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Experimental Investigation of B_4C Particulate Reinforced Aluminium 6061 Based Composite Material in Wire-Cut EDM

Ş. Karabulut, U. Gökmen[*], H. Karakoç, Ö. K. Kalkan, and R. Çıtak[**]

Hacettepe University,
Department of Mechanical Program,
06935 Ankara, Turkey
[*]*Gazi University,*
Technical Sciences Vocational School,
06935 Ostim, Ankara, Turkey
[**]*Gazi University,*
Faculty of Technology,
Department of Metallurgy and Materials Engineering,
06500 Ankara, Turkey

In the present paper, the influences of cutting parameters on surface roughness in wire electric-discharge machining of (WEDM) process of particle-reinforced aluminium AA6061 alloy composite are investigated. The composites are produced using 15% wt. B_4C fraction using powder metallurgy. Experimental trials are performed based on Taguchi L18 ($2^1 \times 3^2$) with a mixed orthogonal array, and the WEDM cutting parameters are optimized for the best surface quality. The investigation results are evaluated by response surface plots and main effect graphs. The machined surface of the metal matrix composite is investigated using scanning electron microscopy (SEM) micrographs. The effect of WEDM machining variables are determined using analysis of variance (ANOVA). The analysis result shows that the most significant cutting parameter is peak current for surface roughness. The SEM and optical micrographs indicate that the reinforced B_4C particles are homogeneously distributed in the matrix structure. Mathematical models are also generated using regression analysis for the surface roughness. Confirmation tests are carried out to determine the prediction performance of the mathematical models, and the surface roughness is predicted with an acceptable mean squared error.

В цій роботі досліджено вплив параметрів різання на шерсткість поверхні при обробленні на електроерозійному вирізному станку (ЕЕВС) композита алюмінійового стопу АА6061, армованого частинками. Композити вироблялися з використанням 15% вагової фракції B_4C методою порошкової металургії. Експерименти виконувалися на базі Taguchi L18 ($2^1 \times 3^2$) зі змішаним ортогональним масивом; параметри ЕЕВС-оброблення різанням оптимізувалися, щоб одержати найкращу якість поверхні. Результати досліджень оцінювалися за графіками поверхні відгуку та головного ефекту. Оброблена поверхня композитної металевої матриці досліджувалася з використанням мікрознімків сканівної електронної мікроскопії (СЕМ). Вплив ЕЕВС-оброблення визначався за допомогою дисперсійної аналізи (ДА). Аналіза результатів показала, що найбільш істотним параметром різання для шерсткости поверхні є піковий струм. СЕМ та оптичні мікрознімки показали, що армувальні частинки B_4C розподілені в структурі матриці рівномірно. З використанням реґресійної аналізи були також зґенеровані математичні моделі для поверхневої шерсткости. Випробування на відповідність технічним умовам були виконані з метою попередньої оцінки математичних моделів, і поверхневу шерсткість було спрогнозовано з припустимою середньоквадратичною похибкою.

В данной работе исследовано влияние параметров резания на шероховатость поверхности при обработке на электроэрозионном вырезном станке (ЭЭВС) композита алюминиевого сплава AA6061, армированного частицами. Композиты производились с использованием 15% весовой фракции B_4C методом порошковой металлургии. Эксперименты производились на базе Taguchi L18 ($2^1 \times 3^2$) со смешанным ортогональным массивом; параметры ЭЭВС-обработки резанием оптимизировались с целью получения наилучшего качества поверхности. Результаты исследований оценивались по графикам поверхности отклика и главного эффекта. Обработанная поверхность композитной металлической матрицы исследовалась с использованием микроснимков сканирующей электронной микроскопии (СЭМ). Влияние ЭЭВС-обработки определялось при помощи дисперсионного анализа (ДА). Анализ результатов показал, что наиболее существенным параметром резания для шероховатости поверхности является пиковый ток. СЭМ и оптические микроснимки показали, что армирующие частицы B_4C распределены в структуре матрицы равномерно. С использованием регрессионного анализа были также сгенерированы математические модели для поверхностной шероховатости. Испытания на соответствие техническим условиям были проведены с целью предварительной оценки математических моделей, и поверхностная шероховатость была спрогнозирована с приемлемой среднеквадратичной погрешностью.

Key words: wire electric discharge machining, surface roughness, Taguchi method, response surface methodology.

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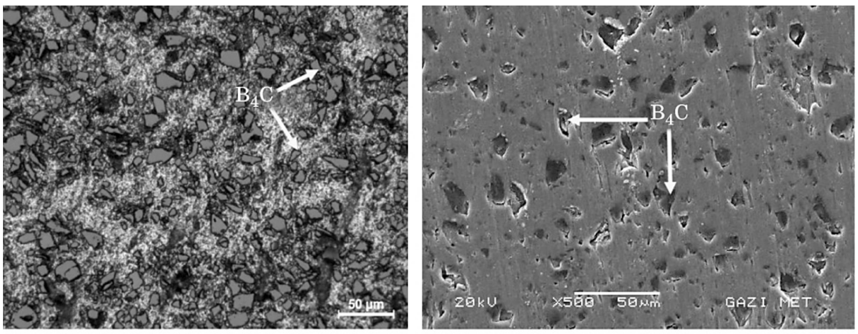
1. INTRODUCTION

Metal matrix composites (MMCs) have been widely investigating in recent years and are now utilized in many engineering fields including aerospace, military, automotive industries, electronic packaging, and sporting goods because of their low density in combination with their excellent wear resistance, high specific strength, hardness, and fracture toughness [1–6]. However, machinability of MMCs is considered difficult in connection with hard reinforcement elements in matrix structure [1–7]. Boron carbide (B_4C) is extremely hard reinforcement material with the superior properties such as good wear resistance, high hardness, low specific weight, corrosion resistance, high melting point, adequate resistance to chemical agents, and good mechanical properties. These outstanding performances of B_4C made it a preferable reinforced material, widely used in numerous industrial applications requiring high resistance, such as the nuclear industry, for tank armour, and ballistic protections. Hence, several researchers have studied the production and machinability properties of MMCs reinforced with B_4C in recent years [8, 9]. However, there are two main problems hindering the superior properties of B_4C, one is that very high temperature is required for its sintering and the other is the low fracture toughness [10]. Wire electrical discharge machining (WEDM) is a high precision machining method widely used for hard materials, metallic alloys, and graphite that would be very difficult to cut with traditional machine tools using the best economic cutting tools. In wire-cutting technique, a thin single-strand metal wire is machined the workpiece submerged in a tank of deionized water to utilize heat from electrical sparks. WEDM uses a nonstop cutting wire electrode to machine the desired shape alongside the cutting path using 0.05–0.30 mm in diameter thin copper, brass or tungsten wire and can machine very small corner radius with high precision [11]. Motorcu *et al.* studied the influence of cutting parameters on the surface roughness and material removal rate (MRR) in cutting of Al/B_4C/Gr hybrid composites using WEDM dependence on the wire speed, pulse-on time and pulse-off time. They observed that the most significant parameter on surface roughness and MRR was the wire speed with 85.94% contribution rate [12]. Yan *et al.* investigated the effects of machining process on surface roughness (R_a), cutting width, and material removal rate and wire breakage behaviour in the WEDM of Al6061 composites with different reinforcement ratios of Al_2O_3. The test results showed that the Al_2O_3 reinforcement volume fraction influences on the R_a, kerf and MMR. They also reported that a high wire speed, very low wire tension, and high flushing rate must be chosen to prevent wire breakage [13]. Shandilya *et al.* studied the effect of the input parameters on average cutting speed during WEDM of Al6061/SiC metal matrix composite. Servo voltage is the more significant input parameter for average cutting speed than pulse-off time and wire feed rate [14]. The surface roughness and material removal rate were increased with increase in pulse-on time and decreased with increase in pulse-off time. MRR was influenced by interactions between pulse-on time (T_{on}) and pulse-off time (T_{off}), pulse-on time (T_{on}) and peak current (IP), pulse-off time (T_{off}) and peak current (IP). Pulse-on time (T_{on}) and peak current (IP) affected the machined surface roughness [15]. Satish Kumar *et al.* investigated the effects of different machining parameters on MRR and R_a in the WEDM of Al6063/SiC MMC at different reinforcement ratios. The researchers reported that surface quality and MRR were decreased with the increasing percentage volume fraction of SiC particles [16]. Surface roughness and gap width were mainly affected by the pulse-on time in the WEDM of Al 6061 reinforced with Al_2O_3 particle MMC [17]. Pulse-on time and current were the most effective parameters for machining speed and surface quality in the WEDM of Al–SiC metal matrix composite [18].

2. EXPERIMENTAL MATERIALS AND METHOD

The experimental workpieces were produced from high-purity aluminium 6061 mixed with 15% commercial-grade B_4C powders using powder metallurgy method. The median size of Aluminium 6061 powder used in metal matrix composite (MMC) was 100 μm and B_4C powders had average size of 10 μm. Aluminium alloy and B_4C powders were mixed to achieve homogeneity for 45 minutes in a three-dimensional Turbula mixer. The mixed powders were compacted by cold pressing under 300 MPa. The specimens were sintered in a vacuum furnace at 550°C for 60 minutes and extruded using a pre-heated extrusion mould of temperature 500°C for 1 hour. The thickness of produced composite sheets was 12.7 mm. Workpiece materials were analysed using a JEOL JSM 6060 LW scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS). The optical and SEM micrograph of the surface texture of the machined composite and B_4C reinforcement elements can be seen in Fig. 1. The optical and SEM micrographs indicat-



a *b*

Fig. 1. Microstructure of Al6061/B_4C.

TABLE 1. Chemical composition of Al6061 alloy elements.

Element	Fe	Si	Cr	Mn	Mg	Zn	Cu	Ti	Al
Al6061	0.5	0.6–1.0	0.1	0.2–0.8	0.8–1.2	0.25	0.6–1.1	0.1	Balance

TABLE 2. Mechanical properties of Al6061/B_4C.

Workpiece material	Hardness, *HV*	Impact energy, J	Maximum tensile stress, MPa	Maximum flexure stress, MPa
Al6061	68.2	26.3	201	467
15% wt. B_4C	74	6.1	194	456

ed that the B_4C particles distribution is fairly uniform in composite specimen and achieved a good interfacial bonding between matrix and B_4C particles. The chemical compositions and mechanical properties of Al6061 alloy and reinforced with 15% wt. B_4C metal matrix composite are presented in Table 1 and Table 2, respectively. The hardness measurements of specimens were performed by Vickers *HV*3 hardness machine EMCO TEST Duravision 200 applying a load of 3 kg for a period of 5 s. The average hardness value for each sample was obtained by measuring five different areas. Impact energy of composite samples was tested using sharply impact-testing machine Instron Wolpert PW30 with maximum hammer energy of 150 J. Impact tests were applied to V-notched specimens for fracture toughness determination of composite samples according to EN ISO 148.01. Tensile and flexural tests were performed using Instron 3363 universal testing machine at a constant strain rate of 1 mm/s. Every impact, tensile and flexural tests were employed at least three times, and the average value for each set of the composites samples was calculated.

The experiments were performed on the Mitsubishi MV1200 series CNC WEDM. Rectangular parts of size 31.7×6.35×12.7 mm^3 were cut from the workpiece material as shown in Fig. 2. A brass wire electrode of diameter 0.30 mm was used as the cutting tool for conducting the experiments and deionized water was used as the dielectric fluid. The machined surface of the workpiece was measured using Mitutoyo Surftest SJ210 device. Surface quality was measured at four different machined surfaces and the average surface roughness value was calculated. Machining parameters and their levels used in the WEDM of MMCs are listed in Table 3.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The purpose of this study is to investigate the effect of wire-EDM ma-

a *b*

Fig. 2. Experimental set-up for WEDM machining.

chining parameters on the surface roughness during cutting of B_4C reinforced metal matrix composite. The effects of spark gap voltage, peak current and wire tension on surface roughness using a brass electrode were investigated. The experiments were carried out based on the Taguchi L18 ($2^1\times3^2$) with a mixed orthogonal array and the analysis of variance (ANOVA) has been employed using statistical software Minitab 16 to determine the significant contribution of machining parameters. The experimental time and cost can be decreased using orthogonal arrays by reducing the number of tests and minimizes the effects of parameters that cannot be controlled.

Furthermore, it ensures a simple, powerful, and systematic ap-

TABLE 3. Machining parameters and their levels.

Factor	Process parameters	Level 1	Level 2	Level 3
A	Wire tension (*WT*)	10 g	13 g	
B	Spark gap voltage (*SV*)	30 V	60 V	80 V
C	Peak current (*IP*)	8 A	10 A	13 A

proach to specifying the optimal machining factors during the experiments. A number of external factors not considered in the experimental design can affect the experimental results. These external factors and their effect on the results in terms of quality characteristics are named 'the noise'. The signal-to-noise ratio (S/N ratio) computes the accuracy of the quality characteristic. The S/N ratio is calculated in two processes. First, mean squared deviation (MSD) between the experimental results and optimal values are calculated by equation (1). Second, computed MSD results are converted using equation (2) [19]. Then, the cutting parameters are analysed based on the S/N. There are three different signal-to-noise ratios and individual desirability functions: larger is better, nominal is best, and smaller is better. S/N ratio indications can be selected depending on the aim of the experiments. The objective of this investigation is to minimize the surface roughness value. Therefore, the-smaller-the-better has been chosen to calculate the S/N ratios using the following formulae:

$$MSD = (y_1^2 + y_2^2 + y_3^2 + \ldots + y_n^2)/n, \quad (1)$$

$$S/N = -10\lg(MSD), \quad (2)$$

where y is the measured value of surface roughness and n is the number of experiments in the experiments. A higher value of S/N means the signal is much higher than the random effects of noise factors. Higher values of S/N ratios are described as control factor settings that minimized the effects of the noise factor; therefore, a high signal-to-noise ratio is always preferred.

The $3D$ response surface plots that obtained response surface method by RSM model in Minitab 16 software were utilized to specify the relationship between the WEDM parameters and surface roughness as shown in Fig. 3. Response surface method is a statistical method and used to determine the relation between various independent parameters and dependent parameters. Figure 3 indicates the influence of spark gap voltage, peak current, and wire tension on the mean quality of machined surface roughness during wire-EDM of MMC. The machined surface quality was decreased with an increase in the peak current and the best surface roughness was observed at lowest peak current and wire tension. This was attributed to low cutting speed at lowest peak current. This is caused by increase of peak current that lead to a higher cutting speed and resulted the decreasing surface quality. Normally, increasing wire tension produces an improved surface quality of machined part due to reducing wire vibration and deflection [20]. On the contrary, surface quality was decreased with increase in wire tension in this study. This may be attributed to increasing forces acting on the wire electrode and wire breakage with increase in wire tension. It was also observed that the brass wire electrode was broken at

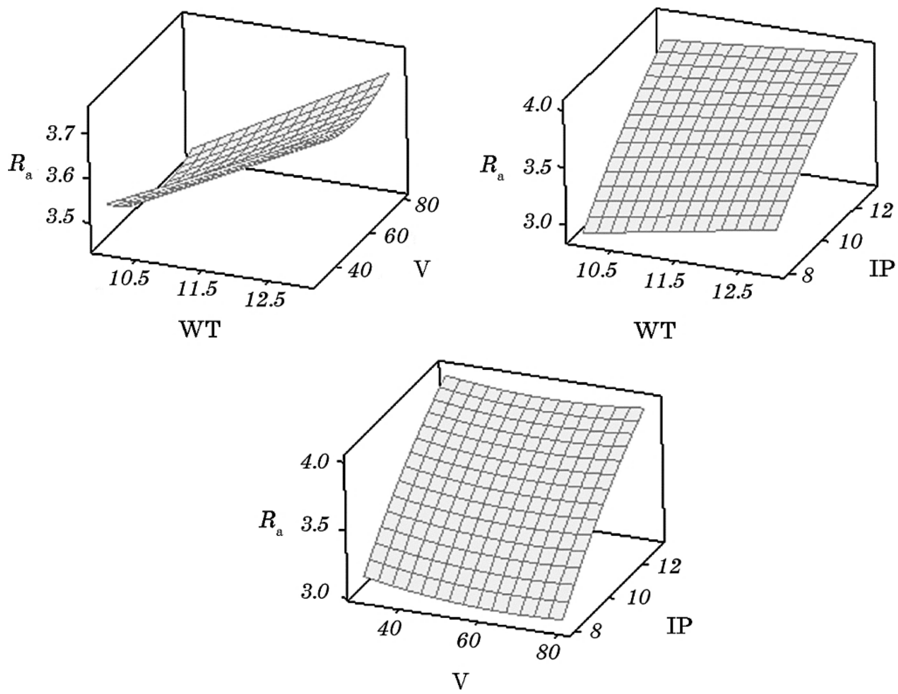


Fig. 3. 3*D* response surface plots relationship between the WEDM parameters.

higher wire tension. This can be ascribed that the harder B_4C particles caused fast wear of brass wire at higher peak current and wire tension depends on increasing cutting temperature.

One of the most significant aims of this experimental study is to determine an acceptable surface roughness using optimal machining parameters. The signal-to-noise ratios and response surface optimization methods were performed in order to specify the best cutting parameters in the WEDM of MMCs. The WEDM parameters, calculated average test results, desirability values, and the S/N ratios for surface roughness are listed in Table 4. The optimal wire-EDM parameters and their levels were determined based on the S/N ratios (Table 4). The higher S/N ratios and composite desirability values indicate the optimum machining parameters and better quality of surface roughness. The best WEDM factors based on the response Table 5 for S/N in the machining of Al6061/B_4C, the optimal surface roughness values were defined as factor A (Level 1, $S/N = 10.579$), factor B (Level 2, $S/N = 3.485$), and factor C (Level 3, $S/N = 3.077$). In the WEDM of Al6061/B_4C, the best machining parameters are determined as a peak current of 8 A, spark gap voltage of 68.89 V and wire tension of 10; the optimized surface roughness value is $R_a = 2.8849$ μm and the desirability value is 0.97336 as shown in Fig. 4.

TABLE 4. Experimental parameters and measured surface roughness values.

Trials number	Wire tension (WT)	Spark gap voltage (SV)	Peak current (IP)	Surface roughness, R_a	S/N ratio
1	10	30	8	3.06	–9.714
2	10	30	10	3.3	–10.370
3	10	30	13	4.01	–12.063
4	10	60	8	2.89	–9.218
5	10	60	10	3.43	–10.706
6	10	60	13	3.78	–11.550
7	10	80	8	2.85	–9.097
8	10	80	10	3.4	–10.630
9	10	80	13	3.92	–11.866
10	13	30	8	3.3	–10.370
11	13	30	10	3.68	–11.317
12	13	30	13	4.02	–12.085
13	13	60	8	3.21	–10.130
14	13	60	10	3.44	–10.731
15	13	60	13	4.16	–12.382
16	13	80	8	3.15	–9.966
17	13	80	10	3.78	–11.550
18	13	80	13	3.96	–11.954

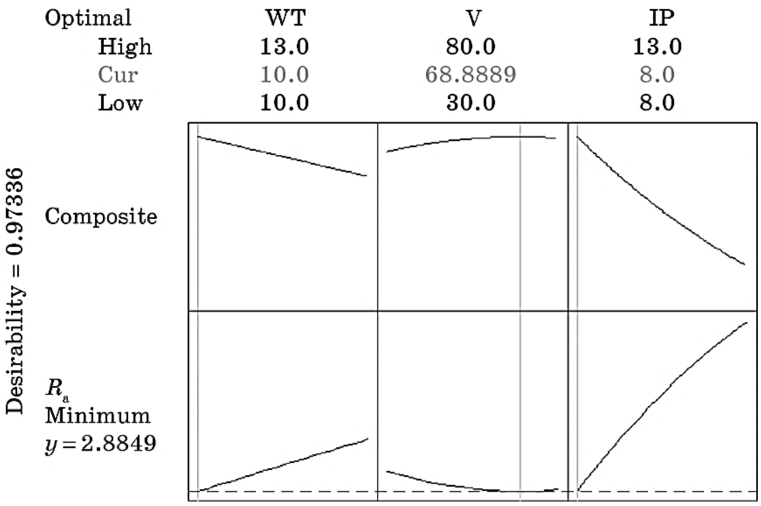


Fig. 4. Optimal wire-EDM parameters in WEDM of Al6061/B_4C.

The analysis of variance (ANOVA) and main effect plots were performed to investigate the influences parameters on surface roughness and contribution rate of wire-EDM parameters on the quality of machined surface. The statistical significance levels were analysed by the machining parameters P and F values at the 95% confidence level. If the P values are smaller than 0.05, the experimental models are considered at a significant level of 95%. The WEDM parameters, P values, and their contribution level for surface roughness are presented in Table 6. From the result of ANOVA, the peak current is the most effective machining parameters with an 84.9% contribution of total variation on surface roughness in the WEDM of Al6061/B_4C. The next effective WEDM parameter is wire tension with a percentage contribution of 8.33% for Al6061/B_4C. It was observed that the spark gap voltage was not showed a meaningful effect on surface roughness in the WEDM of MMCs.

As shown in mean effect plots in Figure 5, the effect of spark gap voltage on surface roughness was almost constant. It can be seen from the mean effect plots that surface quality was decreased with increasing peak current from 8 A to 13 A and wire tension from 10 g to 13 g. At the base of the RSM and Taguchi methods, a regression analysis equation for surface roughness was also developed. The following re-

TABLE 5. Response table for signal-to-noise ratios (smaller is better).

Level	Wire tension (WT)	Spark gap voltage (SV)	Peak current (IP)
1	–10.579	–10.987	–9.749
2	–11.165	–10.786	–10.884
3		–10.844	–11.983
Delta	0.586	0.200	2.234
Rank	2	3	1

TABLE 6. Analysis of Variance (SS—sums of squares, MS—mean square).

Source	DF	Sequential SS	Adjusted SS	Adjusted MS	F	P	Significance level, %
Regression	3	2.64982	2.64982	0.88327	68.562	0.000000	
WT	1	0.23576	0.23576	0.23576	18.300	0.000766	8.33
V	1	0.01011	0.01011	0.01011	0.785	0.390594	0.35
IP	1	2.40395	2.40395	2.40395	186.602	0.000000	84.9
Error	14	0.18036	0.18036	0.01288			6.37
Total	17	2.83018					

gression equations were obtained for Al6061/B_4C metal matrix composite using the least-square method in the regression analysis. R^2 values of the equations obtained from the regression for surface roughness were computed as 93.63%.

$$R_a = 0.869055 + 0.0762963WT + 0.00115351V + 0.177851IP, \quad (3)$$

$$R - S_q = 93.63\%.$$

In order to verify the experimental process, six confirmation experiments were carried out within the limits of predetermined WEDM conditions. The measured surface roughnesses were controlled for the precision of the predicted values calculated from models. Experimental values and predicted values with the percentage of prediction error rates are presented in Table 7. As seen in Table 7, the estimated

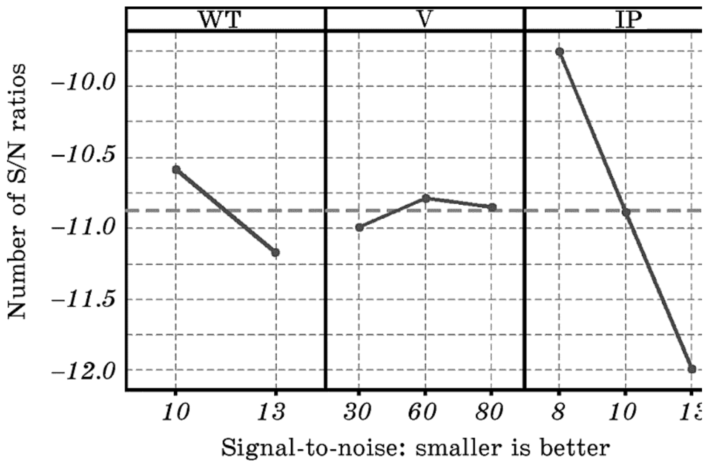


Fig. 5. Effect of machining parameters on surface roughness.

TABLE 7. Confirmation experiments and results.

Wire tension	Spark gap voltage	Peak current (IP)	Surface roughness R_a	Predicted surface roughness	Prediction error
10	8	42	3.22	3.006	6.63%
13	8	42	3.24	3.235	0.15%
13	10	42	3.51	3.591	2.31%
10	10	42	3.72	3.362	9.62%
10	13	42	4.17	3.896	6.58%
13	13	42	4.24	4.125	2.72%

values based on the regression model with the least residual errors are very close to the experimental results and prediction errors are in the acceptable range.

4. CONCLUSIONS

In this experimental study, Aluminium 6061/B_4C metal matrix composite was successfully produced by a powder metallurgy method and investigated for the effect of wire-EDM parameters on surface roughness using brass wire electrode. The WEDM experiments were performed based on the Taguchi L18 orthogonal array. The investigation results were examined using 3*D* surface plots, *S*/*N* ratio results, ANOVA, and main effect graphs. The signal-to-noise ratios, central composite desirability of response surface method, and regression model were used to specify the ideal WEDM parameters for surface roughness.

The following conclusions can be drawn from the experimental study.

The optical and SEM micrographs indicated that the B_4C particles distribution is fairly homogenized in all composite specimens and achieved a good interfacial bonding between matrix and B_4C particles.

The machined surface quality was worsening with an increase in the peak current and the best surface roughness was observed at lowest peak current and wire tension. Surface quality was decreased with increase in wire tension.

Brass wire electrode was broken at higher wire tension. It can be suggested a very low wire tension to avoid wire breakage during WEDM of MMCs with reinforced B_4C.

The optimal WEDM parameters are determined as a peak current of 8 A, spark gap voltage of 68.89 V, and wire tension of 10; the optimized surface roughness value is $R_a = 2.8849$ μm and the desirability value is 0.97336.

From the result of ANOVA, the peak current is the most significant wire-EDM parameters with an 84.9% contribution of total variation on surface roughness in the WEDM of Al6061/B_4C.

The spark gap voltage did not show a meaningful effect on surface roughness in the WEDM of MMCs.

The estimated values based on the regression model with the least residual errors are very close to the experimental results and prediction errors are in the acceptable range.

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