Metallurgical and Materials Engineering
Association of Metallurgical Engineers of Serbia AMES

Research paper
https://doi.org/10.30544/798

INVESTIGATION OF MATERIAL REMOVAL RATE AND SURFACE ROUGHNESS DURING ELECTRICAL DISCHARGE MACHINING ON Al (6061)-5%SiC-10%B4C HYBRID COMPOSITE

Abbas Fadhil Ibrahim [*], *Abdullah Hamad Singal,*
Diana Abed al kareem Noori

University of Technology, Department of Production Engineering and Metallurgy,
Baghdad, Iraq

Received 02.02.2022
Accepted 29.03.2022

Abstract

Electrode Discharge Mechanism (EDM) is a manufacturing process using controlled sparks that occur between an electrically conductive workpiece and an electrode in the presence of an insulating liquid. The EDM process is commonly used to manufacture metallic matrix compounds that have wide applications in the railway sectors and the aircraft industry. Aluminum metal matrix composites (AMMCs) are one of the important kinds of metallic matrix compounds due to their advanced characteristics, such as lightweight and high strength. This lightweight material was developed and used in various manufacturing processes, like the automobile industry to reduce vehicle weight and thus reduce fuel consumption. This paper discussed the experiments of the EDM that were conducted to examine the effect of machining parameters, including peak current (10, 20, and 30 A), pulse on different times (50, 100, and 200 µsec), duty factors (4, 6, and 8) on the material removal rate, and surface roughness of the Al (6061)-5%SiC-10%B_4C hybrid composite as workpiece using copper electrode tool by Box-Behnken design. The analysis data for the dependent and independent variables manifested that the influence of machine parameters whenever Ip and Pon increase, the MRR and Ra increase.

Keywords: Electrical discharge machining (EDM); hybrid composites; material removal rate; surface roughness; stir casting process.

Introduction

An electrical discharge machine (EDM) is one of the non-conventional machining processes and the most advanced in use today. There is no touch between the workpiece and the tool which reduces the vibration, stresses, and chatter when machining superalloy

---

[*] Corresponding author: Abbas Ibrahim, *Abbas.F.Ibrahim@uotechnology.edu.iq*

and hard materials [1]. Although the working principle of electrical discharge machining has already been discussed in the past by researchers, here the authors attempt to briefly explain the working principle of the EDM for better understanding to readers. The metals are removed from the workpiece by controlled sparks that occur between a workpiece and an electrode in the presence of an insulating liquid [2]. EDM is one of the more widely used manufacturing processes for the high-precision processing of all conductive materials, regardless of hardness [3]. The manufacturing processes nowadays focus on producing products that are smaller, more refined; have the best properties, with new reinforcement materials. Metal Matrix Compounds (MMCs) can be considered composite materials and are generally alloys based on aluminum, titanium or magnesium, alumina hardener, silicon carbide, titanium carbide, and boron carbide [4, 5].

The particles reinforcement provides advantageous mechanical, physical or thermal performance, while the load is distributed on the metal matrix and enhances the structure. Thus, the demand for MMCs in manufacturing operations increased because of the high specific characteristics, such as strength, wear resistance, stiffness, and lightweight. Therefore, MMCs can be used in automotive, space, and nuclear plants as an alternative to traditional materials [5]. Non-traditional machines allow materials to be removed from the work surface virtually without any tool wear compared to cutting operations. However, non-traditional cutting methods are considered not economically feasible due to the high energy consumption and thus they are used in the operation of materials and complex shapes that are difficult to cut with the conventional cutting methods [4]. Boron carbide and silicon carbide are important industrial ceramic materials, and they are the hardest types of ceramics after diamond and boron nitride [6].

K. Radakrisan et al. investigated the electrical discharge machining of aluminum metal matrix and analyzed the influence of different input machine conditions on the output. The analysis was done by using response surface methodology, and a prediction equation was developed for material removal rate and surface roughness [7]. *Krishna Mohona et al.* studied the hardness produced in the electrical discharge machining by considering the simultaneous impact of varying machine conditions. Experiments were performed on titanium alloy (Ti6A14V), low carbon steel (15CDV6), aluminum alloy (HE15), and maraging alloy (M-250) at various voltages and currents, and the corresponding data of hardness were obtained [8].

P. Cichosz and P. Karolczak presented the effect of different machining variables on the fibers and matrix material in the affected zone in the electrical discharge machining. The investigation showed the effect of the surface layer in the machining scanning microscope of aluminum made by the electrical discharge process parameters. Roughness measurements were used to analyze the surface after processing. The low current caused a thin layer with increased toughness, and the reinforcing fibers were generally left undamaged [9]. *S. Dhar et al.* found that the matrix composites of aluminum are difficult to manufacture because of the appearance of brittle and hard ceramic strengthening. Therefore, aluminum-metal-particle reinforced matrix composites are used due to their properties, especially in those applications that do not require thermal conditions or heavy loading (for example, automotive components) and have relatively low costs. The influence of current (Ip), air gap (v), and pulse on the time (Pon), tool wear rate, radial over cutting, and (MRR) of Al-MMC fabricated with a strengthening of 20% SiC was studied [10].

Kumar et al. stated that the response surface methodology is a technique for evaluating the electrical discharge machining conditions of the aluminum-based hybrid MMC [11]. *Velmurugan* indicated that a rotatable composite design is one of the methods for determining the input parameters of the electrical discharge machining of Aluminum 6061 hybrid MMCs. Electrical discharge machining of the hybrid (Aluminum-5%SiC-5%B4C) and (Aluminum-5%SiC-5%Glass) MMCs and the L_9 orthogonal array with a copper electrode was investigated [12].

S. Suresh Kumar et al. used aluminum alloy (Al 6351) reinforced with 5%SiC and 10%B_4C particles to improve the EDM parameters through surface roughness, electrode wear rate, and energy consumption [13]. *L. Straka and G. Dittrich* described the mechanism of MR and its physical regularities in the EDM of an electrode tool steel [14]. *Abbas F. Ibrahim et al.* studied the prediction values of material removal rate and surface roughness in EDM by using aluminum alloy (6061) [15].

Nadimpalli Sarada Purnima et al. introduced the simultaneous optimization of surface roughness and the microhardness of D_2 (alloy steel) during the EDM with a tungsten carbide (WC)/cobalt (Co) electrode using powder metallurgy by considering the electrode and machine tool parameters [16]. *Timur R. Ablyaz et al.* conducted electrostatic pretreatment with a hybrid magnetic field assisted powder mixed on silicon carbide (Al-SiC) metal matrix composite, and it was observed that the curing variables, for example, current, pulse on time and pulse off time affected the duration and type of dielectric conditions significantly on the MRR. The fine hardness and roughness of the machined composite material [17].

The importance of the research lies in the manufacture and operation of Al alloy (6061) reinforced with 5% silicon carbide and 10.% boron carbide, and a hybrid composite has been fabricated through stir casting, which is characterized by high wear resistance, stiffness, and lightweight and can be used in molds, automobile industry, and nuclear plants. In the present work, an investigation has been made to identify the influence of EDM parameters on the Al (6061)-SiC-B_4C hybrid composite using Box-Behnken design to evaluate the process by material removal rate and surface roughness, and the corresponding EDM conditions are Ip, Pon, and duty factor (df).

2. Experimental procedures

In this work, aluminum matrix-based composite reinforced with silicon carbide and boron carbide were used as a workpiece. The stir casting technique was used to produce the bulk material. Al-alloy (6061) cast material was preheated in an electrical furnace at 450 °C for about 4 hours before melting. The SiC and B_4C powders have a complex form with sizes varying between 1 and 25 μm, and these reinforcement particles were also preheated at about 1000 °C to 1200 °C to make their surface oxidized. In the MMC manufacturing process, the molten metal is stirred up by mechanical stirring for distributing the hardening powder.

The mechanical properties in the use of this method can be affected by the process conditions, such as the stirring speed as well as the set temperature. After proper stirring, the melt was poured into the mold of length, width, and thickness of 40 mm, 30 mm and 10 mm, respectively, and it was also allowed to cool at room temperature. Carbide silicon and boron reinforced MMCs have high stiffness, maximum thermal conductivity, high strength, and low density. Thus, AMMCs are used in high demanding applications, such as brake rotors, pistons, and pushrods [13, 18, 19]. The mechanical properties of the hybrid composite workpiece are listed in Table 1. The tensile strength and yield strength of the fabricated composites were determined as per standard test methods for tension testing wrought and cast aluminum- and magnesium-alloy products. The prepared composite material is depicted in Figure 1.

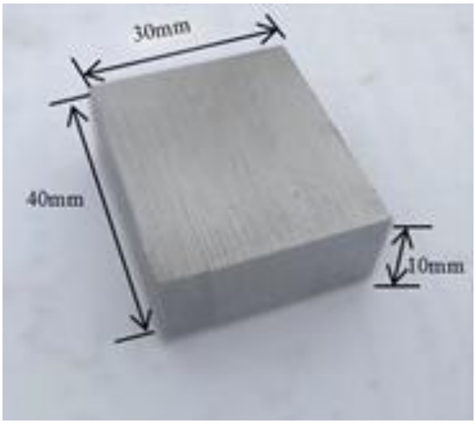

Fig. 1. Composite material workpiece.

CNC-based EDM machine “CHEMER CM 323C”, as illustrated in Fig. 2, was used in the experiments. A copper rod with a diameter of 10 mm was selected as a tool electrode material because it possesses good characteristics efficiently; the chemical composition of the tool, which was the test in the “Central Organization for Standardization and Quality Control”, is presented in Table 2. The kerosene was used as dielectric fluid.

Fig. 2. EDM Machine.

Table1. Mechanical properties of the composite.

Composite Hardness (N/mm^2)	Tensile strength (N/mm^2)	Yield strength (kg/m^3)	Density (HB)
Al-5 wt.% SiC-10wt.% B_4C 75.77	138.43	106.28	2703

Table2. Composition of the copper tool.

Material	Zn%	Pb%	Sn%	Au%	Si%	Bi%	Sb%	Te%	Cu%
Weight%	0.0029	<0.005	0.003	0.0004	0.010	0.003	0.033	0.015	Rem

After machining, the MRR will be determined by dividing the weight of the workpiece before and after machining by the machining time that was achieved [20]:

$$MRR = (WPB - WPA)/MT \qquad 1$$

Where MRR is the material removal rate (g/min), WPB is the weight of the workpiece before machining (g), WPA is the weight of the workpiece after machining (g), MT is the machining time (min). The surface roughness (Ra) was measured by a portable gauge of surface roughness Mahr Federals. The input factors, namely current (Ip), pulse on time (Pon), and duty factor (Df) with three levels for each parameter are given in Table 3.

Table 3. Machining conditions for the experimental work.

Parameters	Symbol	Grade		
		1	2	3
Current (A)	I	10	20	30
Pulse on duration(µs)	Ton	50	100	200
Duty factor	Df	4	6	8

Where the duty factor was calculated by:

$$Duty\ factor(Df) = \frac{Pulse\ on\ Time}{Pulse\ on\ Time - Pulse\ off\ time} \qquad 2$$

The design of experiments for this work includes 15 tests, using the three levels Box-Behnken research plan, and this technique was used to check the significance of the models developed. Each test involves 9 passes of an electrode, as illustrated in Table 4.

Table 4. Machining parameters according to Box- Behnken design.

	Benhaken code			Machining Factors				
No.	X_1	X_2	X_3	I(A)	Ton (µsec)	Df%	MRR (mm^3/min)	Ra (µm)
1	0	-1	1	20	50	0.65	43.76	1.73
2	-1	-1	0	10	50	0.45	39.35	1.57
3	1	0	1	30	100	0.65	44.96	2.44
4	1	1	0	30	200	0.45	43.31	2.63
5	0	0	0	20	100	0.45	39.24	2.12
6	-1	1	0	10	200	0.45	37.22	1.94
7	0	1	-1	20	200	0.25	41.64	2.42
8	0	-1	-1	20	50	0.25	40.23	1.23
9	0	1	1	20	200	0.65	38.47	2.54
10	1	0	-1	30	100	0.25	40.45	2.62
11	-1	0	1	10	100	0.65	40.13	1.98
12	1	-1	0	30	50	0.45	44.83	2.26
13	-1	0	-1	10	100	0.25	38.58	1.34
14	0	0	0	20	100	0.45	39.79	2.23
15	0	0	0	20	100	0.45	39.11	2.17

Optimal design of experiments

Response surface methodology is used to estimate the relationship model, since it is an important and useful tool, and utilized with factors as a general optimal alternative to the chosen design. Designs consisting of more experiences can be created using the Global Design Optimizer. Box-Behnken's best design procedures include level selection, design points selection, and installation model selection. All design points are selected from the set of filter points according to the given model [17,21]. The multiple regressions proposed for this model are a three-way interaction and a quadratic equation:

$$yi = \alpha_i + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{1i} X_{2i} + \beta_5 X_{1i} X_{3i} + \beta_6 X_{2i} X_{3i} + \beta_7 X_{1i}^2 + \beta_8 X_{2i}^2 + \beta_9 X_{3i}^2 \quad 3$$

Where:
Yi: Material removal rate (mm^3/min) or surface roughness (µm)
X_{1i}: Current amplitude (A)
X_{2i}: Pulse on time (µs)
X_{3i}: Duty factor
α_i: Constant value
β: Variable coefficients.

The criterion variable in this model is the MRR and Ra, while the predictor variables are current amplitude (A), (Pon), and (Df). Variables of the electrical discharge process can be used to predict and analyze the rate of MRR and Ra, thus improving the product quality.

Results and discussion

According to the theory of the experiment, the present work was performed, and the RSM (Box-Behnken design) was selected. The Minitab software was used to achieve the regression analysis and calculate the polynomial coefficients. The MRR and Ra from the work of experiments were established to get the coefficients of the regression model from the applied surface response methodology in Minitab software which is entered in equation 3. The following prediction equations were derived to explain the predictive MRR and Ra as a function of the tested control factors:

$$MRR = 32.37 + 0.2284\,X_1 - 0.0128\,X_2 + 17.60\,X_3 + 0.000218\,(X_2)^2 - 0.1208\,X_2 * X_3 \qquad 4$$

$$Ra = -0.943 + 0.0851\,X_1 + 0.01470\,X_2 + 2.725\,X_3 - 0.000041\,(X_2)^2 - 0.1025\,X_2 * X_3 \qquad 5$$

In equations (4) and (5), it was also clear that the duty factor (X_3) was the maximum significant machining parameter and impact on the predicted MRR and Ra, respectively.

From Fig. 3, the material removal rate mainly depends on the current amplitude and pulse on time and alters from 38 to nearly 44 mm^3/min (it increases with the current amplitude and decreases with the pulse on time). While the effect of current amplitude and duty factor on the MRR is shown in Fig. 4. Where the MRR increases with the increase of current amplitude value.

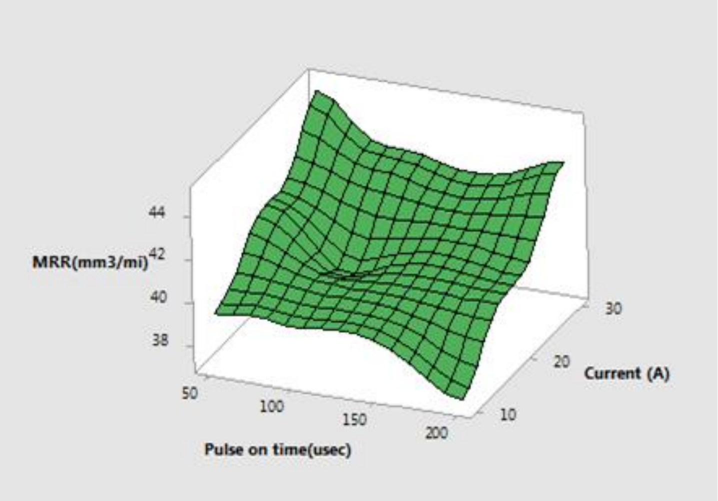

Fig. 3. 3D plot for the effect of current amplitude and pulse time on MRR.

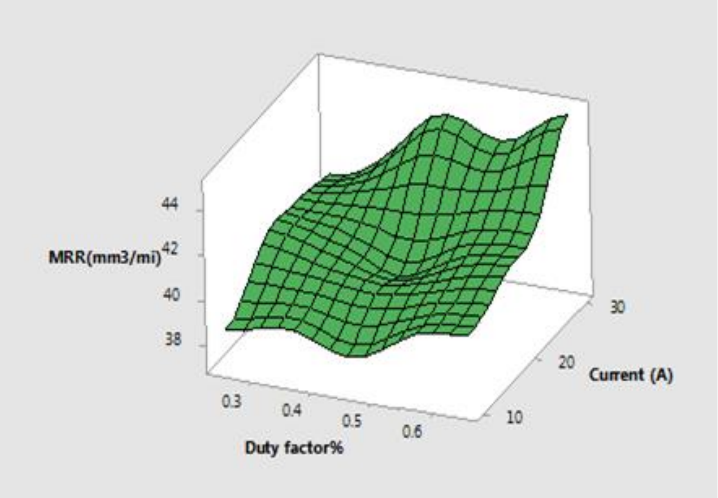

Fig. 4. 3D plot for the effect of current amplitude and Df on MRR.

Fig. 5 manifests the effect of duty factor and pulse on time on the MRR, where the maximum value of the material removal rate occurs at duty factor (0.6%) and pulse on time (50 µsec).

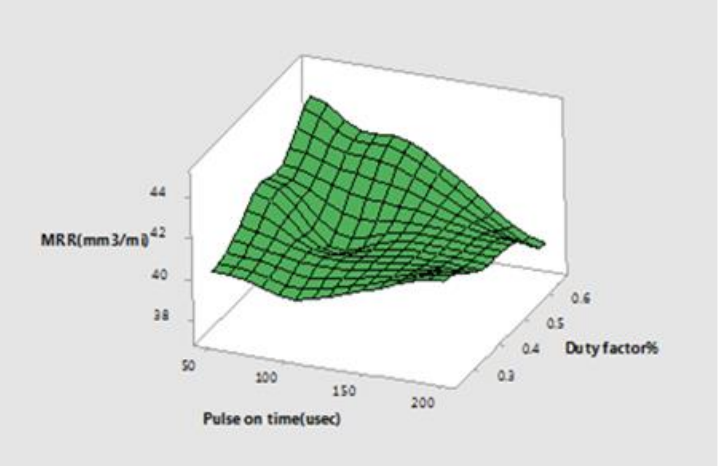

Fig. 5. Relationship among MRR, Pon, and Df.

The influence of the interaction of Ip and Pon on the Ra is evinced in (Fig. 6 and Fig. 7). Ra increases with current, whereas the Pon and Df do not change significantly.

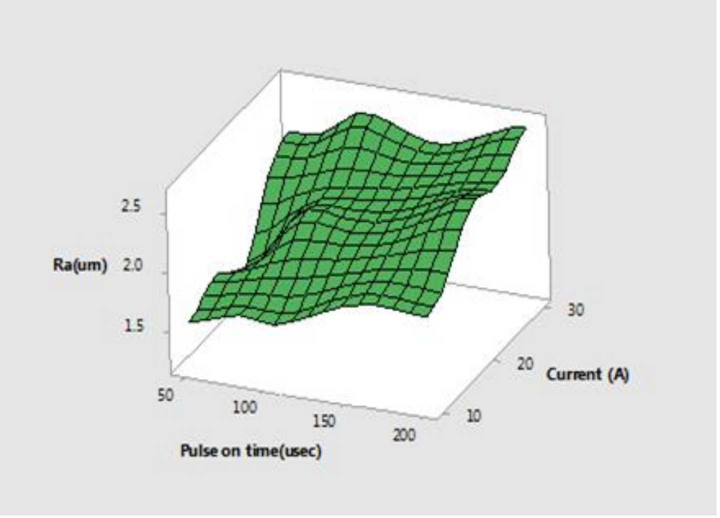

Fig. 6. Relationship among surface roughness, Ip, and Pon.

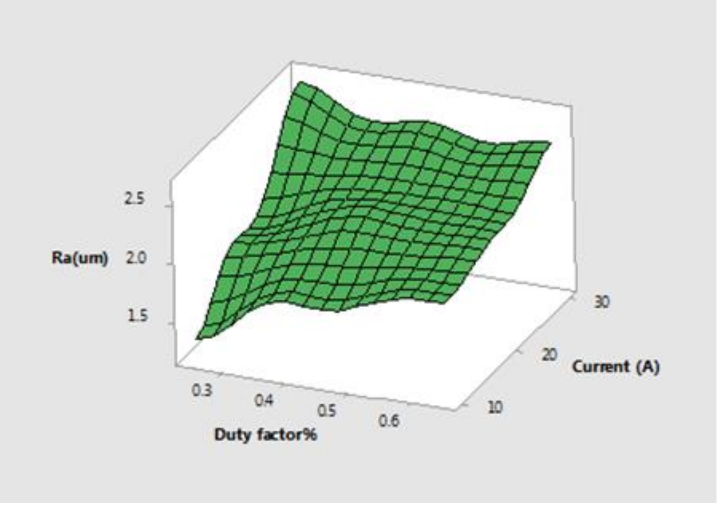

Fig. 7. Relationship among Ra, Ip, and Df.

From Fig. 8, it has been noted that whenever the duty factor and Pon increase, the Ra increases, and the minimum Ra is at the lowest duty factor (0.3%) and Ton (50 µs). While the maximum Ra takes place at the lowest duty factor (0.3%) and the highest value of pulse on time (200 µs).

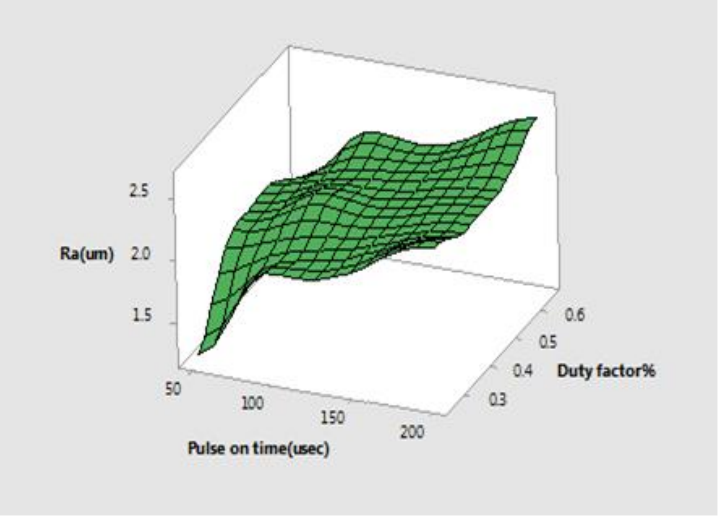

Fig. 8. Relationship between Ra, Pon, and Df.

It has been observed from Figs. (3-8) that the increases of the Ip and Pon increase the MRR and Ra values because of the high energy value of the sparks. This is due to the current Pon pulses remaining active in the circuit. The maximum value of the pulse at the specified time exhibits the maximum current amplitude and this value is the cause of the spark. Therefore, a correspondingly higher capacity value increases the spark energy which serves to remove the unwanted material from the surface. A higher Pon value removes a high amount of material compared to a lower Pon. The material removal rate and surface roughness values are found to decrease with the increases in the duty factor due to the decreasing value of spark power in the circuit. Since the Pon is the time gap between two successive pulses in a circuit, so if the time gap between two successive pulses decreases, then the value of the current during a given time also decreases. Figures 9 and 10 demonstrate the normal probability plots of the residuals response for the material removal rate and surface roughness, respectively, and checking this segment in the figures portrays that the residual values generally lie on a straight line which means that the errors are normally distributed.

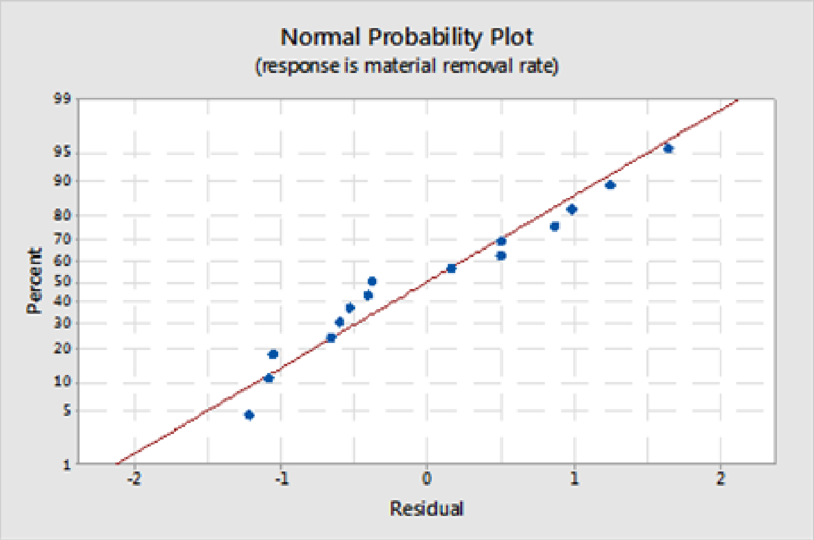

Fig. 9. Probability normal plot for the improvement of average MRR.

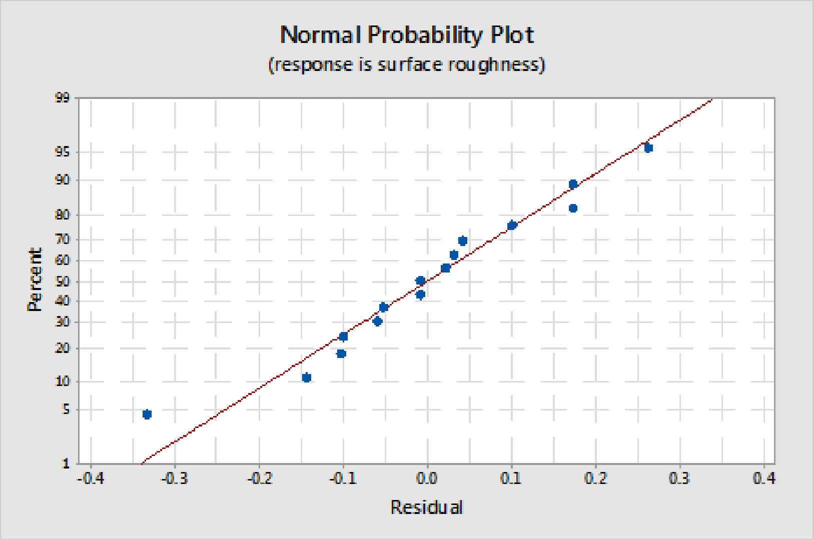

Fig. 10. Probability normal plot for the improvement of average Ra.

SEM analysis of machined surface

Figures 11 and 12 elucidate the analysis of the microstructure of experiments 2 and 4, respectively, where the machining parameters in Fig. 11 are at current (10 A), pulse on time (50 µsec), and duty factor (0.45%). While, the machining parameters in Fig. 12 at current (30 A), pulse on time (200 µsec), and duty factor (0.45%), displayed the presence of a large amount of molten material on the surface as well as deep holes and small cracks. When the Pon value is increased in time, more discharge energy is released, thus generating more heat, which leads to the melting and evaporation of the material particles from the workpiece surface and the formation of large dark holes on the surface. The remaining molten material sticks back to the surface to form debris and spherical pellets. When the carbon interacts with the molten metal, it bonds more than the original element naturally during the cooling process, and when the pressure on the surface exceeds the final tensile strength of the material, cracks form.

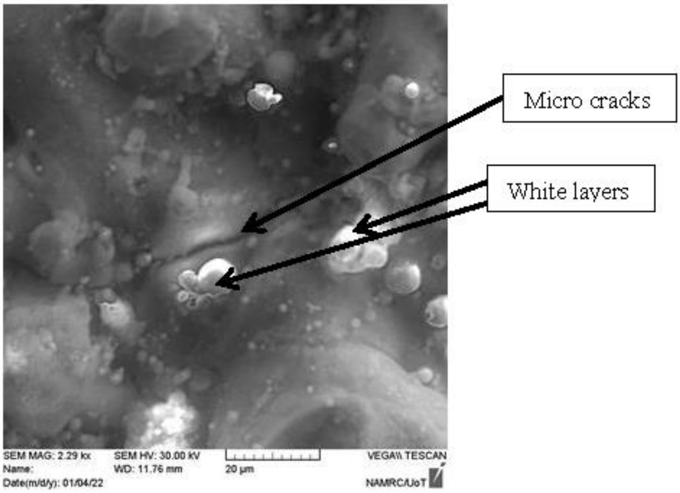

Fig. 11. Microstructure of Machined surface at a low energy input.

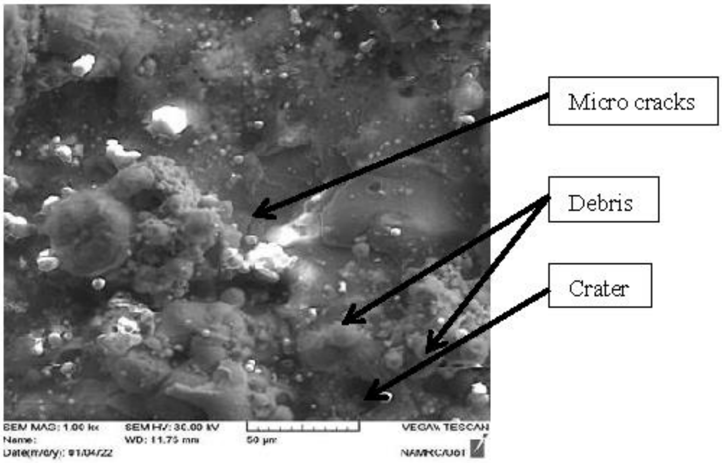

Fig. 12. Microstructure of machined surface at a high energy input.

Conclusions

In this work, experiments of the electrical discharge machining were conducted to examine the effect of EDM parameters on the material removal rate and surface roughness of the Al (6061)-5%SiC-10%B_4C hybrid composite material as a workpiece that was successfully fabricated through the stir casting route. The present work was conducted using the selected input parameters, namely current amplitude, pulse on time, and duty factor. Box-Behnken design was used to predict the optimum input parameters for achieving a higher material removal rate, and lower surface roughness. The duty factor was the maximum significant machining parameter and impact on the predicted MRR and Ra. The increase in Ip and Pon increased the discharge energy of the electrical spark and produced a poor surface finish. Because of the minimum value of the spark energy in the circuit, the values of MRR and Ra decreased with the increases in the duty factor value. It is found that all the three machining parameters in the current study have a significant influence on the material removal rate and surface roughness. When the Pon value is increased with time, more discharge energy is released, thus generating more heat, which leads to the melting and evaporation of the material particles from the workpiece surface causing the formation of large dark holes on the surface.

References

[1] A. Goyal: Journal of King Saud University Science, 29 (2017) 528–535.

[2] S. Chikalthankar, V. Nandedkar, S. Borde: Journal of Engineering Research and Development, 7 (2013) 31-34.

[3] S. Shamsudin, M. Shaik Yusof: International Engineering Convention, 11 (2009) 257- 268.

[4] Z. Liao, A. Abdelhafeez, H. Li, Y. Yang., Diaza G., and D. Axinte: International Journal Machine Tool Manufactiurng, 143 (2019) 63-91.

[5] K. Bch, J. Kumar, and H. Singh: IJRMET, 4 (2014) 27-32.

[6] A. Fadhil Ibrahim: IIUM Engineering Journal, 23 (2022) 349-357.

[7] K. Radakrisan, A. Antony, K. Rajaguru, S. Dinesh: Advances in Natural and Applied Sciences, 11 (2017) 809.

[8] G. Mohana, D. Hanumantha: Journal of Engineering and Applied Sciences, 5 (2010) 72-81.

[9] P. Cichosz, P. Karolczak: Materials Science, 26 (2008) 2172-2192.

[10] S. Dhar, R. Purohit., N. Saini, A. Sharma, G. Kumar: Journal of Materials Processing Technology, 194 (2007) 24-29.

[11] R. Kumar, and I. Singh, and D. Kumar: Procedia Engineering, 64 (2013)1337–1343.

[12] C. Velmurugan, R. Subramanian, S. Thirugnanam, B. Ananadavel: International Journal Engineering Science Technology, 3 (2011) 87–101.

[13] S. Suresh Kumar, M. Uthayakumar, S. Thirumalai Kumaran, P. Parameswaran, E. Mohandas: Hindawi Publishing Corporation Modeling and Simulation in Engineering, 2014 (2014).

[14] S. Luboslav, D. Gabril: MM Science Journal, (2020) 3955-3959.

[15] A. Fadhil I., A. Mostafa, K. Safaa: Engineering & Technology Journal, 34 (2016) 2796-2804.

[16] N. Sarada Purnima, P. Srinivasa Rao, S. Prasad Dora: Metallurgical and Materials Engineering, 27 (2021) 331-350.

[17] T. Rizovich Ablyaz, P. Singh Bains, S. Singh Sidhu, K. Ravilevich Muratov, E. Sergeevich Shlykov: Micromachines, 12 (2021) 2-13.

[18] A. Gore, N. Patil: Procedia Manufacturing, 20 (2018) 41-52.

[19] Bhanudas Bachchhav: International Journal of Industrial Engineering & Production Research, 32 (2021) 93-103.

[20] A. Fadhil Ibrahim: Journal of Physics Conference Series 1973 (2021) 1-9.

[21] R. Myers, R. Montgomery, D. Anderson, C. Anderson: Response Surface Methodology Process and Product Optimization Using Designed Experiments, 4th Edition (2016).