The study of surface roughness and material removal rate using electrical discharge machining on copper-electroplated aluminium under discharge current and pulse-on time variation

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Abstract. This paper presents the effect of conductivity and cutting parameters in electrical discharge machining using material Cu-electroplated Al. Among the machining characteristics determined, the material removal rate (MRR) and surface roughness (SR) have been investigated under the influence of two electrical process parameters; namely discharge current and pulse-on time. The results of the study showed that the higher the value of discharge current and pulse-on time enhance both of the MRR and SR. These results were then studied more detail by SEM observation showing the surface morphology of the object after cutting. The MRR results comparison between Cu-electroplated Al and untreated Al specimen proved that the conductivity affects the MRR results, where in general, both of MRR and SR were increased by using Cu-electroplated Al workpiece.

Keywords: EDM, Cu-electroplated Al, discharge current, pulse-on time, material removal rate, surface roughness

1. Introduction
For several decades, electrical discharge machining (EDM) becomes a promising non-conventional machining technique to process conductive materials, independent to their mechanical properties. In this kind machining, the material removal mechanism is achieved through sequential sparking of high density current at the narrow gap between the conductive electrode and the workpiece [1,2]. Kamath and Kuttan [3] observed that metal cutting is a complex process involving many physical phenomena where EDM is capable to machine hard material and can form complex geometries with good surfaces integrity. By this excellence, EDM is often applied to produce molds (and dies) and cut the tool materials. Most of previous studies were conducted to investigate the EDM cutting for high strength metals, such as steels, carbides, and metallic glass [4–6], however, only a few information of EDM cutting on non-ferrous metals provided in literatures.

Non-ferrous metal, such as aluminium is known as easy-to-cut material due to its low mechanical properties. However, it cannot deny the fact that in many fields, such as aerospace,
automotive, and precision machine part manufacturing, the significant level geometrical accuracy and complexity on such materials cutting have to be achieved. These requirements, of course, are difficult to be reach using conventional machining, therefore, EDM can be a solution for this condition. Among the important factors affecting the cutting process quality, surface roughness (SR) and material removal rate (MRR) became the most determining factors to measure both of the cutting quality and productivity, and these often revealed by several EDM studies collected by Muthuramalingam and Mohan [7].

Efforts had been conducted to characterize the surface finish of machined surface by EDM. The influence of dielectric fluids on EDM machined surface were evaluated by Gill and Kumar [4], indicating kerosene utilization as dielectric fluid formed a hardened and carbonaceous layer on the machined surface, while a softened and decarbonized layer appeared when using distilled water. The effect of powder involvement through dielectric toward the machining performance has also been investigated. Yan et al [8] and Mughal et al [9] found that the metal powder addition into the dielectric can control the machined surface properties such as SR, hardness, and wear resistance, as well as the MRR and EWR. The surface modifications using compact pre-treatment electrode in EDM revealed that the electrode elements could be deposited into the machined surface of the workpiece material. Chen et al successfully modified the EDM machined surface by using semi sintered electrode pre-treatment (electrical discharge alloying) resulting in surface layer, hardness, and corrosion resistance improvement on the workpiece surface. Although the surface modifications could be obtained by the EDM, these techniques remain costly due to the complexity preparation. Therefore, selecting and modifying the EDM parameters properly for surface modification through EDM process is a simple and essential issue.

MRR is defined as material loss under specified machining time. This characteristic, beside the EWR and SR, is highly considered on material processing by EDM, moreover for cutting Al to make it comparable with conventional machining in cutting duration. Current and pulse-on time become the determining parameter to characterize the cutting performance of EDM, including MRR [7]. Many studies revealed that the higher current and lower pulse-on time resulted in higher MRR in case of Al alloy [10,11], stainless steel [12], composite [13,14], and metallic glass [6] Machining due to the higher discharge energy and sparking period. On the other hand, the SR showed inverse phenomenon with those occurred on MRR.

The thermal conductivity of the workpiece was reported to play a role in influencing the machining performance. Several efforts were carried out to improve the machinability of less-conductive materials by combining with conductive materials during alloying. SiC with GNPs and GO conducting filler had been developed by Hanzel et al. [15] to improve the machinability by EDM and higher MRR was observed on the machining of SiC with higher content of GNP which put the electrical conductivity at higher level. On the other hand, Smirnov et al [16] explained that both of electrical conductivity and surface quality of the materials was increased under EDM process by adding high content of TiN on zirconia ceramic matrix. These studies indicate that the EDM productivity and product quality can be increased by improving the electrical conductivity and the workpieces with low conductivity will absorb less quantity of heat during machining, which leads to a low MRR. Al is basically classified as conductive metal, however, the MRR still can be enhanced by further increased its conductivity through surface modification. In this study, the role of EDM parameters, in the form of discharge current and pulse-on time were controlled to investigate the MRR and SR of Cu-electroplated Al material. The electroplating was selected as conductivity modification technique of the workpiece material because of its low cost and simple method. The results were then compared to those on untreated Al material.
2. Material and methods

10 mm-diameter and 20 mm-length cylindrical Cu-electroplated Al workpiece was used in this study. The electrode using CuCr material with a diameter of 25.4 mm and length of 50 mm. The material and electrode surface were firstly cut by lathe machine and ensured their surface parallelism by grinding process at similar grade of sand paper. For preparing Cu-Electroplated Al workpiece, the cylindrical Al and Cu was put at cathode and anode and then processed by electroplating in CuSO4 electrolyte under voltage and current of 1.2 V and 0.05 A, respectively, for 15 minutes. Afterwards, machining was carried out using the C-TEK ZNC 320 EDM Machine by varying the output current and the time to turn on. Because of the larger area of the electrode compared to the workpiece, machining is fully targeted in all surface areas of the workpiece. The complete machining conditions were listed in Table 1. Chevron HONILO 409 dielectric was subjected to cutting area by jet-flushing technique during the process.

After machining, the SR of workpiece was evaluated using surface MITUTOYO Surface Roughness Tester SJ 301 Series and the test was taken on 3 different areas of each surface to ensure the result validity. To measure the weight loss before and after machining, digital scale (OPTIMA OPD-E204) was utilized for material removal rate calculation. PHENOM Scanning electron microscopy (SEM) was applied at the magnification of 500 times to further analyze the Cu-layer thickness and surface topography of machined surface at highest and lowest MRR workpieces.

| Workpiece     |                                                                 |
|---------------|-----------------------------------------------------------------|
| Material      | Cu-electroplated Al and untreated Al                             |
| Diameter      | 10 mm                                                           |

| Electrode     |                                                                 |
|---------------|-----------------------------------------------------------------|
| Material      | CuCr                                                            |
| Diameter      | 25.4 mm                                                         |

| Machining parameter |                                                                 |
|---------------------|-----------------------------------------------------------------|
| Polarity            | Electrode +                                                      |
| Depth of cut (mm)   | 1                                                                |
| Gap voltage (V)     | 40                                                              |
| Pulse-off time (µs) | 4                                                                |
| Discharge current (A)| 4,7,10                                                          |
| Pulse-on time (µs)  | 50,75,100                                                       |

| Dielectric |                                                                 |
|------------|-----------------------------------------------------------------|
| Oil        | Chevron Honilo 409                                              |
| Flash point (°C)| 116                                                            |
| Flushing mechanism | Jet flushing                                                   |
| Viscosity (CST)| 5.7                                                            |

3. Results and discussion

3.1. Cu-layer thickness
By using electroplating with voltage and current applied on 1.2 V and 0.05 A immersed in CuSO4 electrolyte for 15 minutes, the Al workpieces were completely covered with Cu layer as shown on Figure 1a. By using 200 times magnification in SEM, the average Cu layer thickness was calculated at 87.58 µm. The appearance of Cu layer is displayed on Figure 1b.
Figure 1. a) Al workpieces after electroplated by Cu, b) SEM image showing Cu-layer thickness

3.2. Surface roughness

Figure 2 explains that when the higher pulse-on time is applied, the SR value increases so that the surface quality of the Cu-electroplated Al material decreases. This is because the electric arc exposure process that occurs during the EDM process longer, the greater the discharge period for melting and evaporation of material, so that the crater produced is getting bigger and deeper. Moreover, the more debris resulted at longer pulse-on time was easily remained at machined surface after dielectric flushing due to the limited pulse-off time. This process results in high SR of the workpiece. Similar results were also shown by Kiyak and Çakır [17] who examined the machinability of AISI P20 material using EDM. The results of their research indicate that the SR of the workpiece was affected by current and pulse-on time. The higher the pulse-on time value used, the greater the SR obtained. This is because pulse-on time is related to the time the electric spark jumps are caused by the flow of electric current before the break-up time. Therefore, increasing pulse-on time causes the frequency of electric spark jumps in the gap between the workpiece and the electrode will increase. The erosion speed will increase so it can cause the SR of the workpiece tend to increase.

In addition, from Figure 2a it can be observed that discharge current is also more influential parameter other than pulse-on time for SR. This is evidenced in the surface change from 3.46 μm to 6.303 μm with the currents of 4 and 10 A applied to the pulse on time of 50 μs. This proves that as the strength of the current increases, the value of SR increases. Thus, the higher the current
applied to the EDM process, the greater the discharge energy applied to the surface of the Cu-electroplated Al material. This process results in the eroded workpiece surface through a process of melting and evaporation getting bigger, resulting in a thick recast layer and high SR [6].

Figure 2. SR curves as the function of different pulse-on time: a) Cu-electroplated Al under current variation, b) comparison between Cu-electroplated Al and untreated Al

Figure 2b explains the comparison of the SR value of Cu-electroplated Al and untreated Al workpiece cutting. This comparison uses a constant current of 7A and a pulse on time of 50, 75, and 100 µs. Materials with coatings obtained SR values of 5.27, 5.58 and 6.22 µm, while SR values for materials without coating were 4.94, 6.19 and 6.16 µm. The result of SR comparison shows that the conductivity of the material affected on the SR of the material. By using more conductive layer on Al substrate, the spark transferred more often and evaporate more area of workpiece, therefore the larger and more crater was formed and overlapped, thus increased the SR.

3.3 Material removal rate
The MRR was explained as the volumetric material loss for certain machining period on both Cu-electroplated and untreated Al workpiece using designed discharge current and pulse-on time combination. The MRR can be calculated using equation 1 [18].

\[
MRR = \frac{(W_{BW} - W_{AW})}{t \times \rho_w} \, (\text{mm}^3 \, \text{min}^{-1})
\]  

Where \(W_{BW}\) and \(W_{AW}\) are workpiece weight before and after machining (g), \(t\) is machining time (min), and \(\rho_w\) is workpiece density (g mm\(^{-3}\)).

Based on Figure 3a, a 50 µs pulse-on time with a current of 4 A results in a MRR value of 3.46 mm\(^3\) min\(^{-1}\). The MRR value increases with increasing currents and pulse-on time. At higher current and pulse-on time combination occurring in 100 µs pulse-on time and 10 A current resulted in the maximum MRR value of 45.26 mm\(^3\) min\(^{-1}\). The figure also shows a tendency for an increase in MRR if the higher current strength is applied with a constant pulse-on time. This happens because the higher the current that is used for the EDM process, the greater the discharge energy used to produce an electric spark between the electrode gap and the workpiece when the workpiece disposal process on the EDM machine is getting bigger [11,19]. This process triggers an increase in high temperatures which can increase the ability to melt and evaporate the material quickly to form the cutting crater, so that the MRR increases. The higher MRR value, the more it can increase the amount of debris generated per unit time, so that the EDM process becomes faster and more efficient in processing time.
Figure 3. MRR curves as the function of different pulse-on time: a) Cu-electroplated Al under current variation, b) comparison between Cu-electroplated Al and untreated Al

On the other hand, the higher MRR was observed along with the use of the higher pulse-on time, although the enhancement is not significant. This phenomenon is clearly different with our previous study, where EDM was applied to cut Zr-based bulk metallic glass [6]. The thermal stability of Al becomes the issue of this MRR improvement, because Al is well known as metal having low melting and boiling point. By using longer sparking period by longer pulse-on time (100 µs), the Cu layer evaporates quickly, afterwards, Al substrate was melted, evaporated, and removed from the workpiece surface at larger amount in the similar time span before it flushed and cooled by dielectric during pulse-off time, compared with other pulse-on time. This is also occurred on the study conducted by Wang and Yan [19].

Figure 4. SEM images of Cu-electroplated Al machined surface at: a) 4 A, 50 µs combination, b) 10 A, 150 µs combination using 500 times magnification

Figure 3b provides the comparison of MRR values of Cu-electroplated Al and untreated Al workpiece cutting. In this comparison using a constant current of 7 A and a pulse on time of 50, 75 and 100 µs. In the material with the coating obtained MRR values of 25.18; 26.73; and 29.83 mm³ min⁻¹, while the MRR values for the untreated Al material were 24.53, 26.11 and 28.51 mm³ min⁻¹.
This result shows that MRR in coating material is higher than material without coating. MRR results occur because of differences in electrical conductivity. The Cu-electroplated Al material increased in conductivity than material without Cu coating. Therefore, Cu-electroplated Al material with higher conductivity values will increase the MRR value in the sinking EDM process.

Figure 4 presents SEM test results on lowest and highest MRR machined surface that have been processed using an EDM machine with 200 times magnification. Figure 4a shows Cu-electroplated Al surface after EDM with a current parameter of 4A and a pulse-on time of 50 µs. Meanwhile, Figure 4b uses the highest combination: current parameter of 9A and a pulse-on time of 100 µs. Figures 4a and 4b have significant differences in debris and crater in case size and amount. Where the crater at highest current and pulse-on time remains higher and severe. This occurred because of differences in the discharge energy of the EDM machining process for the two samples.

4. Conclusion
Based on the results, the conclusions of this study are presented as follows: when the higher current applied in the EDM machining of Cu-electroplated Al material, the material removal rate (MRR) and surface roughness (SR) were increased up to 45.26 mm³ min⁻¹ at the combination of 10 A and 150 µs. On the other hand, the longer pulse-on time used shift the MRR and SR at the higher value. The conductivity improvement on the Cu-electroplated Al material was clearly improved the MRR but also deteriorate the surface quality.

5. References
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