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# Investigation of magnetic field effect on MRR, EWR and surface roughness during EDM of AISI420 tool Steel

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**Abstract.** Electrical discharge machine (EDM) is a machining process that is not affected by the toughness or hardness of the sample material but the electrical and thermal conductivity. In EDM process, good surface quality can only be produced if low peak current is used but the machining process will take a long time causing material removal rate (MRR) to be too low. While the accumulated machine debris in the machining zone can cause abnormal discharge and disrupt the material removal process. The present research aims to study the magnetic field effect on MRR, EWR and SR for EDM process improvement. In addition to MRR, electrode wear rate (EWR) and surface roughness illustrate the effectiveness of the EDM process. The installation of magnetic devices in the EDM machining area were implemented and the experiments were conducted using graphite electrode and AISI420 as the workpiece. Permanent magnets having 0.54 Tesla were applied to produce magnetic fields during EDM operations. The presence of this magnetic field also contributes to the effectiveness of the flushing process because the evaporated debris will be attracted and attached to the magnet, then purify the spark gap medium for the next discharge process. Dielectric that stays clean and sparks under magnetic field influence increases the effectiveness of the material removal process. Surface roughness from Ra measurement has recorded 12.6% to 28.1% improvement when magnetic devices were applied on EDM. The spark ignition delays and the refinement of EDM spark enhanced the surface quality compared to conventional EDM. Comparison of images through optical microscopy and SEM also proves that the Magnetic Field Assisted EDM (MFAEDM) method is capable of producing better surface quality. This MFAEDM shows that action to hybridize EDM is necessary to increase EDM competency by attaining both of machining efficiency and high quality of surface integrity.

## 1. Introduction

Several EDM hybrid techniques have been introduced to improve EDM machining performance. Those include dielectric-powder based EDM, dry EDM, ultrasonic vibration-assisted EDM and magnetic field-assisted EDM (MFAEDM) where the main purpose is to solve EDM limitations. EDM material removal performance depends on the combination of electrode and machining parameters as these factors will determine the material removal rate, the electrode wear rate and the surface roughness. This study to present the performance of MFAEDM compared to conventional EDM of AISI420 tool steel using graphite electrode. Report by Ming, et al. [1] and Khan, et al. [2] suggest that MFAEDM is suitable for machining of ferromagnetic and non-ferromagnetic materials because of its advantages such as easy application, facilitating flushing system, economically competence and environmentally friendly. In this investigation, constant magnetic field was proposed and applied perpendicularly to the discharge channel. The use of magnetic fields in EDM machining was introduced to facilitate the



removal of machined iron dust from machining areas. Perfect flushing circulation provides an excellent medium for the spark process and there is no delay in spark processing. The findings from Shabgard, et al. [3], Gholipoor, et al. [4], Singh Bains, et al. [5] show the use of magnetic fields can improve spark gaps cleaning because ferromagnetic material is extracted and sticks to the magnetic material rapidly.

Material removal process occurs when there is a spark which is caused by different potential of voltage on the electrode and sample material. Spark discharge begins with the formation of an ionization channel on the spark gap and it increases until there is a spark eruption [6]. The experiment used peak current ( $I_p$ ) and pulse time ( $t_{on}$ ) as the main machining parameters to study its effect on MRR, EWR and surface roughness (SR). Apart from the selected parameters, the MRR, EWR and SR are also subjected to the type of electrode used. The results from Haron, et al. [7], Lin, et al. [8] and Pavan and Sateesh [9] show that the MRR is higher and the EWR is lower with copper electrode than graphite electrode. However, graphite is increasingly becoming the material of choice as an electrode especially for roughing process [10]. The EWR is enhanced in the case of magnetic MFAEDM because effective ionisation improves discharge progression so the machining process can be completed in shorter time. The relationship of peak current and the surface roughness is evident as they are directly proportional to each other until it reaches the machining limit where the specimen surface burns out. Surface roughness increases with rising pulse time but once it reaches its maximum value, surface roughness decreases with increasing pulse duration. When pulse duration is too long, energy density in the discharge area decreases. Therefore, surface roughness tends to decrease with longer pulse duration [11]. Another important topic to review on MFAEDM output is micro-crack and white layer. The layers from EDM machining are composed of recast layer, heat-affected zone and base metal. The severely affected layers are formed on recast layer surface from rapid heating and cooling effects caused by the discharge process based on peak current values and pulse time duration [12].

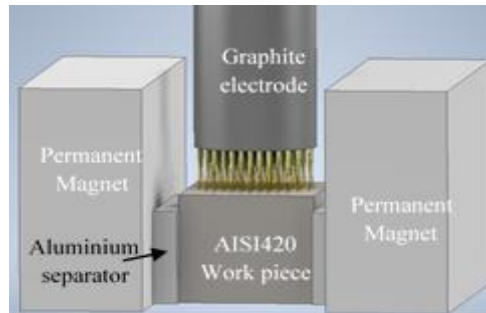
## 2. Method and materials

The experimental arrangement was developed using electrode graphite as EDM tool, too steel AISI 420 as material specimen and kerosene as dielectric which will also act as insulation to avoid shortening between tool and workpiece. The electrodes used are cylindrical in size  $\text{Ø}25 \times 40$  mm mounted on the tool holder for EDM machining depth of 2mm cut. Table 1 shows the properties of graphite electrodes where electrical conductivity and thermal conductivity play an important role for the machining and value rate of the tool. The workpiece sample used is from the AISI 420 tool steel family, commercially it is better known as Stavax ESR which is widely used in mold making industry. This raw material has been milled into cube-shaped specimens in dimensions of  $30 \times 30 \times 30$  mm. Specimens have the composition of the mass elements Fe - 84.32%, C - 0.38%, Si - 0.9%, V - 0.3%, Cr - 13.6% and Mn - 0.5% [13][Pavan, 2020 #221]. The first part of the experiment was performed under the normal range labeled as conventional EDM. As for MFAEDM a set of permanent magnets with a combined magnetic flux density of 0.54 T was applied on the Charmilles Roboform EDM machine. The magnetic bar is clamped side by side with the AISI 420 sample interspersed by a 5 mm aluminum spacer. This is to avoid the sample being directly magnetized by the magnetic bar mounted close to it. An illustration of the schematic diagram of the study is shown in Figure 1. While the details of the experiment parameters were summarized in Table 2.

**Table 1.** Properties of graphite electrode.

| Physical properties                              | Graphite |
|--|----------|
| Electrical conductivity compared with silver (%) | 0.11     |
| Thermal conductivity (W/mK)                      | 160      |
| Melting point (°C)                               | 455      |

|  |                       |
|--|-----------------------|
| Specific heat (J/kgK)                          | 0.17-0.2              |
| Specific gravity at 20 °C (g/cm <sup>3</sup> ) | 1.75                  |
| Coefficient of thermal expansion (1/°C)        | 7.8 x10 <sup>-6</sup> |



**Figure 1.** Schematic diagram of MFAEDM.

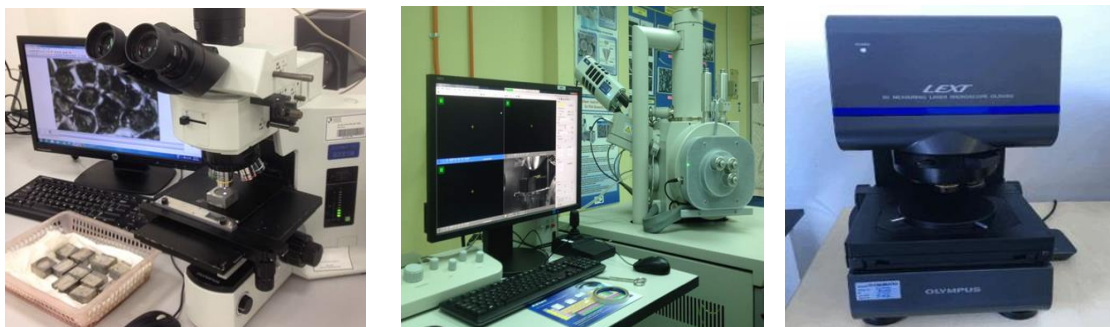
**Table 2.** Experiment parameters set up.

| Working conditions        | Descriptions                     |
|---------------------------|----------------------------------|
| Work piece (mm)           | AISI 420 Stavax ESR)<br>30×30×15 |
| Electrode (mm)            | Graphite Ø25×40                  |
| Dielectric fluid          | Kerosene                         |
| Depth of cut (mm)         | 2                                |
| Magnetic flux density (T) | 0 - 18                           |
| Peak current (A)          | 8 - 24                           |
| Pulse duration ( $\mu$ s) | 50 - 100                         |

Machining outputs from both conventional EDM and MFAEDM were evaluated and compared by electrode wear rate, EWR (g/min), material removal rate, MRR (g/min) and surface roughness,  $R_a$  ( $\mu$ m). Material removal rate (MRR) value for this study was calculated by using a formula shown in equation 1.

$$\text{MRR} = \frac{\text{Mass of Material Removed from Part}}{\text{Time of Machining}} \quad (\text{g/min}) \quad (1)$$

Surface roughness measurements are used to assess the surface quality of the machine surface. Once the experiments were completed, sample surface roughness was measured by using surface roughness measuring device (SURFPAK) SJ-301 which is stylus type surface roughness measuring system that has diverse high-precision function feature for ease of operation. Figure 2 shows the visualization equipment of (a) optical microscope, (b) scanning electron microscope (SEM) and (c) 3D profilometry were used to make comparisons of sample surface topography after EDM machining.



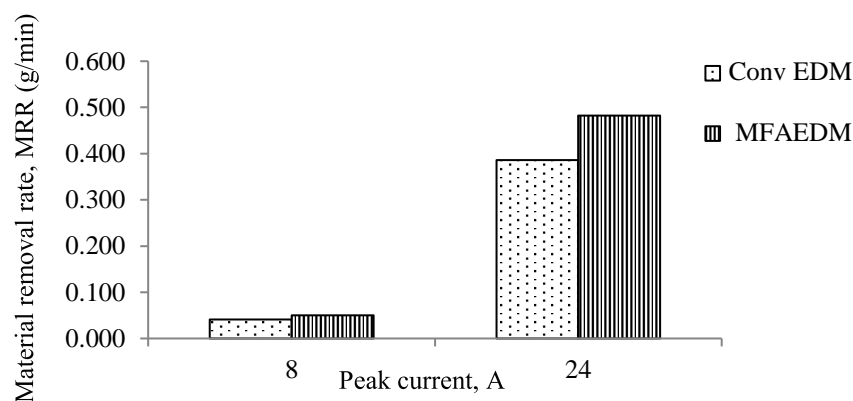
**Figure 2.** (a) Optical microscope, (b) scanning electron microscope and (c) 3D profilometry

### 3. Results and discussion

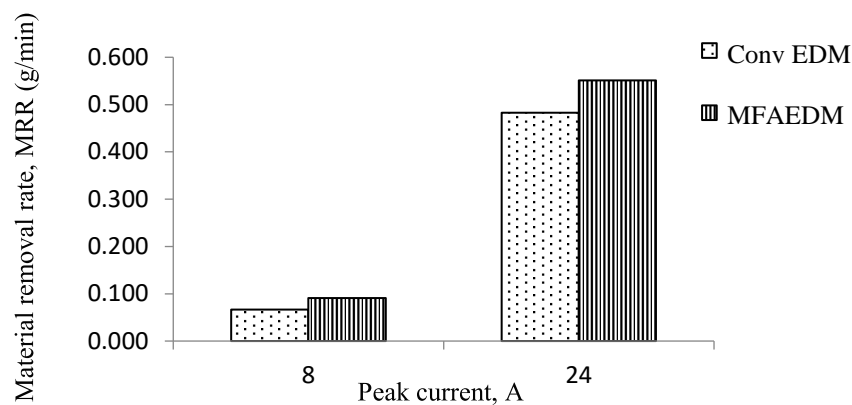
During EDM material removal process, a continuous cycle of discharge sparks was created through electrode towards workpiece to erode work material. Theoretically, when EDM is in discharge progression, melting and vaporisation course in the machining area does not only remove the work piece materials but also erodes the electrode materials. Experiment outcomes such as material removal rate (MRR), electrode wear rate (EWR) and surface roughness (SR) were obtained so that responses from conventional EDM and magnetic field-assisted EDM were compared. In this experiment, mass of electrode and work piece material were weighed accordingly for further reflexion. First, MRR between conventional and MFAEDM are compared.

#### 3.1. MRRF

Material removal rate (MRR) figures were gained by calculating sample mass difference before EDM and after EDM machining against machining time. Throughout the investigation, data record shows that machining time reduced when peak current increased. Experiments by some researchers such as Pavan and Sateesh [9], Bains, et al. [12], Qudeiri, et al. [14] and [15] also show the role of peak current in accelerating the machining period while increasing the value of MRR. The data also shows that machining time decreased even lower when MFAEDM was applied. When machining time was thoroughly reduced, MRR increased. MRR for EDM experiments elevated when peak currents were increased from 8 A (0.041 g/min) to 24 A (0.386 g/min) for conventional EDM and 8 A (0.042 g/min) to 24 A (0.454 g/min) for MFAEDM as illustrated in Figure 3. Similar result trend was discovered when the experiments were repeated with higher pulse time value. It is evident in Figure 4 which illustrates MRR comparison between normal and MFAEDM with higher pulse time at 100  $\mu$ s. Machining improvement can be clearly visualized in both Figure 3 and Figure 4; whereby higher MRR values were recorded for MFAEDM compared to conventional EDM. For example, at peak current of 24 A and 100  $\mu$ s pulse time MFAEDM recorded MRR 0.551 g/min compared to 0.483 g/min for conventional EDM.



**Figure 3.** Comparison of MRR between conventional EDM and MFA EDM at 50  $\mu$ s.



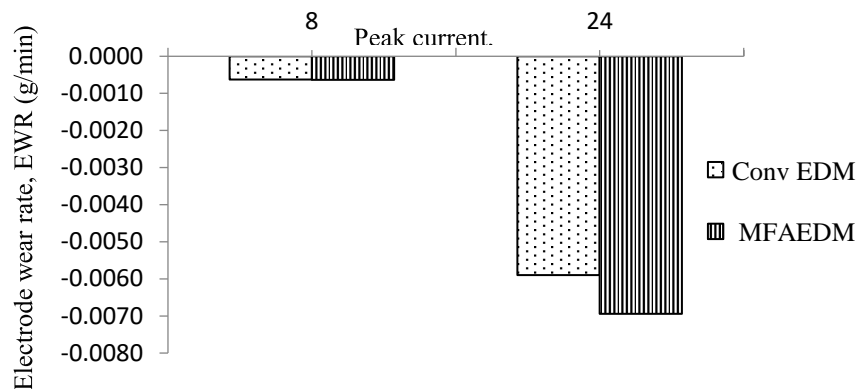
**Figure 4.** Effect of MRR between conventional EDM and MFA EDM at 100  $\mu$ s pulse time.

The increment of MRR value produced because higher current led to superior spark and bigger implosion on sample surface [14]. The charts also reveal that MRR improved when magnetic field was applied in EDM machining area. Gap condition stability improved when magnets were attached in the EDM machining area by absorbing most debris particles from the spark gap. Hence, it improves sparking cycle which contributes for better EDM machining performance. The resulting magnetic field at the MFAEDM synchronizes any electron and any rotating ion releasing from the core atom to increase the ion concentration thereby increasing the ionization process [3, 12]. The increases in ion density and plasma pressure has improvised the plasma channel to spark down and melt the material more effectively.

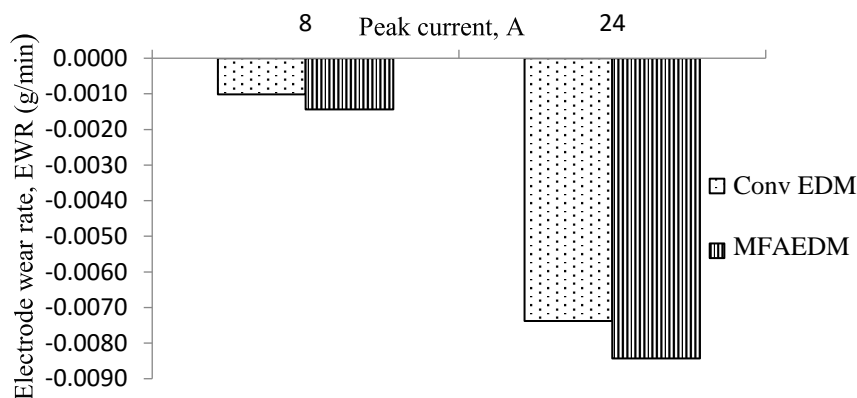
### 3.2. EWR

There is an inter-relationship between the volume of electrode wear and machining time in EDM known as electrode wear rate (EWR). As EDM cycle increases the temperature; the electrode starts to wear [16]. EWR results from EDM process mostly rely on machining parameters such as peak current, pulse time and machining time factors. Besides MRR, EWR is considered as a good tool to measure machining efficiency and to indicate cost-effective process. From the experiments performed, data obtained was calculated to determine EWR of graphite electrode for conventional EDM and MFAEDM comparison.

Figure 5 illustrates the comparison graph of EWR for conventional EDM and MFAEDM at 50  $\mu$ s. The recorded EWR for graphite electrode was in negative values for both conventional EDM and MFAEDM. The electrode wear rate for conventional EDM was -0.0006 g/min with peak current at  $I_p$ , 8 A; whereas EWR value was -0.0058 g/min with peak current at 24 A. Supposedly, high peak current yields high EWR because high electric field strength energy causes greater electrode wear rate [16]. However, it was the opposite with graphite electrode; whereby, as peak current increased EWR value decreased correspondingly. This negative value trend in EWR of graphite has arisen due to a combination of peak current and thermal pyrolysis of carbon layers formation onto graphite electrode surface [17]. Thus the mass of the electrode after machining is higher than before machining causing the result of the EWR calculation to be negative value. Figure 6 shows similar EWR investigation but the experiment was conducted at higher pulse time (100  $\mu$ s). On the other hand, EWR value was lower for MFAEDM. In MFAEDM, EWR recorded at 24 A (100  $\mu$ s) was -0.0084 g/min which differs as much as 0.0009 g/min compared to conventional EDM (-0.0075 g/min).



**Figure 5.** Comparison graph of EWR for conventional EDM and MFAEDM at 50  $\mu$ s.



**Figure 6.** Comparison graph of EWR for conventional EDM and MFAEDM at 100  $\mu$ s.

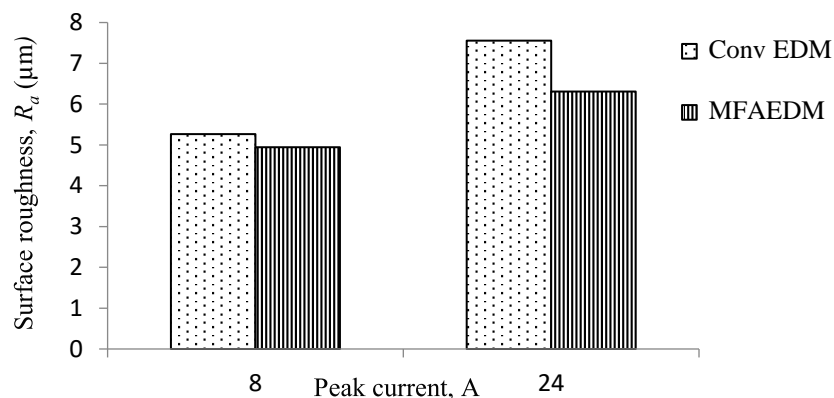
### 3.3. Surface roughness

Surface roughness measurement normally represents surface finish texture state and aesthetic appearance value. EDM machining parameters such as peak current and pulse-on time have prominent effect on sample's surface roughness. Peak current is the parameter that determines spark length and spark explosion magnitudes. Pulse time, which is time exposure ( $t_{on}$ ) to spark and time for dielectric re-ionization ( $t_{off}$ ), also corresponds to surface integrity in EDM [5, 18]. Due to the significant characteristic, analysis of sample surface roughness were carried out for conventional EDM and MFA EDM.

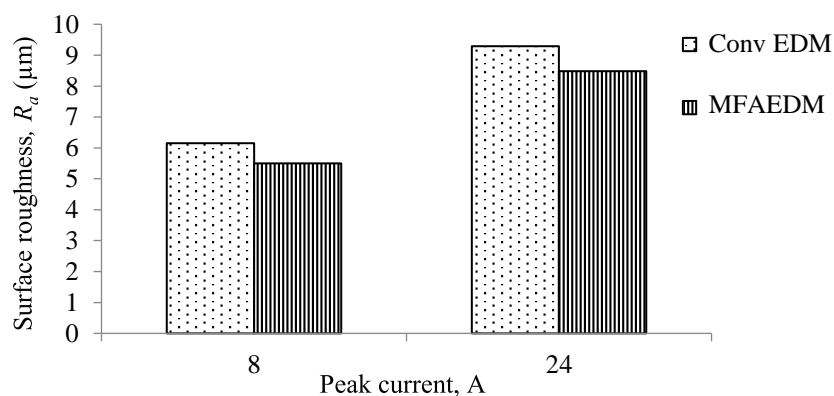
Figure 7 and Figure 8 show comparison graphs of surface roughness between conventional EDM and MFAEDM at different peak currents at 50 $\mu$ s and 100 $\mu$ s, respectively. From both charts,  $R_a$  values increased when higher peak current applied. At higher current, spark intensity increased and higher heat energy created at the gap; hence, producing more micro-features on sample surface. This spark state created craters in the sample which in turn determined surface finish. In the case of conventional EDM at 100  $\mu$ s, surface roughness value ( $R_a$ ) increased from 6.152  $\mu$ m to 9.294  $\mu$ m for peak current of 8 A and 24 A respectively. The lower  $R_a$  number represents a small surface roughness. When higher peak current applied, the crater is larger and deeper; as a result, the surface finish is coarse. Meanwhile, if low peak current employed; the craters are small and surface finish is better.

As shown in the both graphs, there is a significant effect of magnetic fields in EDM machining. At the presence of magnetic field,  $R_a$  is lower than the value obtained by conventional EDM. At peak

current of 8A (50  $\mu$ s), the difference of  $R_a$  value between conventional EDM (5.437  $\mu$ m) and MFAEDM (4.751  $\mu$ m) was 12.6%. Followed by peak current of 24A (50  $\mu$ s),  $R_a$  difference value between conventional EDM (7.583  $\mu$ m) and MFAEDM (5.456  $\mu$ m) was 28.1%. The sparks produced by the influence of the magnetic field are of better quality due to the higher plasma pressure as well as the squeezing effect of the magnetic field flux so that the discharge crater produced on the surface of the machine is small and shallow. Surface roughness obtained by MFAEDM was lower than conventional EDM which was not only at low current but also at higher current practice. Therefore, modification of the magnetic tool on the EDM gives a smoother surface finish.



**Figure 7.** Surface roughness comparison of conventional EDM and MFAEDM at 50  $\mu$ s.



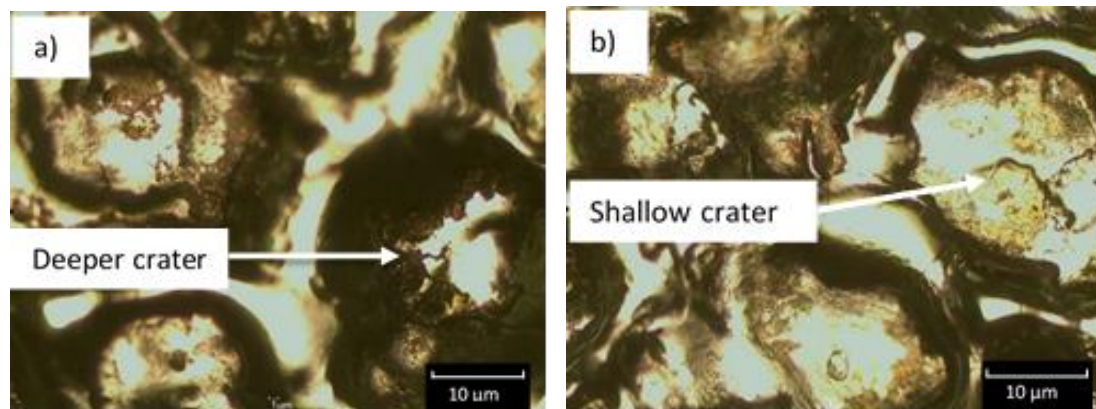
**Figure 8.** Surface roughness comparison of conventional EDM and MFAEDM at 100  $\mu$ s.

### 3.4. Surface topography

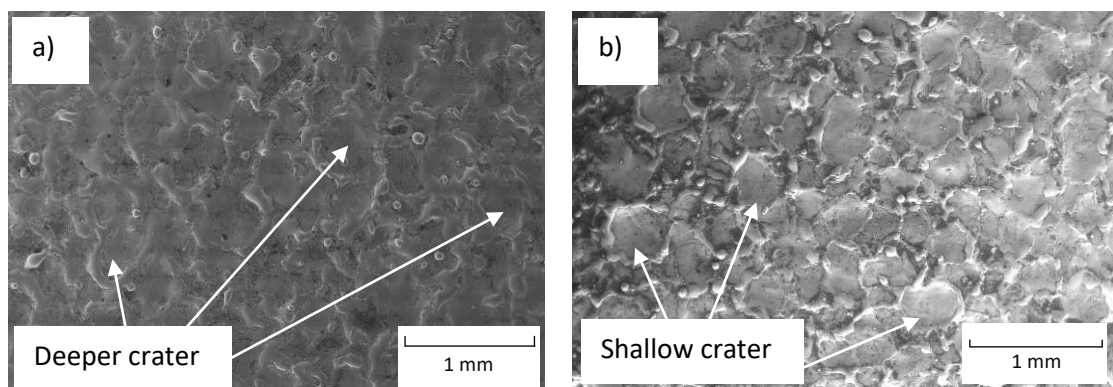
Surface topography comparison for conventional EDM and MFAEDM by optical microscope can be observed in Figure 9 where the depth of the spark crater produced by conventional EDM (Figure 9(a)) was deeper than that of MFAEDM whose crater was shallower and wider (Figure 9(b)). While Figure 10 shows the comparison of the both surfaces via SEM images, whereby the bumpier feature and deeper valley attributes can be observed for conventional EDM in Figure 10(a) compared to MFAEDM which has superior surface integrity as witnessed in Figure 10(b). The texture of EDM sample surface is caused by the amount of heat generated by the discharge process which involves melting and vaporisation of sample material followed by rapid cooling [5]. The surfaces were blasted by discharge spark and the crater produced reflects



the pattern caused by the spark. Under conventional EDM machining condition, beside the irregular topography the surface shows high amount of tiny loose metal particles which were initially melted due to spark discharges compared to MFAEDM. These small melted metals were unable to be thoroughly washed in dielectric fluid without magnetic field assistance. As a result, metal debris immediately solidified and formed many tiny particles on the machined surface.

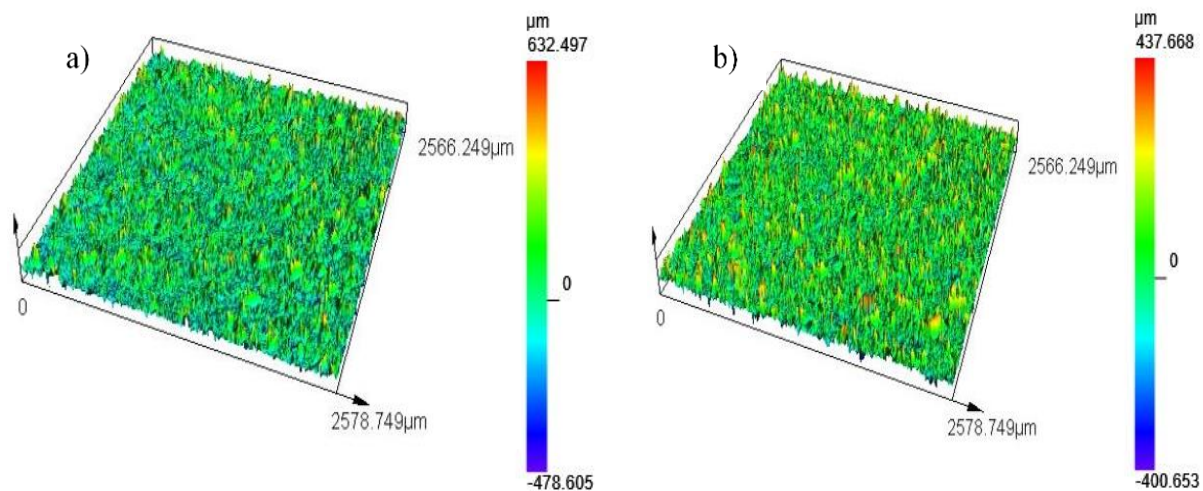


**Figure 9.** Surface topography of (a) conventional EDM and (b) MFAEDM via optical microscope at 24 A, 100  $\mu$ s.



**Figure 10.** Surface topography of (a) conventional EDM and (b) MFAEDM via SEM: 100 $\times$  (24 A, 100  $\mu$ s).

It was evident that MFAEDM had a higher quality surface appearance than conventional EDM as the samples were further examined through 3D profilometry as illustrated in Figure 11. The illustration shows the gap between peak and valley for conventional EDM was 1,111.102  $\mu$ m which is higher than MFAEDM (838.321  $\mu$ m). Anyhow these observation of crater surfaces verified that application of MFAEDM has significant improvement on EDM machined surface. It was observed that surface finish quality mostly depended on pulse current and pulse time selection. The combination of discharge spark strength, magnetic field pattern and formation of recast layer influence the surface roughness state [5]. From those observation of microscope, SEM and 3D profilometry evidenced that the crater shape produced by MFAEDM were horizontally smoother because pressure from magnetic fields pattern refined the discharge spark quality by concentrating ionization process in the plasma channel.



**Figure 11.** Surface 3D profilometric of (a) conventional EDM and (b) MFAEDM at  $5\times$  for 24 A, 100  $\mu\text{s}$ .

#### 4. Conclusion

From this research, MFAEDM clearly provides better MRR and surface quality but in terms of electrode wear rate it is quite difficult to determine which method gives better effect because there is pyrolytic carbon formed on the electrode. This phenomenon occurs when a graphite electrode is used. Surface topography shows that higher peak currents result in poor surface finish as shown by the deeper, wider and irregular shape of the crater. The SEM observations of the micro structure confirm that the craters produced in MFAEDM are less bumpy and shallower than conventional EDM. While 3D profilometry measurement shows that thicker restructuring layer was found in normal EDM surface, while in MFAEDM a thinner restructuring layer is formed. Therefore, the use of MFAEDM is an option for better machining efficiency in terms of MRR, surface roughness as well as EDM machine care because the debris attracted to the magnetic device instead of circulated into the dielectric filter.

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