between the Cu-electroplated Al workpiece and untreated Al workpiece specimen

Comparison Cu-electroplated Al workpiece and untreated Al workpiece material EWR was taken from the same step in taking EWR on Cu-electroplated Al workpiece material. This data uses a discharge current parameter of 7A and a pulse-on time of 50, 75, 100 µs. The choice of discharge current value of 7A was because it had more stable EWR increment compared to the discharge current value of 4A and 10A with a combination of pulse-on time parameters used. The result of CuCr EWR calculation after untreated Al workpiece machining was listed in Table 4.

| No | Current (A) | Pulse-on time (µs) | Weight before machining (g) | Machining time (min) | Weight after machining (g) | EWR (mm³ min⁻¹) |
|----|-------------|--------------------|------------------------------|----------------------|---------------------------|----------------|
| 1  | 7           | 50                 | 89.944                       | 3.5                  | 89.942                    | 0.068          |
| 2  | 7           | 75                 | 89.942                       | 3.9                  | 89.940                    | 0.030          |
| 3  | 7           | 100                | 90.907                       | 3.49                 | 89.907                    | 0.012          |
Figure 3. Graph of Comparison in EWR on Cu-electroplated Al and untreated Al Workpiece EDM

The comparison of EWR curve between the Cu-electroplated Al workpiece and untreated Al workpiece specimen under discharge current of 7 A is provided on Figure 3. Both specimens show the reduction of EWR using longer pulse-on time period as common phenomena with other discharge current. On the other hand, from the figure, it is also clear that the EWR of Cu-electroplated Al shows a higher value than that of untreated Al workpiece. This trend is different with study done by Khan, where the EWR of Cu electrode was higher at mild steel cutting compared with the Al cutting having higher electrical conductivity, which which causes comparatively more heat energy to dissipate into the electrode during machining of mild steel [2]. However, in this study the Cu-Electroplated Al may induce relatively large amount of debris from Al-Cu separation in their interface, therefore, thermal splatting occurred at high intensity, thus the electrode material melted and evaporated at larger area.

3.3 SEM observation

Figure 5 shows the SEM images of the CuCr electrode after sinking EDM process. The two electrode samples were chosen to analyze on both lowest (I = 4 A and Ton = 100 µs) and highest (I = 10 A and Ton = 50 µs) EWR values where the significant difference can be seen from Figure 5(a) and (b), respectively. These figures show the existence of almost the similar carbonaceous layer formed during the EDM sinking machining process. Furthermore, a crater with relatively smaller dimensions is formed on electrode surface after machining (Figure 5a) compared with those on Figure 5(b). This is due to the discharge current and pulse-on time set at 4 A and 100 µs resulted in the lowest discharge energy which evaporated and thermally spalled only the small amount of electrode material during material removal. As a result, most the melt will freeze again during the cooling process by the dielectric flushing at pulse-off time. On the other hand, the debris that still remained after the dielectric fluid flushing process is still stuck on the surface. Contrary, Figure 5 (b) shows a larger crater dimension resulted by the highest thermal spalling at electrode material during sparking at the current and pulse-on time of 10A and 50 µs, respectively. Formation of craters that are irregular and piled up will produce cavities with micro sizes. Research Lee, et al.
[18] revealed that the higher discharge energy released, the more difficult the electrode wear rate to be controlled.

![SEM images of CuCr Electrodes](https://example.com/sem_images.png)

**Figure 4.** SEM images of CuCr Electrodes at (a) $I = 4\ A$ and $T_{on} = 100\ \mu s$ (b) $I = 10\ A$ and $T_{on} = 50\ \mu s$

Cu-electroplated Al workpiece cutting with 2000 times magnification

4. **Conclusions**

Both of Cu-electroplated and untreated Al workpieces can be successfully machined using EDM and showed different electrode wear rate (EWR) characteristics under different current and pulse on time. The higher discharge current was directly proportional to the CuCr EWR. Contrary, The pulse-on time showed different effect on the CuCr EWR, where the shorter pulse-on time resulted higher EWR. The highest EWR occurred at discharge current and pulse-on time combination 10 A and 50 $\mu s$ of 0.478 mm$^3$ min$^{-1}$ while the lowest one was found at pulse-on time of 100 $\mu s$ and discharge current of 4 A combination with 0.008 mm$^3$ min$^{-1}$. On the other hand, The electrical conductivity of the workpiece material used also affects the EWR value in the sinking EDM machining process. The CuCr EWR on Cu-electroplated Al workpiece cutting is higher than those on untreated Al workpiece cutting. Workpiece material with a coating such as Cu-electroplated Al can be machined using EDM sinking, but the process parameters used must be maintained to produce low discharge energy due to the higher thermal conductivity to avoid excessive EWR.

5. **References**

[1] Markopoulos AP, Papazoglou EL, Svarnias P, Karmiris-Obratanski P, 2020 *Procedia Manufacturing* 41 787–794
[2] Khan AA, 2008 *Int. J. Adv. Manuf. Technol.* 39 482–487
[3] Gatto A, Bassoli E, and Iulia
[4] no L, 2011 *Alum. Alloy. Theory Appl., IntechOpen*, CH17
[5] Imran M, Shah M, Mehmood S, and Arshad R, 2017 *Adv. Sci. Technol. Res. J.* 11, 72–79
[6] Hanzel O, Annebushan M, Marla D, Sedlák R, and Pavol Š, 2019 *Journal of the European Ceramic Society* 39, 2626–2633.
[7] Smirnov A, Seleznev A, Pinargote NWS, Pristinskiy Y, Peretyagin P, and Bartolomé JF, 2019 *Nanomaterials* 1–10.
[8] Khan AA and Mridha S, 2016 *J. Manuf. Sci. Prod.* 7, 1–8.
[9] Muthuramalingam T and Mohan B, 2015 *Arch. Civ. Mech. Eng.* 15, 87–94
[10] Ashok Kumar U, and Laxminarayana P, 2018 *Mater. Today Proc.* 5, 1824–1831
[11] Prayoga BT, 2010 *Forum Tek.* 33, 33–40
[12] Mohal S, and Kumar H, 2017 *Mater. Today Proc.* 4, 3987–3993.
[13] Pradana YRA, Fanani FA, Aminnudin A, Wahono W, and Jang JSC, 2020 Measuring the
influence of process parameter on CuCr electrode tool wear rate for biocompatible Zr-based BMG cutting using sinking-EDM Proceeding of International Conference on Renewable Energy, ICORE 2019 Key Engineering Materials 851 68-75
[14] Wang CC and Yan BH, 2000 J. Mater. Process. Technol. 102, 90–102.
[15] Mohan B, Rajadurai A, and Satyanarayana KG, 2002 J. Mater. Process. Technol. 124, 297–304
[16] Yeo SH, Tan PC, Aligiri E, Tor SB, and Loh NH, 2009 Mater. Manuf. Process. 24, 1242–1248
[17] Khanra AK, Pathak LC, and Godkhindi MM, 2007 J. Mater. Sci. 42, 872–877
[18] Pandey SN, Alam S, and Siddiqui MA, 2015 International Journal of Technical Research and Applications 3, 199–202
[19] Lee CS, Heo EY, Kim JM, Choi IH, and Kim DW, 2015 Robot. Comput. Integr. Manuf. 36, 70–75