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Study of mixed nanopowder into electrochemical machining process

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Electrochemical machining (ECM) is considered as most favored machining processes to produce many press tools and dies because of its good capability to manufacture complicated different shapes and machinability of very brittle and hard materials. This method has enabled the machining of all electrical conducting materials. In this research, the material of the electrode tool is made of copper, and it makes an impermeable cavity in the workpiece. The technique of nano graphite powder mixed could be more advanced to improve the capabilities of traditional ECM. The goal of this research is to enhance performance and quality of ECM process including enhancement of material removal rate (MRR) by discuss the results of using many input parameters like nano graphite powder concentration with values of (0, 5, and 10 g/L), voltage with values of (10, 20, and 30 V), and gap with values of (0.1, 0.2, and 0.3 mm) for machining stainless steel 304 ASTM A 240 on MRR. Minitab statistical software is utilized to analyze results statistically by general full factorial design to know how selected input parameters affect MRR. It is concluded that adding nano graphite powder with a mixture of water and sodium chloride (NaCl) increases MRR. Maximum MRR is (36.892 mm3/min) acquired at a nano graphite powder concentration of (10 g/L), a voltage of (30 V), and a gap of (0.3 mm). when nano graphite powder concentration, voltage, and the gap increase, MRR increases.

Keywords: Nanotechnology; Electrochemical machining; Nanopowder; Electrolyte.

1. INTRODUCTION

The capability of traditional machining is limited because it results in issues including tool wear, higher energy consumption, and shorter tool life, which reduces dimensional accuracy and surface finish [1]. So, the need for new processes became necessary which led to the innovation of nontraditional machining processes [2]. Nontraditional machining processes include new and enhanced machining processes, like ECM process that removes material without heat. Most likely, all types of metals can be machined by this process [3]. Even composite materials with high specific stiffness, resistance to corrosion and fatigue, and a low weight-to-strength ratio, like glass fiber reinforced polymer, can be cut by ECM [4]. ECM process has a lot of advantages like: good surface quality, the absence of electrode wear, and neglect of the hardness and ductility of the material [5] [6]. There is no tool wear because defective layers are not produced on the workpiece due to the tool [7]. ECM process has applications in many fields, such as aerospace and electronics industries, for shaping and finishing operations, in which parts are a few microns in diameter [8]. ECM process depends on an anodic dissolution for the workpiece and the tool in an electrolytic solution [9]. Voltage is applied between the electrodes (the workpiece and the tool) by connecting the positive pole at the workpiece and the negative pole at the tool which makes the positive ions attract to the tool surface and negative ions attract to the workpiece surface. So, ECM process removes material by attracting atoms of both workpiece and tool materials without any thermal effect or mechanical contact. The tool should be placed as close as possible to the workpiece and the electrolyte should be pumped through the gap [10]. During ECM process generation of thermal energy between the tool and workpiece is low, which keeps the microstructure of the material without cavities creation [11]. It is frequently necessary to have a quantifiable relationship between the input variables and the operating parameters [12].

The electrolyte significantly affects in material removal rate (MRR) and tool wear rate (EWR). It has two functions in ECM process including: carrying the current between the workpiece and tool and removing the iste of reactions from the gap [13]. The selection of the electrolyte determines the good performance of the electrochemical machining process [14]. The electrolyte in ECM process should possess many properties like: low toxicity and corrosive nature, high electrical conductivity, and high chemical and electrochemical stability. The polarization curve is the tool that identifies the suitable properties of the electrolyte. It describes the relationship between the voltage and the current or between power density with current density of the electrolyte cellular stack [15]. The main condition in choosing the electrolyte is to prohibit the deposition of the metal on the tool. Tool shape will deform and workpiece surface finish will reduce if the deposition exists. Another function of electrolyte is to remove the excess heat produced during ECM process [16]. Authors in [17] produced micro holes on titanium alloys with a mixture of glycerol ($C_3H_8O_3$) and C_8O_7 with different levels for an applied voltage of (8,10,12, and 14 V). there is a use of Taguchi method L16 orthogonal array. They achieved the MRR at a voltage of 14V and the lowest overcut at an electrolyte concentration of 65g/L. Authors in [18] studied the effect of adding an electrolyte of sodium nitrate ($NaNO_3$) to machine aluminum scrapped wheel. Three input parameters are selected including voltage, electrolyte concentration, and duty cycle and two output parameters including material removal rate (MRR) and overcut (OC). Using Taguchi design, the SN ratio is used to specify the optimization of input parameters and ANOVA is used to analyze the contribution of each parameter. The results showed that MRR is improved and optimal parameters are a voltage of 10 V, a duty cycle of 90%, and an electrolyte concentration of 25 g/L, while OC is reduced and optimal parameters are a voltage of 12 V, a duty cycle of 80%, and an electrolyte concentration of 25 g/L. Authors in [19] conducted a study on a copper-based shape memory alloy (Cu-SMA) as a workpiece using an electrolyte solution consisting of ethylene glycol (EG) and NaCl in electrochemical micromachining (μECM) process. The effect of input parameters like voltage, electrolyte concentration, and micro-tool feed rate on material removal rate (MRR) and surface roughness (SR) has been investigated by forming micro-slots. Micro-slots with high quality are successfully obtained achieving the maximum MRR of 0.323 mg/min and the minimum SR of 0.384 μm. In addition, it is revealed that an ethylene glycol electrolyte containing NaCl gave superior surface integrity and shape accuracy for micro-slots compared to a water-based electrolyte. Authors in [20] investigated adding a non-newtonian fluid (polyacrylamide (PAM)) and PAM–NaOH and compared them to study the effects on SS304 as a workpiece. The three parameters are pulse voltage, frequency, and duty ratio. The good quality is obtained in a microhole array with a diameter average of 330.11 μm, a depth average of 16.13 μm, and a depth-to-diameter ratio of 0.048. The results showed that (PAM–NaOH) can dissolve process effectively and improve the accuracy of the microholes. Authors in [21] presented a study about using potassium chloride (KCl) and potassium sulphate (K_2SO_4) solutions to machine a workpiece from stainless steel AISI 316 by a tool from copper. The values of electrolyte concentration are (10, 20, and 30 g/L), the values of current are (2, 5, and 10 A), and the values of voltage are (6, 12, and 20 V), While surface roughness (Ra) and material removal rate (MRR) are the outputs. They concluded that the highest Ra and the highest MRR are with potassium chloride (KCl), while potassium sulphate (K_2SO_4) gave lower values. Authors in [22] immersed a workpiece of stainless steel 316 H in a solution of sodium chloride (NaCl) and a solution of sodium sulphate (Na_2SO_4) with three levels (10, 20, and 30 g/L) to remove the workpiece from its length about 1 mm, using a copper tool. Current values are (2, 5, and 10 A), and voltage values are (6, 12, and 20 V). It is found that Na_2SO_4 solution produced better material removal rate (MRR) and lower surface roughness (Ra). Authors in [23] presented a study about electrochemical micromachining (EMM) process on a nickel plate in sulphuric acid (H_2SO_4) electrolyte. It is concluded that low voltage, small pulse on time, and small diameter of electrode are the values that improve the accuracy of machining.

This study aims to increase removal efficiency without causing surface damage, achieve surface smoothness and dimensional accuracy, help in heat dissipation and ensure stable current conduction between the tool and the workpiece, and reduce the occurrence of side reactions and formation of deposit and harmful gases, all that by determining the best values of nano graphite powder concentration.

2. EXPERIMENTAL

Experiments are performed by an ECM machine that is housed in the University of Technology in the production and metallurgy department in the Machine Tool Lab. As shown in Figure 1, The tool is fastened to the main screw and the workpiece is secured inside the machining chamber (tank). The tool is as close as possible to the workpiece with three different levels of gap, including 0.1, 0.2, and 0.3 mm. The process parameters, like voltage and gap are changed by the control panel. Through a reservoir, the electrolyte is pumped. In the form of sludges, the material of the workpiece precipitates by the chemical reaction that occurs in the electrolyte cell. Just like that, a complex profile can be created in a single machining process on even the hardest material.

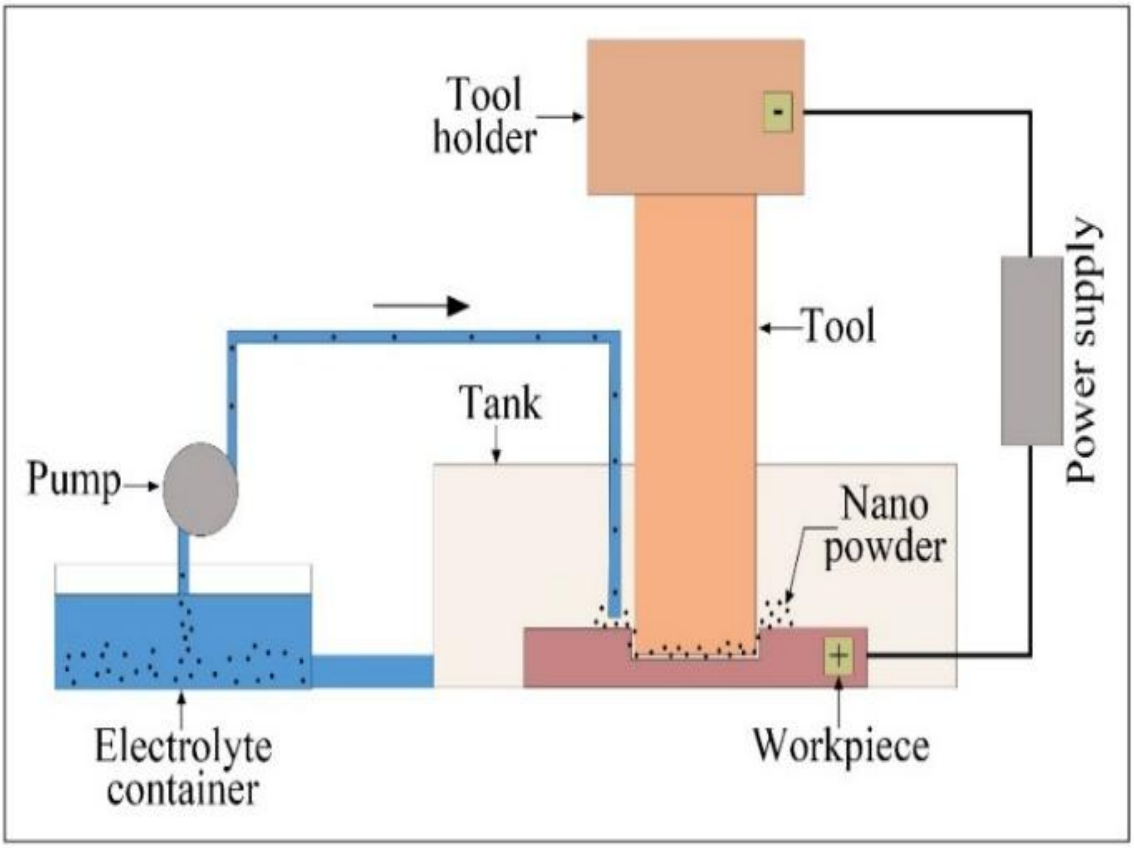


Figure 1 Block diagram of ECM process.

2.1. Selection of workpiece and tool

Figure 2 shows the rectangular block of 40 mm length, 30 mm width, and 1.7 mm height, which is selected as a workpiece. It is made of stainless steel 304 ASTM A 240, and its chemical composition is summarized in Table 1. It has high hardness and corrosion resistance, making it difficult to machine in traditional methods, but easy to machine in ECM process with accurate surface and creating complex shapes like small channels and narrow slots. The workpiece examined in the central organization for standardization and quality control in the Ministry of Planning in Iraq, and according to the (ASTM E415) standard. Table 2 presents many mechanical and physical characteristics of the workpiece. The tool is composed of 99.74 % pure copper and has a diameter of 5 mm.

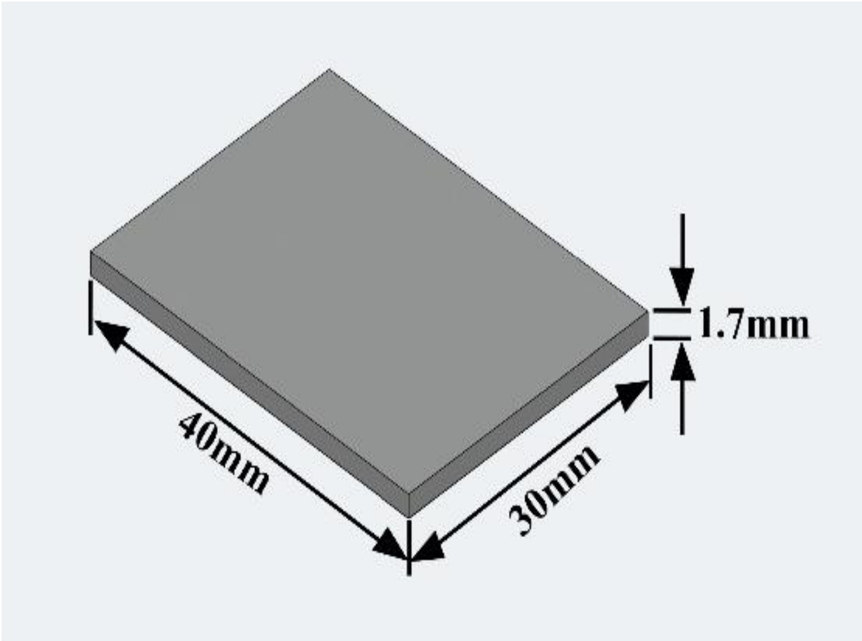


Figure 2 Shape of the workpiece before machining.

Table 1 Chemical composition of stainless steel 304 ASTM A 240 workpiece.

Material	Carbon	Silicon	Manganese	Phosphorus	Sulfur
Weight %	0.055	0.58	1.08	0.03	0.02
Material	Vanadium	Chrome	Molybdenum	Nickel	iron
Weight %	0.142	19.4	0.24	8.95	balance

Table 2 Mechanical and physical properties of stainless steel 304 ASTM A 240 workpiece

Property	**Value**
Hardness (Kgf/mm^2)	170
Elongation (percent in 50 mm)	60
Tensile strength (Mpa)	621
Density (g/cm^3)	8.03
Melting point (ºC)	1400 - 1450

2.2. Selection of electrolyte

Nano graphite powder is added to a mixture of water and sodium chloride (NaCl). It is a black appearance powder as shown in Figure 3, it is an ultra-fine powder with a high BET surface area of 350 m^2/g, which means it is very suitable for chemical catalytic and has a particle size of 80 nm which is examined in the University of Technology, Nanotechnology and Modern Materials Research Center, which refers to high accuracy in size, and it is very pure with 99.92% carbon content as shown in Table 3. Because its nanoparticles have a tendency to form tenacious agglomerates, it is challenging to size-classify nano graphite powder because they are largely constituted of ultra-fine particles. This electrolyte has high electrical conductivity, high lubrication ability, and high absorption, its specific uses are: conductivity applications, lubrication in the chemical industry, and lubrication in aerospace.

Figure 3 Nano graphite powder.

Table 3 Physical and chemical properties of nano graphite powder mixed.

Property	Value	Property	Value
BET surface area	350 m^2/g	Carbon content	99.92%
particle size	80 nm	Diameter	3-6 µm
Thickness	< 40 nm	True density	2.16 g/cm^3
Moisture	0.96 %		

2.3. Specifications of ECM process

Table 4 shows the input machining settings of ECM machine that control the process but did not change. According to the recommendations of the manufacturer, the remainder of the electric impulse parameters is kept constant (negative tool polarity and positive workpiece polarity).

Table 4 Constant process settings.

Constant settings	Description
Tool polarity	negative
Workpiece polarity	positive
High voltage	140 V 1.2 A
Pulse off time	25 µseco
Servo feed	75 %
Working time	5 sec
Jumping time	2 mm
Gap code	10
Depth of cut	1 mm

Three variable process settings are selected with three levels for each one, including a voltage of (10, 20, and 30 V), a concentration of nano graphite powder of (0, 5, and 10 g/L), and a gap of (0.1, 0.2, and 0.3mm) as shown in Table 5.

Table 5 Variable process settings.

Factors	Level 1	Level 2	Level 3
Voltage (V)	10	20	30
Concentration of nano graphite powder (g/L)	0	5	10
Gap (mm)	0.1	0.2	0.3

2.4. Measurement of material removal rate (MRR)

Material removal rate represents the erosion rate of the workpiece, it mainly depends on the feed rate of the tool. When the tool moves near to the workpiece the magnitude of the current increases. This process continues until the current removes the metal at a rate corresponding to the rate of tool advance [23-25]. With a fixed spacing between the work and the tool which is called a machining gap, a stable cut happens. The weight of the workpiece is tested before and after machining utilizing an electronic weighing scale with a precision of 0.0001 g. MRR is measured by dividing the difference between workpiece weight before and after machining on the machining time, as shown in the following equation [26, 27]

$$MRR = \frac{W_B - W_A}{M_T \times \rho} \quad (1)$$

where MRR is material removal rate (g/min), W_B is workpiece weight before machining (g), W_A is workpiece weight after machining (g), M_T is machining time (min), and ρ is workpiece density (g/mm^3).

Experiments design is created to improve process quality and know the best conditions for MRR for future experiments. Table 6 shows the experimental and predicted results of MRR. Minilab17 software is used to design the trials, which determines full factorial design to provide 27 experiments from the equation (level ^{factor}), giving $3^{3.}$

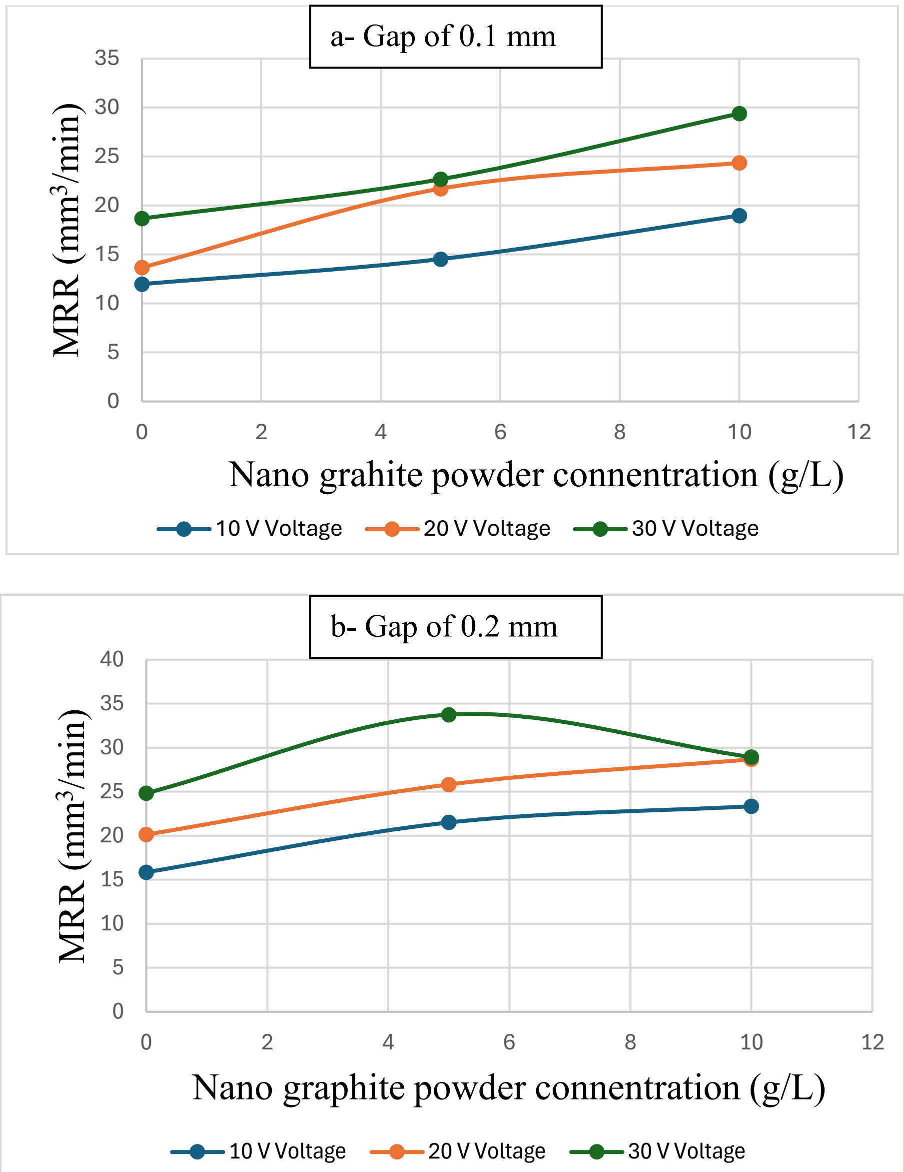
Table 6 Variable, measured, and predicted parameters.

Exp No.	Nano graphite powder concentration (g/L)	Voltage (V)	Gap (mm)	MRR (mm^3/min)	Predicted MRR (mm^3/min)
1	0	10	0.1	11.981	11.7824
2	5	10	0.1	14.535	16.2571
3	10	10	0.1	18.977	21.3711
4	0	10	0.2	15.862	20.5224
5	5	10	0.2	21.508	21.8011
6	10	10	0.2	23.356	23.3647
7	0	10	0.3	17.784	22.1641
8	5	10	0.3	19.892	24.9104
9	10	10	0.3	22.594	26.7417
10	0	20	0.1	13.671	18.2691
11	5	20	0.1	21.725	23.7857
12	10	20	0.1	24.351	28.8407
13	0	20	0.2	20.138	27.451
14	5	20	0.2	25.825	29.3467
15	10	20	0.2	28.682	29.9754
16	0	20	0.3	25.544	28.5907
17	5	20	0.3	29.784	31.4671
18	10	20	0.3	30.561	33.2284
19	0	30	0.1	18.672	23.6715
20	5	30	0.1	22.683	29.2542
21	10	30	0.1	29.391	34.3542
22	0	30	0.2	24.844	32.5665
23	5	30	0.2	33.762	34.8902
24	10	30	0.2	28.934	35.3679
25	0	30	0.3	31.275	34.1832
26	5	30	0.3	35.247	36.8675
27	10	30	0.3	36.892	38.7549

3. RESULTS AND DISCUSSION

3.1. Effect of nano graphite powder concentration on MRR

It is obvious in Figure 4 at a stable gap of: a) 0.1 mm, b) 0.2 mm, and c) 0.3 mm, that as nano graphite powder concentration increases, MRR increases because of the process of traveling ions far from the machining area, this prohibits the unwanted accumulation of iste of reactions and effectively insurance continuing the electrochemical reaction [28]. In addition to the fact that nano graphite powder has high electrical conductivity because of connected carbon layers and it provides chemical stability. But, for 10 g/L of nano graphite powder concentration and voltage of 30 V at a gap of 0.2 mm, MRR decreases because the increase in nano graphite powder temperature, which increases its viscosity and forms gas bubbles that reduce ions movement [29]. However, there is an optimal limit to electrolyte concentration. Excessive electrolyte concentration can lead to deposition of reaction iste on the workpiece surface, which can impede electrolyte flow and reduce removal efficiency [30]. Comparing the results with previous studies, there is good agreement with the scientific literature, which indicates that improving conductivity and ionic transport in the electrolyte are critical factors in increasing the efficiency of the ECM process [31]. This supports the hypothesis that electrolyte concentration is a key factor that can be used to control the removal rate according to manufacturing requirements [32]. Based on the above, it can be said that increasing electrolyte concentration is an effective strategy for improving ECM performance, but within carefully considered limits to achieve a balance between efficiency and surface quality [33].


a- Gap of 0.1 mm
MRR (mm³/min)
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
Nano grahite powder connentration (g/L)
10 V Voltage
20 V Voltage
30 V Voltage
b- Gap of 0.2 mm
MRR (mm³/min)
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
Nano graphite powder connentration (g/L)
10 V Voltage
20 V Voltage
30 V Voltage

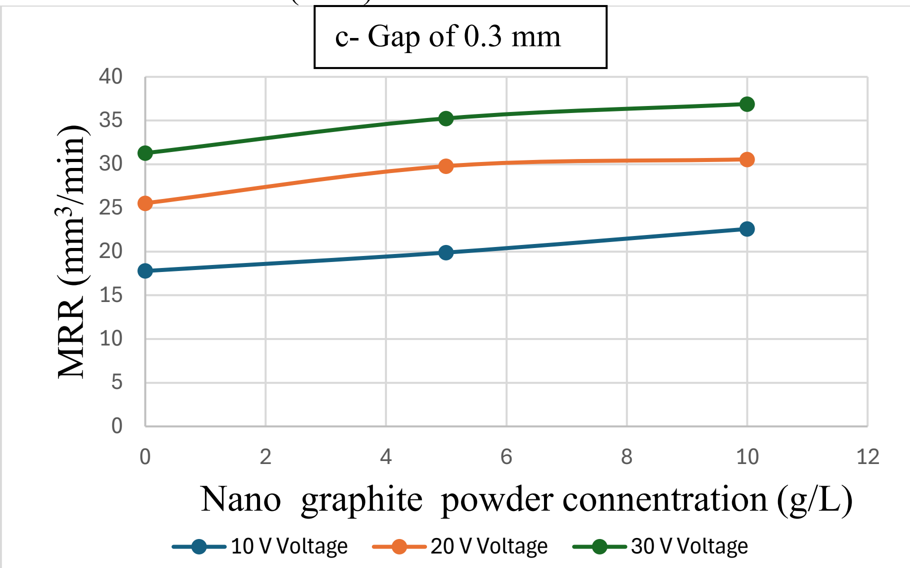


Figure 4 Effect of nano graphite powder concentration on MRR using different gaps.

3.2. Analysis of variance (ANOVA)

It is the tool that specifies the effect of each parameter on the output (MRR). As listed in Table 7, p-value for all parameters is lower than 0.05, which means all factors significantly affect MRR. Voltage is the parameter that has the highest effect with 44.20% of percentage contribution followed by gap of 26.92% then concentration of nano graphite powder of 20.97%. Error value is 7.91%, which means that the selected parameters explain most of the variation in data [34, 35].

Table 7 Analysis of variance (ANOVA) of experiments.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Concentration	2	240.24	120.120	26.49	0.000	20.97%
Voltage	2	506.45	253.227	55.85	0.000	44.20%
Gap	2	308.44	154.220	34.02	0.000	26.92%
Error	20	90.68	4.534	-	-	7.91%
Total	26	1145.81	-	-	-	100%

3.3. Model summary

The value of R-sq represents the ratio of variation of input parameter that the model explains. 92.09% of R-sq is high value, as shown in Table 8, which means that the model is accurate. R-sq (adj) is near in value to R-sq, but it takes into consideration the number of variables in the model. There is a difference between R-sq and R-sq (pred), which reveals some variation during the use of the model to predict future data.

Table 8 Model summary of experiments.

S	R-sq	R-sq (adj)	R-sq (pred)
2.12928	92.09%	89.71%	85.58%

3.4. Influence of input parameters on MRR

Figure 5 shows that all parameters have a clear effect on MRR with an upward trend and direct relationship. As nano graphite powder concentration increases, MRR increases because removing the iste of reactions from the gap and effectively insurance continuing the electrochemical reaction. There is a rise in the relationship between voltage and MRR, and this is back to increasing current density and the pushing force of the electrons that improves the efficiency of electrochemical reactions. When the gap changes from minimum to maximum values, MRR increases because improving electrolyte flow helps in removing the results of reactions like gases and oxides and reduces accumulation.

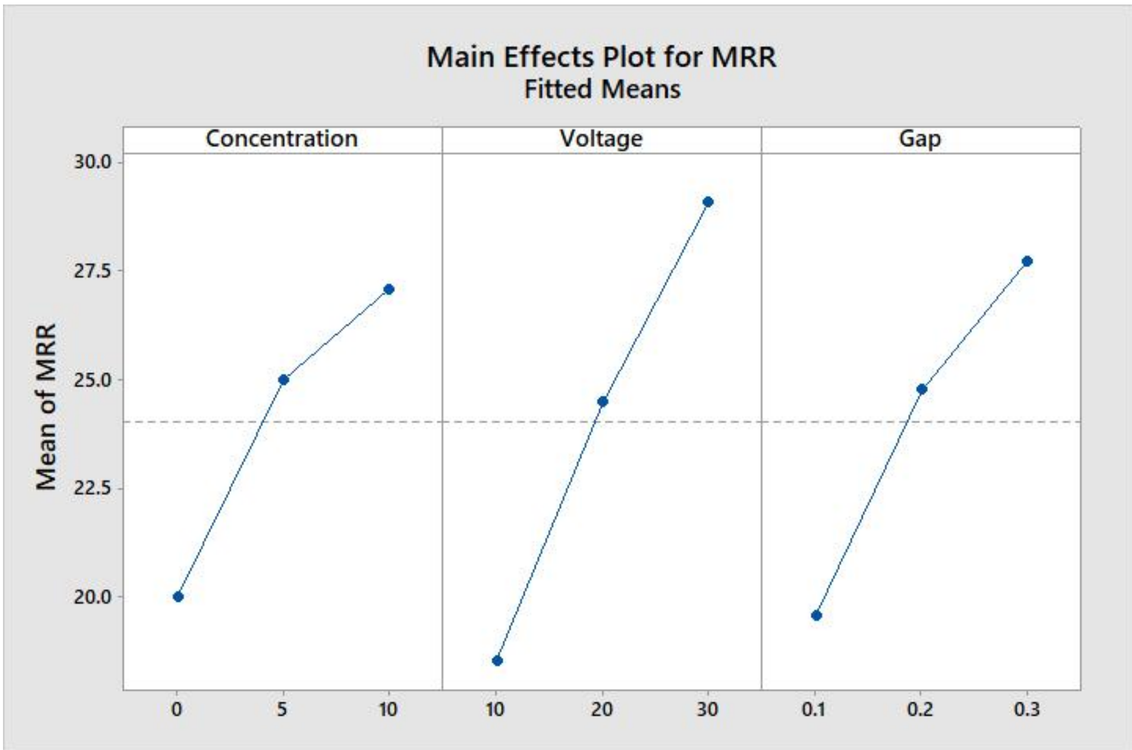


Figure 5 Effect of nano graphite powder concentration, voltage, and gap on MRR.

3.5. Equation of regression model

MRR=24.017- 4.043 Concentration_0+ 0.978 Concentration_5+ 3.065 Concentration_10- 5.519 Voltage_10+ 0.458 Voltage_20+ 5.060 Voltage_30- 4.463 Gap_0.1+ 0.750 Gap_0.2 + 3.713 Gap_0.3.

4. CONCLUSIONS

This research discussed the effect of process parameters like nano graphite powder concentration, voltage, and gap on MRR for a workpiece of stainless steel 304 ASTM A 240 and a tool of pure copper. The following conclusions can be noted:

- Adding nano graphite powder to a mixture of water and sodium chloride (NaCl) improves MRR, which means that nano graphite powder was better than just a mixture of water and sodium chloride (NaCl).
- The highest value of MRR from the experimental work was 36.892 mm^3/min and the lowest value is 11.981 mm^3/min.
- From Anova table of factorial design, all selected parameters including nano graphite powder concentration, voltage, and gap affect significantly, but the highest percentage contribution was for a voltage of 44.20%, followed by a gap of 26.92% then a concentration of nano graphite powder of 20.97%.
- The best obtained conditions for improved MRR were at a concentration of nano graphite powder of 10 g/L, a voltage of 30 V, and a gap was 0.3 mm.
- From plot of factorial design, values of MRR increase as values of nano graphite powder concentration, voltage, and gap increase.

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