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ORIGINAL ARTICLE

An experimental investigation into the micro-electro-discharge machining behaviour of aluminium alloy (AA 2024)

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Abstract Aluminium (*Al*) alloys are extensively used in all areas of manufacturing including automotive and aerospace industries due to its lightweight, excellent machinability, good surface finish at high cutting speed, low cutting forces and outstanding tool life. Although *Al* alloys have excellent machinability with conventional machining processes, electric discharge machining (EDM) and micro-EDM are often used to machine intricate features in *Al* alloys for plastic injection moulds and electronic applications. Present study aims to investigate the influence of various operating parameters on the micro-EDM behaviour of an important *Al* alloy AA 2024, commonly known as 'Duralumin'. The machining behaviour has been investigated by engraving micro grooves on the surface of the AA 2024 using different parameters settings from a resistance-capacitor (RC) type pulse generator. The operating parameters studied were capacitance, resistance, supply voltage, electrode rotational speed and gap control parameters. The micro-EDM machinability of the AA 2024 alloy was evaluated in terms of the material removal rate (MRR), tool wear ratio (TWR), surface roughness (SR) and machining depth of the micro grooves. It has been found that the increase of capacitance and voltage results in increase of discharge energy, causing higher MRR at the expense of higher tool wear and rougher machined surface. On the other hand, too low capacitance and gap voltage result in unstable machining by creating arcing and short-circuiting, which again makes the surface defective in addition to reducing the machining speed. The careful selection of gap control parameters improves the machining stability by reducing the arcing and short-circuiting as well as improves the overall machining performance. For stable micro-EDM with higher machining speed and improved surface finish, the identification of optimum parameters is needed. With this said, the recommended settings of parameters for micro-EDM of AA 2024 were found to be the voltage of 160 V, capacitance of 10,000 pF and resistance of 470 Ω, spindle speed of 720 rpm, gap feed rate of 0.01 mm/s, gap control factor of 50 and gap threshold voltage of 80 %.

Keywords Micro-EDM · Aluminium alloy · AA 2024 · Duralumin · Operating parameters · Machining characteristics · Material removal rate · Surface finish

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1 Introduction

In recent years, there is an increasing demand for lightweight materials from various industry sectors. Lower density, higher strength-to-weight ratio and better mechanical properties of the products are the major requirements from the industry perspective. Among the lightweight materials, aluminium (*Al*) and its alloys is becoming the potential candidate for aerospace and automotive industries, as well as for other areas of transportation and structural designs. Oxides and sulfates of *Al* are the most functional compounds since they can provide lower weights [1]. Low cost and better machinability have made *Al* alloys more popular in automotive and aerospace industries [2]. The aluminium alloy AA 2024, formerly known as 'Duralumin', is commonly used in aircraft structures, rivets, hardware, truck wheels, screw machine products and other structural applications [3].

Electric discharge machining (EDM) is a promising technology that can be used to perform accurate machining of any electrically conductive materials including *Al* and its alloys. EDM is a non-conventional machining process where the material is removed by the heat generated during the repetitive electric discharge. The discharge occurs between the electrode and the work piece with the presence of dielectric liquid. As a result of the heat production in each discharge, materials are removed in the form of tiny craters and the molten craters are flushed away from the machined zone by the dielectric liquid. Various studies have been conducted on the machining performances during the conventional EDM of *Al* and its alloys. Khan [4] studied the effect of major parameters during the EDM process. The main purpose of Khan's research was to obtain a maximum material removal rate (MRR) with minimal electrode wear (EW) during the EDM of aluminium [4]. Gatto et al. [5] investigated the optimization of machining parameters for EDM and HSM (high speed machining) of *Al* alloy for mould production. They reported that higher thermal conductivity of *Al* causes comparatively higher energy waste into workpiece than the electrode, which results in lower tool wear [5]. Kathiresan and Sornakumar [6] conducted EDM studies on 'Aluminum alloy-Silicon Carbide' composite and reported that increasing the discharge current could increase the material removal. Similar findings were reported by Arooz et al. [7] in their study, where they investigated the effect of current during the EDM of 'Aluminium 6061-T6'. They reported that the increased spark discharge energy helps in melting and vaporisation process and promotes the large pulse force in the spark gap, which makes the machining process faster by increasing MRR [7]. Kumar and Mohit [8] had also realised during their research that the current has more influence on higher MRR than pulse time and voltage. The MRR was found to increase non-linearly with increase in current for constant gap voltage and pulse on time [8]. The MRR also increased with increase of pulse duration as reported in the same study [8]. Nanimina et al. [9, 10] investigated the effect of EDM parameters during the machining of 'Aluminum Metal Matrix Composite (AMMC)'. Guleryuz et al. [11] also investigated the influence of EDM process parameters on the surface roughness of 'Aluminium Matrix Composites Reinforced with SiC Particulates'. Chose et al. [12] reported that the peak current has considerable effect on the material removal rate (MRR), tool wear rate (TWR) and surface roughness (SR) during EDM of Al_2O_3/6061Al workpiece. They also urged that due to the demand of increased productivity and improved performance in machining, the MRR should be high while the TWR is kept low [12]. The low TWR can reduce the time of altering the tool as well as decreases the cost of tool [12]. Ahamed et al. [13] studied the EDM behaviour of hybrid Al–SiCp–B4Cp and Al–SiCp–Glass metal matrix composites.

In addition to MRR and TWR, the surface finish and surface modification are important research questions during the EDM and micro-EDM. In contrary to steels, the base material in aluminium is harder than the heat effected layer and is not susceptible to cracking. In order to obtain hard layers with increasing corrosion resistance, specific electrodes and fluids were employed during the surface modification of aluminium by EDM [5]. The researchers also focused on improving the machining accuracy during the EDM of aluminium by minimising the electrode wear and improving the surface morphology [5, 10, 11].

In order to analyse the EDM process and for solving the complex interrelationships between process parameters and performance measures, researchers used the Taguchi's approach, grey relational analysis (GRA) and other mathematical models and optimization techniques. Chose et al. [12] used Taguchi's approach to conclude that electrical parameters have more significant effect on EDM characteristics, such as MRR, TWR and SR, compared to the non-electrical parameters. Lin et al. [14] presented optimization of the EDM process for machining of aluminium alloy based on the orthogonal array with fuzzy logic and grey relational analysis. Taguchi's approach was also used to optimise the accuracy of the high speed EDM process [15]. Moreover, Kamguem et al. [16] used response surface methodology and desirability functions to investigate surface finish and metallic particle emission during EDM of aluminium alloys.

In addition to the above mentioned research works in conventional EDM, several research works have been conducted on the micro-EDM of aluminium alloys. Rosochowski et al. [17] investigated the machinability of ultra fine grain (UFG) aluminium using micro-EDM. Hu et al. [18] conducted a similar study to investigate the machinability of silicon carbide particle reinforced aluminium matrix composite (SiCp/Al) using the micro-EDM process. The study claimed that the use of appropriate parameters and reasonable processing methods could improve machining performance during the micro-EDM of SiCp/Al. Modica et al. [19] used the micro-EDM milling process to fabricate micro features in 'Aluminium – Magnesium' alloy.

Although many researchers have investigated the feasibility of machining of various types of aluminium alloys using macro-scale EDM process, very few research have been reported on the micro-EDM of aluminium alloys. Micro-EDM can be used for machining complex shapes and features for plastic injection moulds made of aluminium alloys. Micro-EDM can produce micro-holes, micro-channels and other thin-walled micro-features in aluminium without burrs. In addition, micro-EDM can be used for machining very high-aspect-ratio micro tools that are difficult to machine using conventional micro-turning process due to breakage of tool owing to cutting forces. However, the effect of various operating parameters on the micro-EDM performance during machining aluminium alloys is not well understood. Moreover, most of the studies have been conducted using transistor-type pulse generator, which is suitable for conventional EDM at macro scale. There are very few studies on the EDM or micro-EDM of *Al* alloys using RC-type pulse generator. In addition, no study has reported the importance and effect of gap control parameters, which have significant influence in the machining stability during the micro-EDM process. There are differences in the parameters, working principle and the amount of discharge energy produced in transistor and RC-type pulse generator. It is easier to control the performance of a RC-type pulse generator by controlling comparatively fewer parameters. This study presents a detail experimental investigation into the micro-EDM machinability of an important aluminium alloy AA 2024, commonly known as 'Duralumin'. The micro-EDM performance of the AA 2024 alloy was evaluated in terms of MRR, TWR, SR and machining depth. The effects of various electrical and gap control parameters from a RC-type pulse generator on the machining performance parameters were also investigated.

2 Experimental details

2.1 Machine tool

A desktop machine tool was used for the micro-EDM of AA 2024. The basic set-up of the machine consists of the mechanical body, a drive and control system, a measurement system, optional units for different micromachining technique, dielectric system and a PC to input command program into the control system. Figure 1a shows the schematic view of the multi-purpose miniature machine tool.

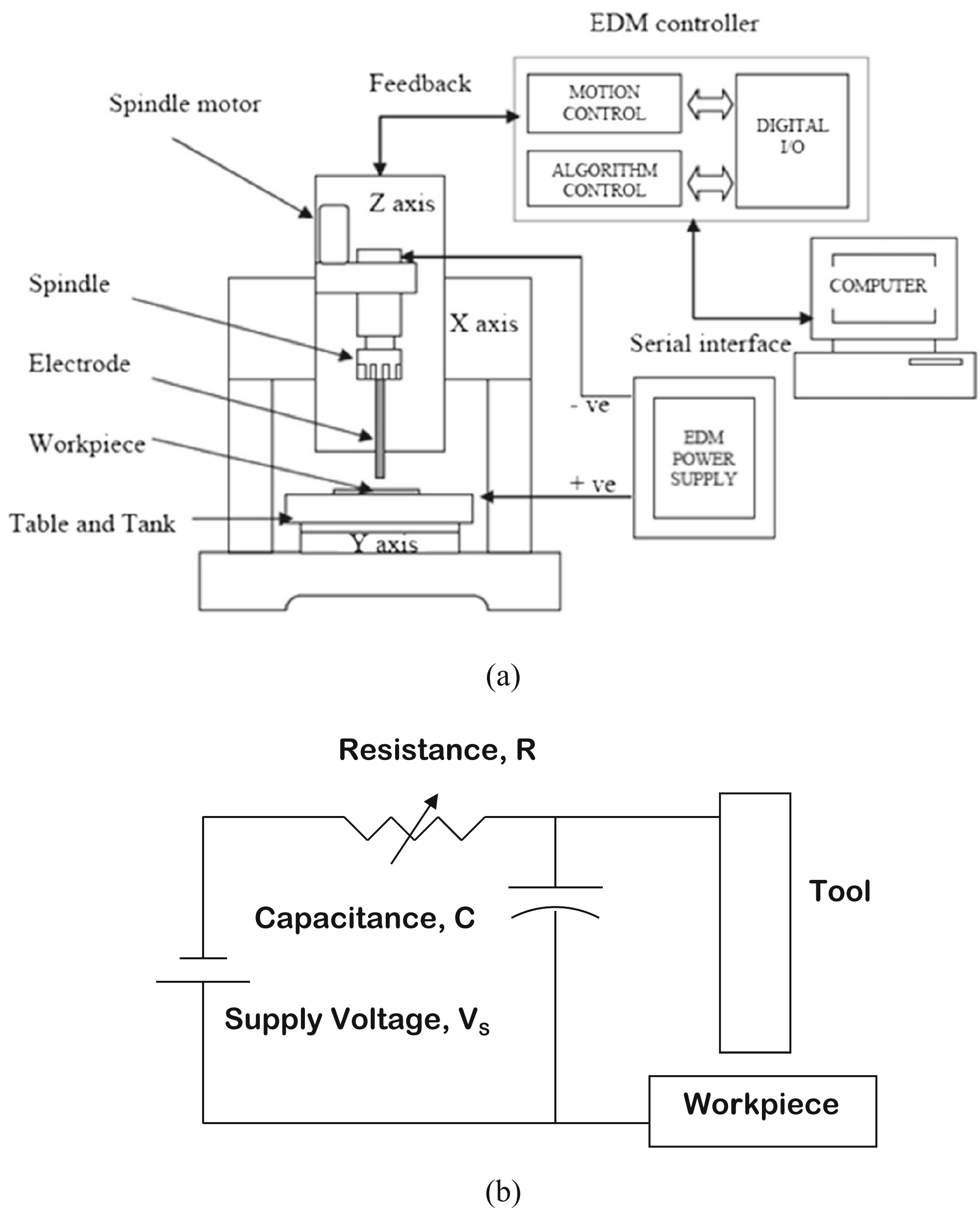

Fig. 1 **a** Schematic representation of the micro-EDM machine tool, **b** RC circuit for supplying discharge energy for machining

The mechanical body is composed of *X*-, *Y*- and *Z*-axes with a changeable spindle (*C*-axis). The system employs a 4-axis controller with 0.1 μm of stepping resolution in *X*-, *Y*- and *Z*-axis and 0.045° of rotary resolution in *C*-axis. Its travel range is 200, 110 and 110 mm in *X*-, *Y*- and *Z*-axis, respectively. The drive and control system and measurement system are housed within a main control box. Basically, the control system manages the operation that the operator has input through the PC. The dielectric system maintains the dielectric level in the work tank by constantly emptying (debris filled dielectric) and pumping (debris removed dielectric) into the tank. The dielectric system is paramount to the micro-EDM process as it removes excessive debris that builds up during the machining process. The PC component of the set-up allows the operator to dynamically input commands to the controller such that the micro-EDM process may be programmed and executed. An RC-circuit has been used as pulse generator for supplying discharge energy for machining. The simple schematic diagram of a typical RC-circuit is shown in Fig. 1b.

2.2 Materials

The workpiece material used in this study was an aluminium alloy with a composition of 93.5 % Al, 4.4 % Cu, 1.5 % Mg and 0.6 % Mn (Duralumin/AA 2024). The tool electrode material used was the tungsten electrode (99 % W). The tungsten electrode was used for its high melting point and high wear resistance, which help in reducing the migration of materials from electrode. The specifications of the workpiece and electrode materials are listed in Table 1. Deionized (DI) water was used as dielectric material.

2.3 Experimental procedure

In this study, the micro-electric discharge machining behaviour of AA 2024 has been investigated by engraving micro grooves on the surface. As shown in Fig. 2, the targeted slot length L=2 mm, machined depth=0.04 mm or 40 μ and width of slot=0.2 mm. To engrave the groove, the machine tool moves in X–Y plane at a given constant speed while the *Z*-axis position is controlled to maintain the spark gap as demonstrated in Fig. 2 [20]. To maintain continuous spark in between the electrode and workpiece, the speed of the *Z*-axis is controlled based on the following equation [20]:

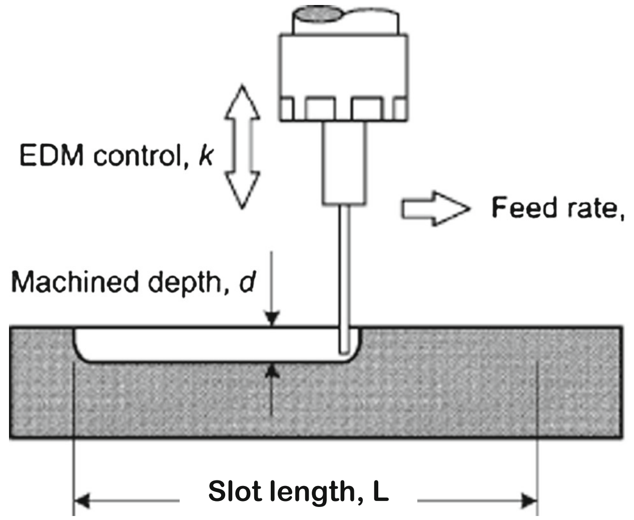

Fig. 2 Schematic diagram showing the process of engraving grooves or machining slots by micro-EDM process [20]

$$F_Z = k\,\mathrm{sgn}\left[V_{gap} - V_{th}\right] \quad (1)$$

Where F_Z is the *Z*-axis feed rate, V_{gap} is the gap voltage between the electrode and workpiece, V_{th} is the threshold value for the gap control and *k* is a control parameter that determines the speed of the micro-EDM gap control.

In this study, to understand the micro-EDM characteristics of AA 2024, the effect of operating parameters on the machining characteristics was investigated. The operating parameters varied were capacitance, resistance, supply voltage, spindle speed, gap control factor, gap feed rate and gap threshold voltage. The corresponding output parameters studied were MRR, TWR, mean machined depth and SR. The machining conditions for the micro-EDM of AA 2024 are listed in Table 2.

The MRR is the volume of the material removed per unit time. However, due to the irregular shape of the slots, the volumes were not easy to calculate using normal mathematical formulas. Therefore, the volume was measured using the surface profiler machine (Form Talysurf), where the general profile of the workpiece was first determined and after that the computer software (Talymap Universal 2.0) used the finite element method to calculate the volume of the slot. An example of the data obtained from the surface profiler is shown in Fig. 3a. The red region in the diagram represents the shallow region (top surface of the work piece), and the black region is the deepest region of the slot.

Table 1 Properties of the workpiece and electrode materials

Material	Workpiece AA 2024	Electrode Tungsten
Composition (%)	4.4 % Cu 1.5 % Mg 0.6 % Mn 93.5 % Al	99.9 % W
Diameter (mm)	N.A	0.2
Density (g/cm^3)	2.7	19.3
Melting Point (°C)	658	3370
Specific resistance (μ/Ω/mm)	27.4–27.8	56.5

Table 2 List of machining parameters for micro-EDM of AA 2024

Parameters (Unit)	Settings
Capacitance (pF)	470, 1000, 4700, 10,000
Resistance (Ω)	220, 470, 1000, 4700
Supply voltage (V)	140, 160, 180, 200
Gap threshold voltage (% of supply voltage)	20, 40, 60, 80
Spindle/tool rotational speed (rpm)	180, 360, 720, 1440
Gap feed rate (mm/s)	0.005, 0.01, 0.02
Gap control factor, k	10, 50, 100

The MRR is given by the equation:

$$MRR = \frac{\text{Volume measured by the surface profiler}}{\text{Time taken for the EDM process}} \quad (2)$$

The mean depth of the slot is a measurement of the average depth of the slot and it may be seen as a representation of the effectiveness of the process. Mean depth was measured using the surface profiler as shown in Fig. 3a.

The SR of the slot essentially reflects the surface finish of the machined surface. The SR of the slot was measured using the optical multisensor, and results were evaluated by the '*Kmess*' software as shown in Fig. 3b. The software tries to fit one side of the slot such that it lies between two lines. After that, the outline of the slot is plotted using 100 points. From the plotted points, the maximum peak-to-valley value was determined and reflected as the SR of the slot.

It was a challenge to measure the values of surface roughness parameters inside the micro slot using the traditional surface roughness profilometer for several reasons. First of all, the profile of the micro slot machined in this study was hemispherical shaped due to corner tool wear. Secondly, the slot was only 200 μ wide. It was difficult to position the tip of the roughness profilometer inside 200-μ-wide slot. On the other hand, the Mahr optical multisensor allowed taking an optical image of the slot as well as calculating the maximum peak-to-valley distance from 100 points along any selected straight line.

The tool wear ratio (TWR) is defined as the volume of metal lost from the tool divided by the volume of metal removed from the work piece. High tool wear ratio results in

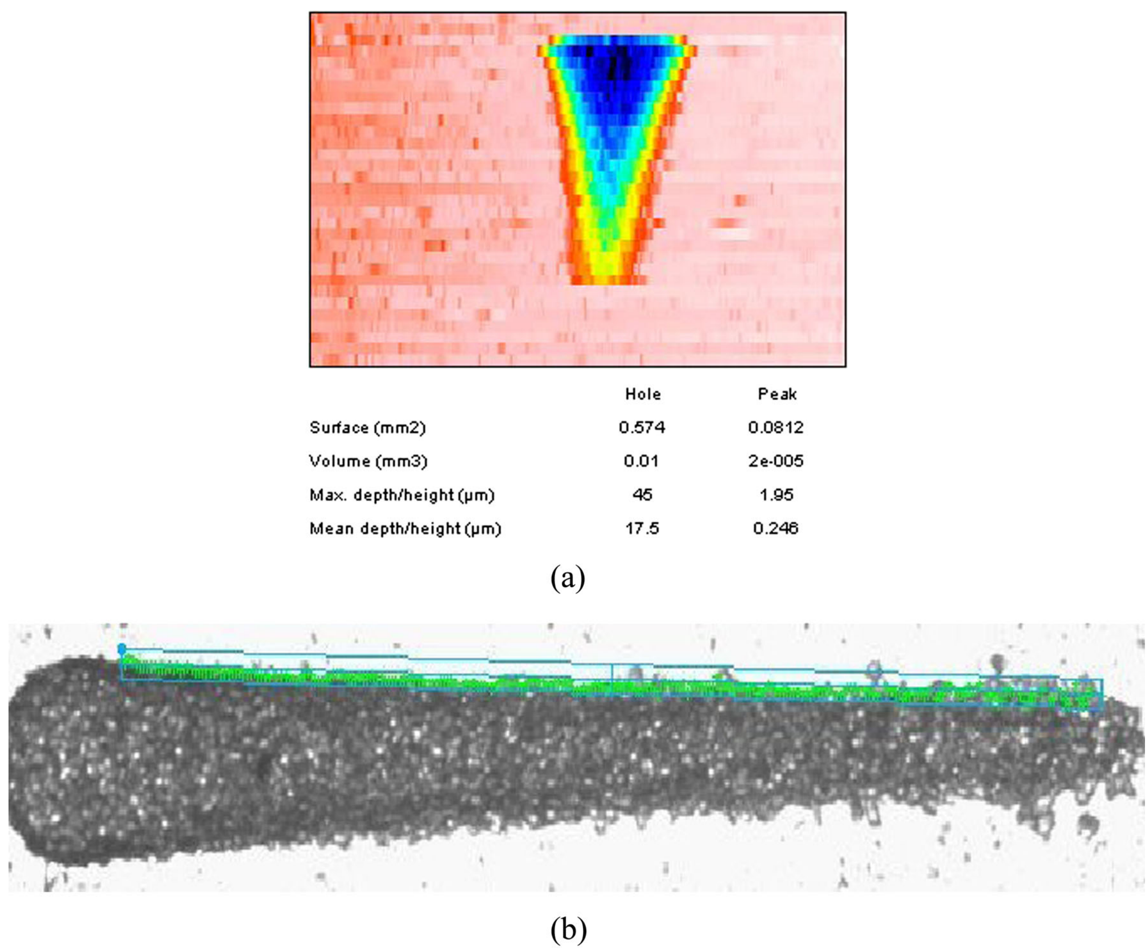

Fig. 3 **a** Measurement of volume of material removed from the machined slot and mean depth of the slot by Talysurf profiler, (**b**) Measurement of surface roughness by Mahr optical multi-sensor

inaccurate machining and increases manufacturing cost of the product. TWR was calculated using the following equation:

$$TWR = \frac{\text{Volume of tool wear}}{\text{Volume of material removed from workpiece}} \quad (3)$$

The volumetric tool wear given by $= \frac{\pi D^2 T}{4}$, where T is the frontal electrode wear and D is the tool diameter.

In this study, the corner wear of the tool was not considered for calculating the volume of tool wear and hence TWR. The corner wear of the tool was not considered for few reasons. First of all, a single tool was used for machining several slots. After machining each slot, the worn out length of the tool was measured in situ by touching the tool before and after machining. After that, the tool was dressed by reversing the polarity, to remove the corner wear of the tool and to make it flat before machining next slot. All those steps were done in situ without taking out the tool electrode. Secondly, in order to consider the corner wear, we probably have to take out the tool after machining each slot and measure the corner wear or the profile of the tool. As we conducted many experiments for this study, it would make the process very slow. In addition, more frequent changing of tool electrode could induce handling error due to bending of the tools.

3 Results and discussion

3.1 Effect of capacitance

The resistance and capacitance are the two integral parts of the RC circuit pulse generator. In this study, the effect of capacitance has been studied at different settings of resistance and vice versa. The values of capacitance were varied for four different settings: 470, 1000, 4700 and 10,000 pF. It was found that the MRR increased with increasing capacitance as shown in Fig. 4a. The reason being that with higher capacitance the energy per pulse is also larger. The craters formed were dependent on the energy of the spark and thus larger craters were formed at higher values capacitance resulting in poorer surface finish. However, it was observed that at very low capacitance the edge of the slots was jagged which also made the surface finish of the slot inferior as can be seen from Fig. 5. This contradiction is due to the fact that at very low capacitance, the time constant of the charging circuit decreases and eventually leads to continuous arcing, which then results in poor surface finish [21]. It can be observed from Fig. 4b that the TWR decreased with capacitance. Although the spark energy increases with the capacitance, the machining instability caused by arcing and short circuiting at lower settings of capacitance plays a dominating role in increasing the TWR. At very low capacitance, the effect of arcing becomes dominant, which leads to poor machining conditions and thus increases wear rate of the electrode. This phenomenon was found to become even worse at lower settings of resistances. It can be seen from Fig. 5a that the slot was shorter when 470 pF capacitance was used at 220Ω due to significantly higher tool wear. The TWR was lowest when the value of capacitance was 10,000 pF. The mean depth of the machined slot was found to increase with capacitance, as the discharge energy increased as can be seen in Fig. 4c. Since the mean depth is related to the MRR, with increasing MRR the depths of the slots also increase.

One important observation from Fig. 4 is that, except for 220Ω resistance, the effect of capacitance on MRR, TWR, mean depth, and SR was followed uniform trend. The inconsistency in the trend at lower settings of resistance is due to the higher peak current at lower resistance. For some instances, at lower resistance settings, there were occurrences of arcing, which resulted in unstable machining and inconsistent performance, as shown in Fig. 5b. From the results gathered, capacitance at 10,000 pF was found to give the best machining performance by providing much higher MRR, higher machining depth and moderately lower SR and TWR.

3.2 Effect of resistance

The effect of resistance at different settings of capacitance can be understood from the Fig. 4. Four different settings of resistances, 220, 470, 1000 and 4700 Ω, were used in this study to investigate the effect of resistance. It was found that for all settings of capacitances, the MRR and surface roughness increased with decreasing resistance. The MRR was found to be almost inversely proportional to the values of resistance settings as seen from Fig. 4a. The SR was found to increase as the sparking frequency increased at lower resistance due to lower time constant. Since the dielectric fluid cannot deionise quickly enough at lower time constant, continuous arcing occurs, which leads to a higher SR and poor surface finish [22]. In addition, with the decrease of resistance, the values of peak current increase, which result in removal of coarser debris. Due to large size debris, the MRR increases as well as surface becomes rougher. It was observed that the mean depth increased with the decrease of resistance. As the mean depth is dependent on the MRR, it is obvious that the mean depth will also increase with the decrease of resistance. With the decrease of resistance, the peak current increases, which results in an increase of discharge energy helping to remove more materials and increase the depth of the machined slot.

In case of TWR, there was slight reduction in TWR with the decrease of resistance at higher settings of capacitance. On the other hand, there was a significant reduction of TWR with the decrease of resistance at lower settings of capacitance like

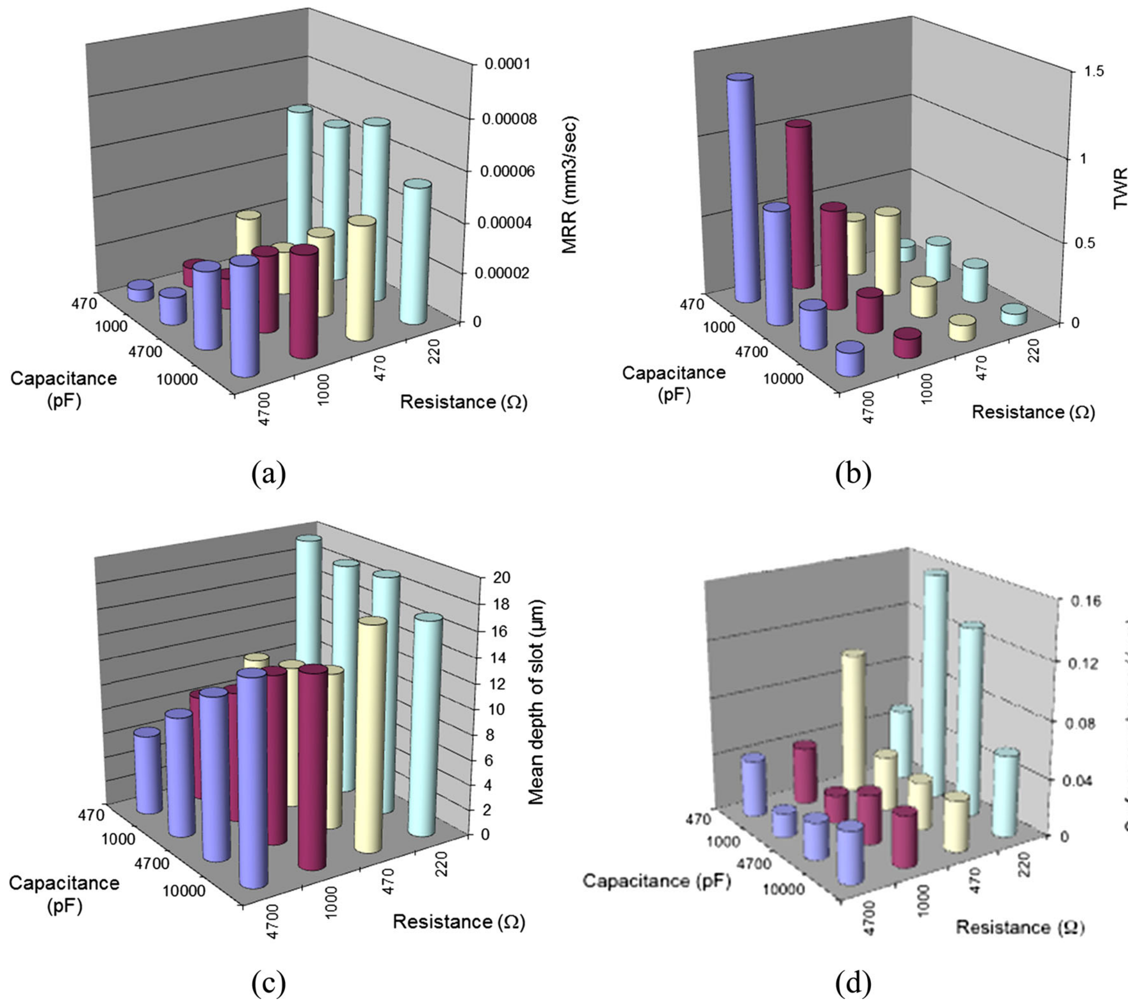

Fig. 4 Variation of **a** MRR, **b** TWR, **c** mean depth of slot and **d** surface roughness of slot with the variation of capacitance and resistance during micro-EDM of aluminium alloy AA 2024 (Fixed parameters; supply voltage=160 V, spindle speed=720 rpm, threshold voltage=80 %, feed rate=0.01 mm/s)

470 and 1000 pF. This is due to the reason that at both the lower settings of capacitance and higher settings of resistance, the machining time is much higher and also the discharge energy is lower. The longer machining time causes more material removal from the workpiece compared to tool electrode, whereas the lower discharge energy also results in less material removal from the workpiece, thus finally resulting in lower values of TWR. From the results obtained, a resistance value of 470 Ω was found to be most suitable as it offered a relatively higher MRR, lower TWR and lower SR. Figure 5c shows the machined slot when a resistance of 470 Ω was applied at optimum capacitance.

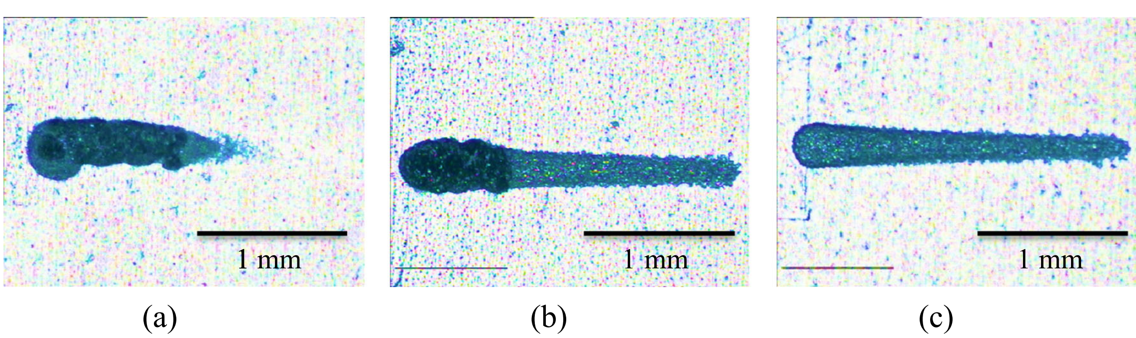

Fig. 5 Comparison of quality of micro slots machined at different settings of capacitance and resistance; **a** capacitance of 470 pF and resistance of 220 Ω, **b** capacitance of 470 pF and resistance of 470 Ω, **c** capacitance of 10,000 pF and resistance of 470 Ω (Fixed parameters; supply voltage=160 V, spindle speed=720 rpm, threshold voltage=80 %, feed rate=0.01 mm/s)

3.3 Effect of supply voltage

The effect of supply voltage at different tool rotational speed is shown in Fig. 6. In general, the MRR increases with increasing supply voltage, as increasing the supply voltage also increase the spark energy per pulse. At higher supply voltage, the resultant electric field is also higher. Therefore, the crater removes in a single pulse is broader, which results in higher MRR. However, it was observed that there was no uniform trend of tool electrode wear ratio with the increase of supply voltage, as can be seen in Fig. 6b. It was found that with the increase of supply voltage the TWR decreased first up to moderate range of voltage, after that became higher again at very high voltage setting. This is due to the fact that higher voltage can lead to unfavourable concentrated discharge because of insufficient cooling of the electrode. As a result, the TWR could increase beyond an optimum value, which in this case is about 180 V, as can be seen from Fig. 6b.

In case of mean depth of the machined slot, a gradual increase in mean depth was observed with increased supply voltage, as can be seen in Fig. 6c. This is due to the higher MRR at higher voltage. The SR, which is dependent on the spark energy, also increased as bigger craters were formed when voltage was higher, as shown in Fig. 6d. The ideal value of supply voltage for optimum micro-EDM performance was found to be about 180 V.

3.4 Effect of spindle speed

The effect of spindle speed can also be understood from Fig. 6. When the electrode is rotated, the tool wear becomes more uniform at the tip. The rotation creates a flow current in the dielectric, which facilitates the removal of the debris formed. As can be seen in Fig. 6a, the values of MRR were found to remain the same around 5×10^{-5} mm^3/s except for spindle speed of 1440 rpm, when the MRR dropped. Although rotation aids in the removal of debris, when the electrode is rotating too fast it may actually affect the machining stability due to too much turbulence created around the machining zone. The TWR and the SR were found to increase with increased spindle speed, as shown in Fig. 6b and d. The value of 180 rpm seems to be enough for the shallow slots machined

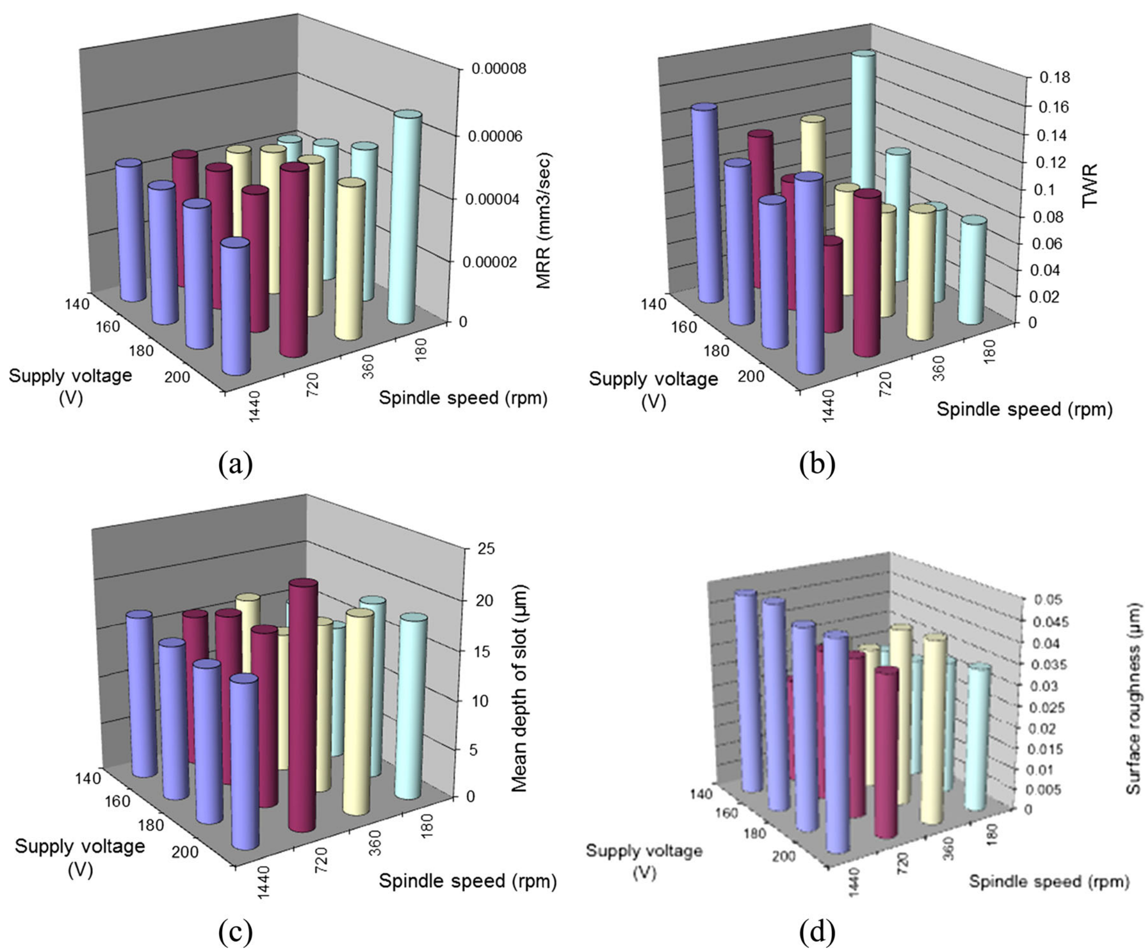

Fig. 6 Variation of **a** MRR, **b** TWR, **c** mean depth of slot and **d** surface roughness of slot with the variation of supply voltage and spindle speed during micro-EDM of AA 2024 (Fixed parameters; capacitance=10000 pF, resistance=470 Ω, threshold voltage=80 %, feed rate=0.01 mm/s)

in this study (target depth 40 μm). The effect of tool rotational speed shown in this study for machining lower machining depth may not be appropriate for the machining of high-aspect-ratio holes or deep slots. When deeper slots are machined, a higher rotation speed may be needed to enhance the removal of debris. Therefore, the author recommends rotation speed to be increased to 360–720 rpm for deep slot machining.

3.5 Effect of gap threshold voltage

The gap threshold voltage is a user defined parameter to control the minimum allowable gap distance between the work piece and the electrode. When the gap voltage between the electrode and work piece is above the pre-set threshold voltage, the electrode will move forward and vice versa. The threshold voltage is normally presented as a percentage of the supply voltage. Generally, machining only takes place when the tool moves close towards the work piece. When the gap threshold voltage is lower than the discharge voltage, the spark occurs. Setting a low threshold voltage when using the conventional step control for gap distance control will lead to more frequent sparking. However, sometimes at low threshold voltage, due to more sparking, there may be arcing leading to poor machining conditions. As can be seen from Fig. 7a, the MRR increased gradually with the increase of threshold voltage, especially at the setting of lower feed rate. This is due to the fact that arcing might have occurred when low threshold values were used, leading to poor machining conditions. Due to the increased MRR with threshold voltage, the mean depth of slot also increased, as can be seen from Fig. 7b. Therefore, for stable machining conditions, threshold voltage of about 80 % of the supply voltage is recommended. On the other hand, when using proportional control to control the gap distance, as shown in Fig. 8a, lower threshold voltage resulted in higher MRR, which is opposite to the step control. In proportional control, the feed rate is constantly changing and proportional control uses the equation {Feed rate=k [Actual gap voltage – Threshold voltage]} to control the feed rate. From the equation, it is clear that by selecting a lower threshold voltage, the feed rate value increases and thus increases the chance of arcing. Although a higher MRR is obtained by using a lower threshold voltage, the SR of the slot increases

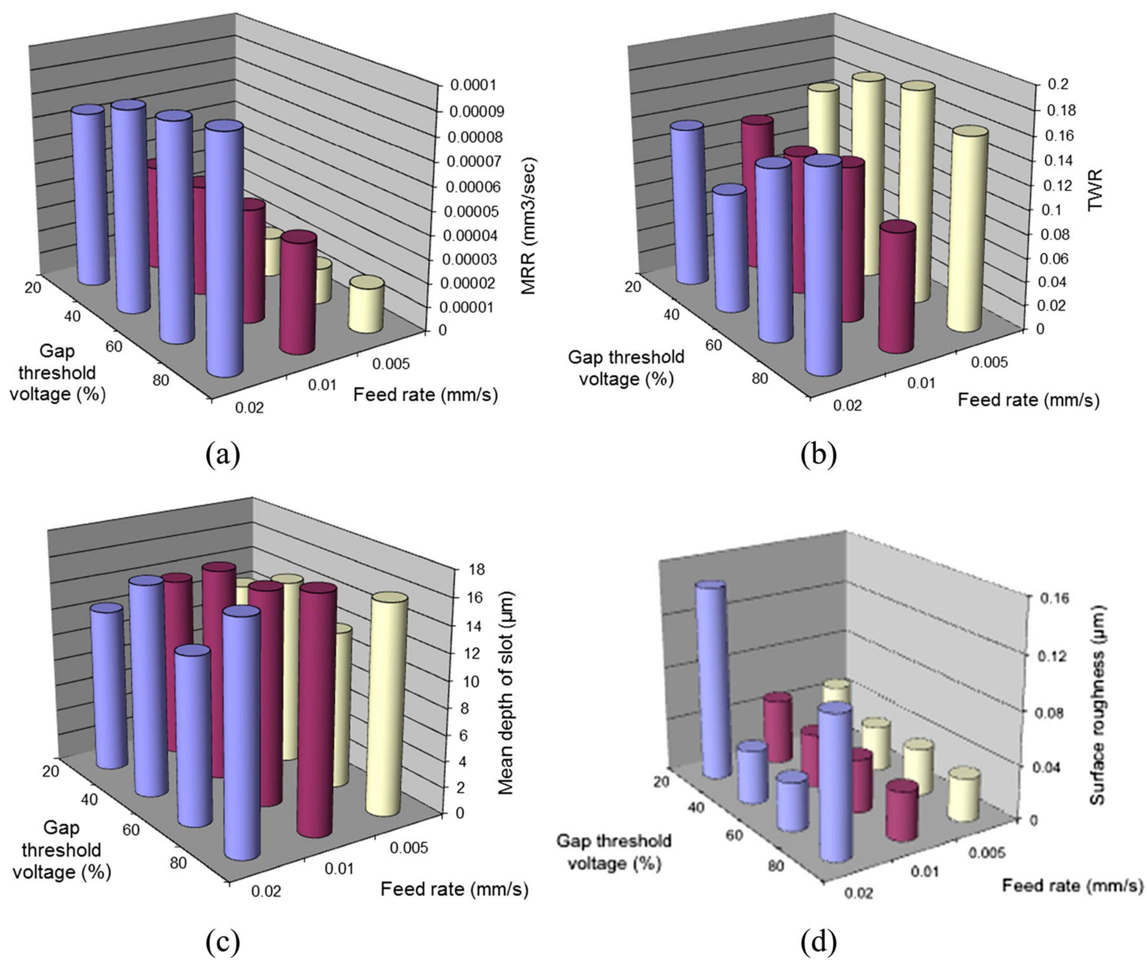

Fig. 7 Variation of **a** MRR, **b** TWR, **c** mean depth of slot and **d** surface roughness of slot with the variation of gap threshold voltage and feed rate during micro-EDM of AA 2024 (Fixed parameters; supply voltage=160 V, spindle speed=720 rpm, capacitance=10,000 pF, resistance=470 Ω)

due to the effect of arcing. It was found that both the lower and higher values of threshold voltage were not suitable for good surface finish. Thus, if a good surface finish is needed, choosing a value of threshold voltage at 60 % of the supply voltage is recommended.

3.6 Effect of gap feed rate

The gap feed rate defines the speed at which the tool advances towards the work piece. Having an excessive gap feed rate increases the possibility of arcing, which then leads to poor machining conditions. The gap feed rate determines how fast the tool is approaching the workpiece. The general trend is that by having a faster feed rate will increase the MRR of the process, as plotted in Fig. 7a. However, it can be seen from Fig. 7d that the SR was affected when the gap feed rate was increased. This is due to the increasing possibilities of arcing brought by the increased feed rate. It was found that moderate feed rate value was favourable for obtaining lower SR and TWR. The machined depths of slots were also higher for moderate values of gap feed rate. Therefore, for grooving or shallow slot machining, gap feed rate of 0.01 mm/s was found to provide improved performance. Gap feed rate of 0.005 mm/s can only be used when surface finish is the main priority, as the MRR becomes much lower at lower setting of gap feed rate.

3.7 Effect of the gap control factor, k

The gap control factor influences the speed at which the tool electrode advances towards the workpiece. However, the gap control factor is used with the proportion control program, whereby feed rate is defined as Feed rate=k [Actual gap voltage–Threshold voltage]. Thus, k is essentially a magnification factor used in the above equation. When using proportional control to control the gap distance, the gap feed rate is not constant but is constantly changing. This constantly changing value is then multiplied to a constant value known as the gap control factor. Increasing the gap control factor has the same effects as increasing the feed rate. It was found that higher gap control factor resulted in higher MRR, as can be seen from Fig. 8a. Increasing the gap control factor leads to

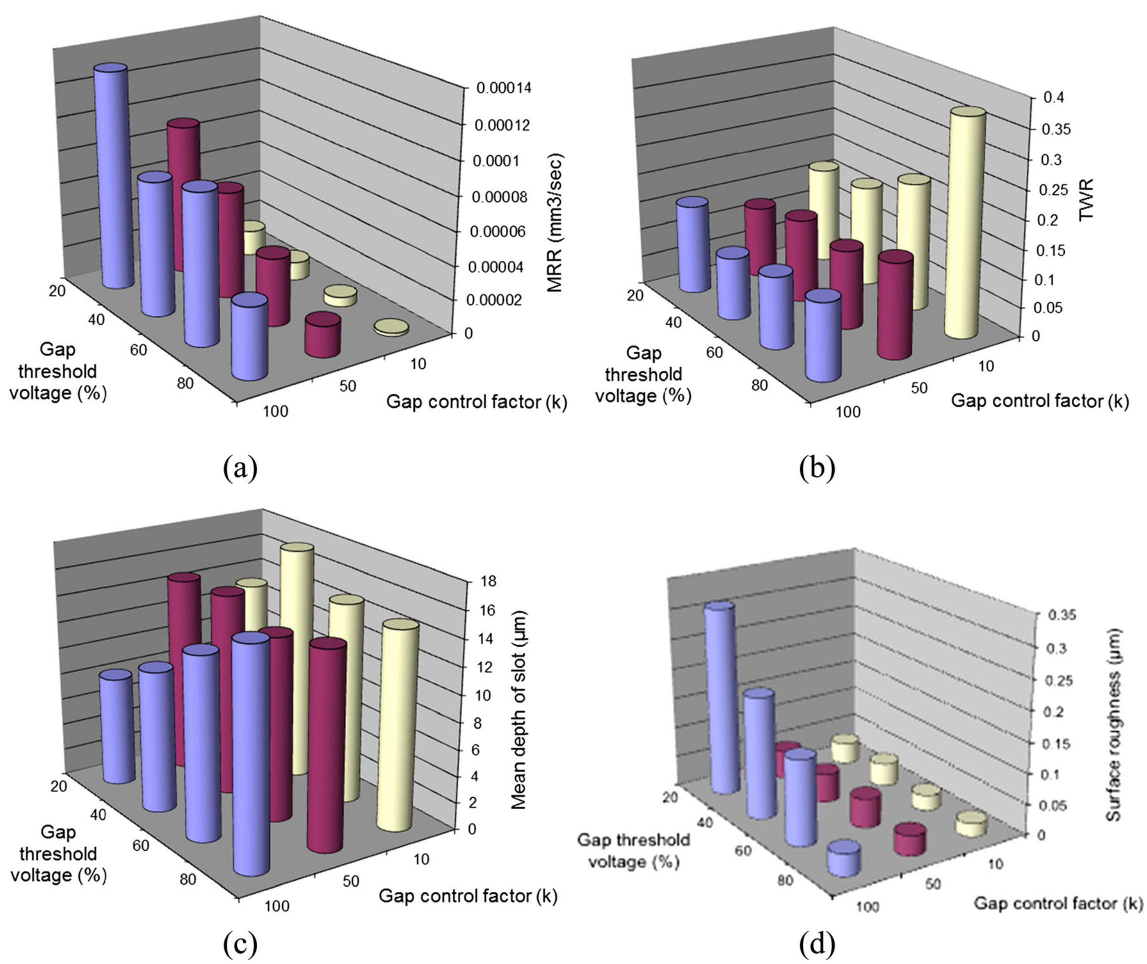

Fig. 8 Variation of **a** MRR, **b** TWR, **c** mean depth of slot and **d** surface roughness of slot with the variation of gap threshold voltage and feed rate during micro-EDM of AA 2024 (Fixed parameters; supply voltage=160 V, spindle speed=720 rpm, capacitance=10,000 pF, resistance=470 Ω)

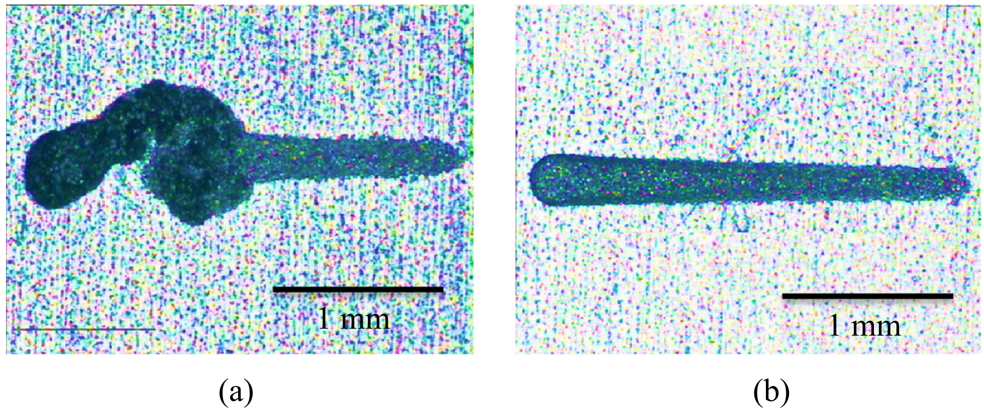

Fig. 9 Slots fabricated by using a gap control factor of **a** k=100 and **b** k=50 (Fixed parameters; supply voltage=160 V, spindle speed=720 rpm, capacitance=10,000 pF, resistance=470 Ω)

more arcing, and as a result, the surface roughness was also found to increase. Figure 9 shows the comparison of the quality of slots fabricated by using a gap control factor of 100 and 50. The fabricated slot was found to be irregular shaped at higher gap control factor (k=100) due to the unstable machining. On the other hand, uniform shaped slot was obtained at gap control factor of 50. Therefore, for optimum machining process, a gap control factor of k=50 was used. Although k=100 provides higher MRR, it leads to more arcing and invariably leads to complications of the machining process.

4 Machining with identified optimum parameters settings

In this experimental study, the optimal setting of each parameter was identified first using 0.2 mm tool electrode by machining micro slot of 40 μ depth. After that, the optimal parameters were tested for machining higher depth (50 μ) using a larger diameter tool (0.3 μ). In this way, we can say that the identified optimal set of parameters works for other dimension of micro slots and tools.

The machining depth of 50 μ was provided in a continuous feed in one cut. Only a single pass was used to machine the slot using optimal parameters setting. For all the slots machined for this study, we used single pass to machine the slots. In order to maintain the correct machining depth due to tool wear, the servo was controlled for constant spark gap. As the tool wears with the machining, the servo pushes the tool electrode downwards to maintain the same spark gap throughout the machining process. The servo pulls the electrode as soon as the required machining depth is reached at any point in the slot, thus stopping the machining process.

In this study, the optimum parameters have been identified experimentally. The optimum parameters were identified

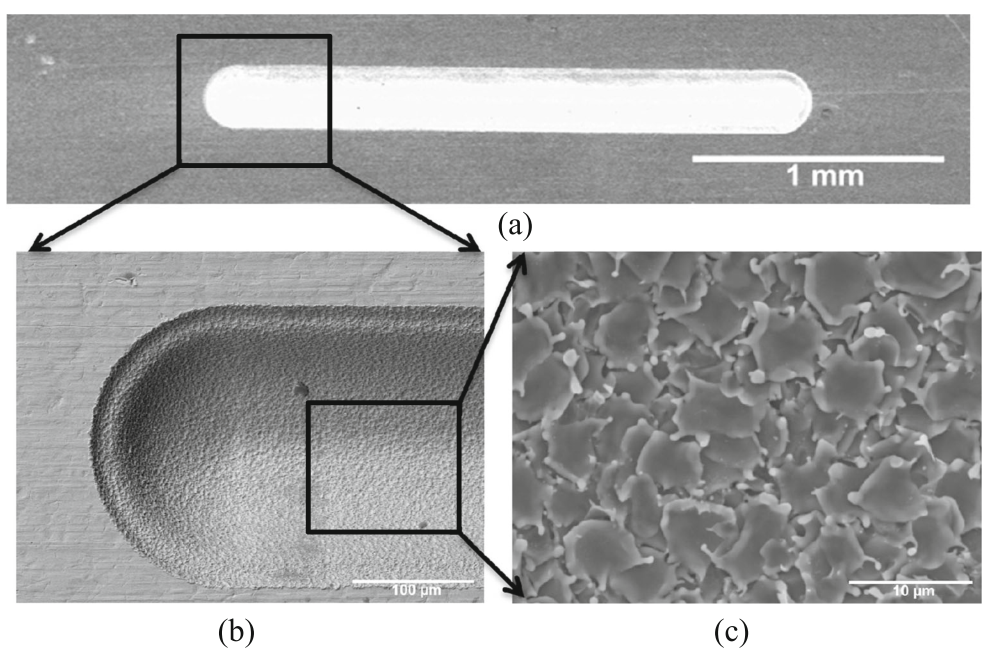

Fig. 10 **a** A micro-slot of 2 mm length, 300 μm width and 50 μm depth on aluminium alloy AA 2024 machined using optimum parameters, **b** magnified image of the slot showing smooth surface finish, and **c** further magnified image showing uniform crater arrangement with crater sizes of 8–10 μm

based on a compromise between moderately higher MRR, lower SR, higher machining depth and lower TWR; arranged in order of priority. A detailed experimental investigation has been done by varying each operating parameters within available range and plotting the process performance parameters against variation of each parameter. After investigating the effect of various operating and gap control parameters on the micro-EDM performance of AA 2024, a suitable setting of each parameter was identified by the best judgement. It has been concluded that the following settings of machining parameters could provide improved micro-EDM performance on the AA 2024 aluminium alloy:

- Capacitance of 10,000 pF
- Resistance of 470 Ω
- Supply voltage of 180 V
- Spindle speed between the ranges of 360–720 rpm
- Frequency of 436 kHz
- Duty-cycle of 50 %
- Gap threshold voltage of 80 % of the supply voltage
- Gap feed rate of 0.01 mm/s (roughing) and 0.005 mm/s (finishing)
- Gap control factor of 50

In order to test the identified optimum parameters, micro-slots were machined using the optimum parameters settings. A 300-μm tungsten tool electrode was used to machine micro-slots of 2 mm length and 50 μm depth on AA 2024 surface. Figure 10 shows the SEM images of a machined micro-slot, surface topography and crater arrangement on the machined surface. The slot was found to be of a good dimensional accuracy (less taper), smoother surface finish and uniform crater arrangement.

5 Conclusions

An extensive experimental study has been conducted to investigate the effects of various machining parameters on the machining characteristics during the micro-EDM of an important aluminium alloy AA 2024. The machining parameters varied were capacitance, resistance, supply voltage, spindle speed, gap feed rate, gap control factor and the gap threshold voltage. The micro-EDM performance of the aluminium alloy was evaluated based on the effect of above mentioned parameters on different machining characteristics such as MRR, TWR, machining depth and SR. The following conclusions have been drawn from this experimental investigation:

- The MRR, mean machining depth of the slots and SR, increases with the increase of capacitance and decrease of resistance. The higher values of capacitance result in broader craters due to increased pulse energy and lower settings of resistance result in higher peak current, which facilitates the MRR.
- Lower settings of capacitance and higher values of resistance are not suitable for the micro-EDM process in an RC-type pulse generator. The machining becomes unstable due to short circuiting and arcing providing inconsistent performance. The micro-EDM performance becomes very poor at combined settings of low resistance and high capacitance from a pulse generator.
- The increase of supply voltage results in increased spark energy per pulse. Therefore, the MRR, depth of the machined slot and SR, increases. The TWR is higher at both lower and higher settings of supply voltage due to shorter spark gap and increased pulse energy, respectively.
- Gap control parameters play an important role in determining the machining performance during the micro-EDM process. The higher settings of gap threshold voltage, feed rate and gap control parameter tend to make the machining process faster. However, the process becomes unstable due to more frequent arcing. An optimum selection of gap threshold voltage, gap feed rate and gap control factor can ensure machining stability, which is more important in controlling the micro-EDM performance.

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References

1. Ponappa K, Aravindan S, Rao PV, Ramkumar J, Gupta M (2010) The effect of process parameters on machining of magnesium nano alumina composites through EDM. Int J Adv Manuf Technol 46: 1035–1042
2. Patil NG, Brahmankar PK (2010) Some studies into wire electro-discharge machining of alumina particulate-reinforced aluminum matrix composites. Int J Adv Manuf Technol 48:537–555
3. Songmene V, Khettabi R, Zaghbani I, Kouam J, Djebara A (2011), Machining and Machinability of Aluminum Alloys, Aluminium Alloys: Theory and Applications, Chapter 18, pp. 377–400, Prof. Tibor Kvackaj (Ed.), ISBN: 978-953-307-244-9, InTech
4. Khan AA (2008) Electrode wear and material removal rate during EDM of aluminum and mild steel using copper and brass electrodes. Int J Adv Manuf Technol 39:482–487
5. Gatto A, Bassoli E, Iuliano L (2011) Performance Optimization in Machining of Aluminium Alloys for Moulds Production: HSM and EDM, Aluminium Alloys: Theory and Applications, Chapter 17, pp. 355 – 376, ISBN: 978-953-307-244-9, In Tech
6. Kathiresan M, Sornakumar T (2010) EDM Studies on Aluminum alloy-Silicon Carbide composites developed by Vortex Technique and pressure die casting. J Miner Mater Charact Eng 9:79–88
7. Arooj S, Shah M, Sadiq S, Jaffery SHI, Khushnood S (2014) Effect of current in the EDM machining of Aluminum 6061-T6 and its effect on the surface morphology. Arab J Sci Eng 39:4187–4199
8. Kumar HG, Mohit H (2008) Mathematical Modeling of Electric Discharge Machining of Cast Aluminium Alloy (AA6061) – 15 Wt. % SiCp Composites. Int J Emerg Technol Adv Eng 3(9): 469–496

9. Nanimina MA, Rani AM, Ahmad F, Zanuddin F, Lo SH (2011) Effect of electro discharge machining of aluminum metal matrix composite. J Appl Sci 11(9):1668–1672
10. Nanimina MA, Rani AM (2012) Surface quality of electro-discharge machined aluminum metal matrix composite. J Appl Sci 12: 2442–2447
11. Guleryuz LF, Ozan S, Kasman S, Ipek R (2013) The influence of process parameters of EDM on the surface roughness of aluminum matrix composites reinforced with SiC particulates. Acta Phys Polon A 123(2):421–423
12. Chose A, Sharma V, Kumar N, Krishnamurthy A, Kumar S, Botak Z (2011) Taguchi-Fuzzy based mapping of EDM-machinability of Aluminum foam. 18(4): 595–600
13. Ahamed AR, Asokan P, Aravindan S (2009) EDM of hybrid Al–SiCp–B4Cp and Al–SiCp–Glassp MMCs. Int J Adv Manuf Technol 44:520–528
14. Lin CL, Lin JL, Ko TC (2002) Optimization of the EDM process based on the orthogonal array with fuzzy logic and grey relational analysis method. Int J Adv Manuf Technol 19(4):271–277
15. Patel KM, Pandey PM, Rao PV (2008) Understanding the role of weight percentage and size of silicon carbide particulate reinforcement on Electro-Discharge Machining of Aluminium-based composites. J Mater Manuf Process 23:665–673
16. Kamguem R, Djebara A, Songmene V (2013) Investigation on surface finish and metallic particle emission during machining of aluminum alloys using response surface methodology and desirability functions. Int J Adv Manuf Technol 69:1283–1298
17. Rosochowski, A., Olejnik, L., Roginskic, S., Richert, M., Micro-EDM of UFG Aluminium, In 4M 2007, Proceedings of 3rd International Conference on Multi Material Micro Manufacture, Borovets, Bulgaria, Oct 3–5, 2007
18. Hu FQ, Song BY, Bai JC, Hou PJ, Che HC, Zhang H (2010) Micro-EDM for an Aluminium Matrix Composite. Key Eng Mater 447–448:233–237
19. Modica F, Marrocco V, Moore P, Fassi I, Wiens, G (2012) Al-Mg Micro-Features Using Micro-EDM Milling, In: Proceedings of 6th International Conference on Micro- and Nanosystems. In: Proceedings of 17th Design for Manufacturing and the Life Cycle Conference Chicago, Illinois, USA, August 12–15, 2012, 5:161–167
20. Lim HS, Wong YS, Rahman M, Lee EMK (2003) A study on the machining of high-aspect ratio micro-structures using micro EDM. J Mater Process Technol 140:318–325
21. Jahan MP, Wong YS, Rahman M (2009) A study on the quality micro-hole machining of Tungsten Carbide by micro-EDM process using Transistor and RC-type pulse Generator. J Mater Process Technol 209(4):1706–1716
22. Jahan MP, Wong YS, Rahman M (2009) A study on the fine-finish die-sinking micro-EDM of tungsten carbide using different electrode materials. J Mater Process Technol 209:3956–3967