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Investigation of the WEDM of Al/B_4C/Gr reinforced hybrid composites using the Taguchi method and response surface methodology

Abstract: In this study, the effects of machining parameters on the material removal rate (MRR) and surface roughness (Ra) were investigated during the cutting of Al/B_4C/Gr hybrid composites by wire electrical discharge machining (WEDM). Wire speed (W_S), pulse-on time (T_{on}) and pulse-off time (T_{off}) were chosen as the control factors. The L_{27} (3^3) orthogonal array in the Taguchi method was used in the experimental design and for the determination of optimum control factors. Response surface methodology was also used to determine interactions among the control factors. Variance analysis (ANOVA) was applied in the determination of the effects of control factors on the MRR and Ra. According to the ANOVA results, the most effective parameters on MRR and Ra were wire speed with a 85.94% contribution ratio, and pulse-on-time with a 47.7% contribution ratio. The optimum levels of the control factors for MRR and Ra were determined as $A_3B_3C_3$ and $A_1B_1C_2$. In addition, second-order predictive models were developed for MRR and Ra; correlation coefficients (R^2) were calculated as 0.992 and 0.63.

Keywords: Al/B_4C/Gr hybrid composite; material removal rate; surface roughness; Taguchi method; wire electrical discharge machining.

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1 Introduction

Due to the higher strength-density ratios and excellent wear resistance of metal matrix composites (MMCs), their applications in many fields, including the aviation, automotive and military industries, has been increasing in recent years [1–3]. Wire electrical discharge machining (WEDM) is an electro erosion production process in which a thin single-strand metal wire in conjunction with deionized water (used to conduct electricity) allows the wire to cut through metal by the use of heat from electrical sparks [4]. The WEDM process is used to obtain complex products by cutting hard-to-machine metals without using more costly cutting tools [5]. WEDM utilizes a continuously travelling wire electrode of 0.05–0.30 mm in diameter made of thin copper, brass or tungsten, which is capable of achieving a very small corner radius [6]. WEDM is widely used in the industry for the machining of metals, metallic alloys and graphite (regardless of the hardness), with high precision [7]. The most important performance measures in WEDM are the metal removal rate, surface finish and cutting width [5].

Yan et al. studied the effects of cutting duration on material removal rate (MRR), cutting width and surface roughness (Ra) in the WEDM of Al_2O_3p/6061Al composites of different reinforcement ratios. In addition, wire breakage was investigated during the machining. The Al_2O_3 reinforcement volume fraction had significant effects on the *MMR*, kerf and *Ra* and in addition, it was necessary to select a very low wire tension, a high flushing rate and a high wire speed in order to prevent wire breakage [8]. Prakash et al. used the Taguchi Method (TM) to examine the effects of gap voltage, pulse-on time, pulse-off time, wire feed and percentage reinforcement on Ra and MRR in the machining of stir cast A413/Flyash/B_4C composites in WEDM [9]. The effects of type and particle size of second phase [Tungsten Carbide (WC), Titanium carbide (TiC) and Titanium CarboNitride (TiCN), from micro to nano sized particles] in ZrO_2 ceramic matrix composites on the MRR and Ra in WEDM were investigated by Lauwers et al. The particle size of the second phase, which is effective on the microstructure, and the characteristics of the material had significant effects on the WEDM performance [10]. Sharma et al. studied the effects of machining parameters in the WEDM of high-strength low-alloyed steels on the MRR and Ra by response surface methodology (RSM). The MRR and Ra values increased with the increase of pulse-on time and peak current and decreased with the increase of pulse-off time and servo voltage; according to RSM results, the wire tension had no significant effect on MRR and Ra [11]. Prakash et al. used the TM in their study on the effects of machining parameters (pulse-on time, pulse-off time, wire speed and gap voltage) on the Ra and MRR in the WEDM of stir cast Al/Flyash/B_4C [12]. Satishkumar et al. investigated via the TM the effects of pulse-on time, pulse-off time, gap voltage and wire speed on MRR and Ra in the WEDM of Al6063/SiC MMC at different reinforcement ratios. The researchers stated that MRR values decreased and Ra values increased with the increasing percentage volume fractions of SiC particles [13]. Rao and Krishna examined the optimization of Ra, MRR, wire wear ratio, kerf and white layer thickness in the WEDM of ZC63/SiCp MMCs with the aid of the TM and principal component analysis [14]. Shandilya et al. investigated the kerf in the WEDM of SiCp/Al6061 MMCs. The RSM was used in the optimization of machining parameters (servo voltage, pulse-on time, pulse-off time and wire feed rate) [15]. Shandilya et al., in another study, used RSM and artificial neural networks (ANNs) for the estimation of average cutting speed in the WEDM of SiCp/6061 Al composites [16]. Spedding and Wang investigated the effects of machining parameters (pulse width, time between two pulses, wire mechanical tension and wire speed) on cutting speed, surface roughness and surface waviness by the aid of RSM and ANNs in the WEDM of AISI 420 [17]. Tosun et al. employed the TM to examine the effects of machining parameters on the kerf and MRR of AISI 4140 tool steel in WEDM operations [18]. The effects of cutting parameters on the wire wear in WEDM were investigated by Tosun and Cogun. In their study, wire wear rate increased with the increase of pulse duration and open circuit voltage, and decreased with the increase of wire speed and dielectric fluid pressure [19].

In a survey of the literature, it was observed that not much research has been done on the WEDM of Al/B_4C MMCs and no investigation has been carried out on Al/B_4C/Gr hybrid composites. In this study, the effects of control factors (wire speed, pulse-on time and pulse-off time) on surface roughness and material removal rate were examined in the WEDM of Al/B_4C/Gr composites with the aid of the TM and RSM. As a result of this study, the effects of the control factors of B_4C/Gr hybrid reinforced composites in particular have been determined in WEDM, and these findings can serve as a reference for future studies.

2 Materials and methods

2.1 Materials, measurements and test conditions

In the production of Al/B_4C/Gr hybrid composites, 200 µm Alumix 123 alloy was used as the matrix material, and 27 µm B_4C and 150 µm Gr particles were used as the reinforcement elements. Alumix 123 matrix alloy is composed of (wt %) Cu (4.5 max), Si (0.6), Mg (0.5) and Al (balance). The percentage volume ratios of the reinforcement elements for B_4C and Gr were taken at 10% and 5%, respectively. The MMC samples were produced by cold pressing the mixed powders under 100 MPa, and then hot pressing under 40 MPa at 590°C for 15 min. The resulting samples were solution treated at 540°C for 4 h and then immersed in warm water (25°C). Finally, they were subjected to T6 heat treatment by holding in a furnace at 160°C for 12 h. The composite material produced by the hot pressing method had a density of 2.672 g/cm^3 (97.6%) and an average hardness of 138.6 HBN. The microstructure of the hybrid composite showing the B_4C and Gr reinforcement elements can be seen in Figure 1.

The tests were carried out using a Sodick AQ750LH type CNC WEDM. A copper electrode of 0.25 mm in diameter was used as the cutting tool and deionized water

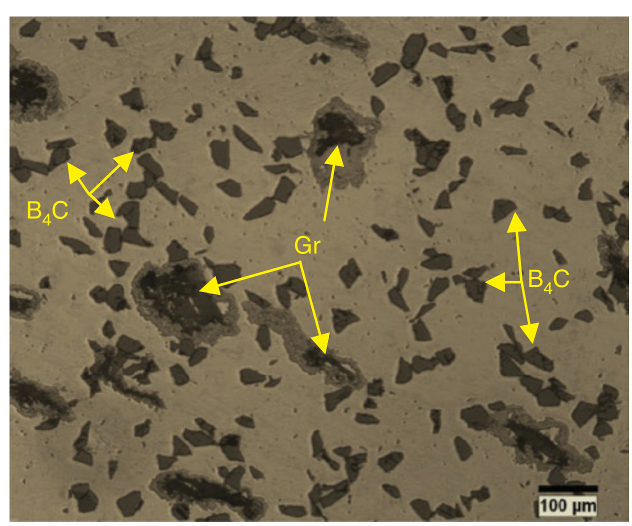

Figure 1 Microstructure of hybrid composite.

(20°C) was used as the dielectric liquid. For the kerf measurements, cuttings of, 3 mm in length were made on the workpiece apart from the surface roughness cuttings (Figure 2). Kerf widths were measured by the aid of the "Dino Capture 2.0" optical microscope and the average value of the measurements taken from five different points along the cutting length was used (Figure 2). The MRR was calculated by using Equation (1).

$$MRR = KhFR\rho \quad (1)$$

In this equation, K is *kerf*, h is workpiece thickness (10 mm), FR is cutting speed and ρ is the density of the workpiece material [18].

The Ra values were measured in order to characterize the surface quality. According to the experimental design, at the specified values of the control factors, three measurements were made from the cut surfaces and the Ra values were determined by taking the average of the measurements. The Ra surface roughness equation for this experimental study can be written as

$$Ra = \frac{1}{3}\sum_{i=1}^{a} |x_i| \quad (2)$$

Here, x_i is the measured surface roughness value. Surface roughness values were measured using a Time-TR 200 surface roughness device (Figure 3).

Table 1 Control factors and their levels.

Control factors	Wire speed (m/min)	Pulse-on time (µs)	Pulse-off time (µs)
Level 1	50	5	7
Level 2	70	7	10
Level 3	100	10	14
Symbol	A	B	C

In the WEDM of the MMCs, the factors and levels indicated in Table 1 were used and the material removal rate (MRR, g/min) and surface roughness (Ra, µm) were investigated. In the experimental study, length of cut and wire tension were kept constant as 10 mm and 180 gf, respectively. The experimental study was completed by following the procedure shown in Figure 4.

2.2 Design of experiment based on the Taguchi method

Traditional experimental design methods are complex and difficult to use. As the machining parameters increase, the number of tests also increases. For this reason, factors causing variations must be determined and be controlled

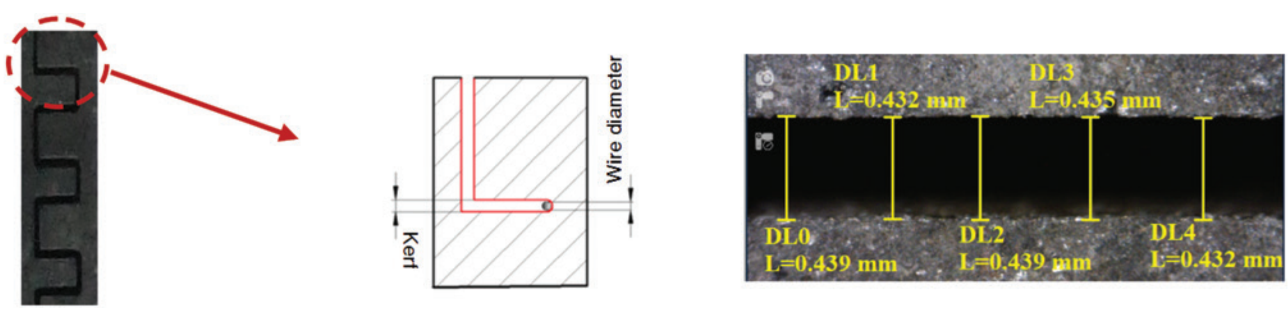

Figure 2 Workpiece after WEDM showing kerf measurement.

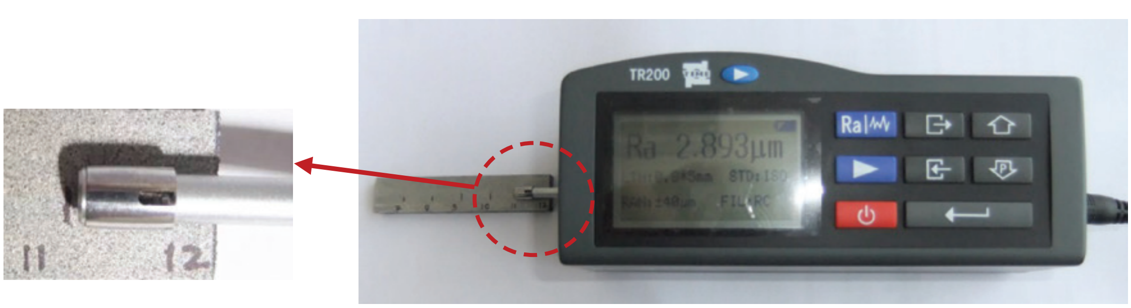

Figure 3 Surface roughness measurements.

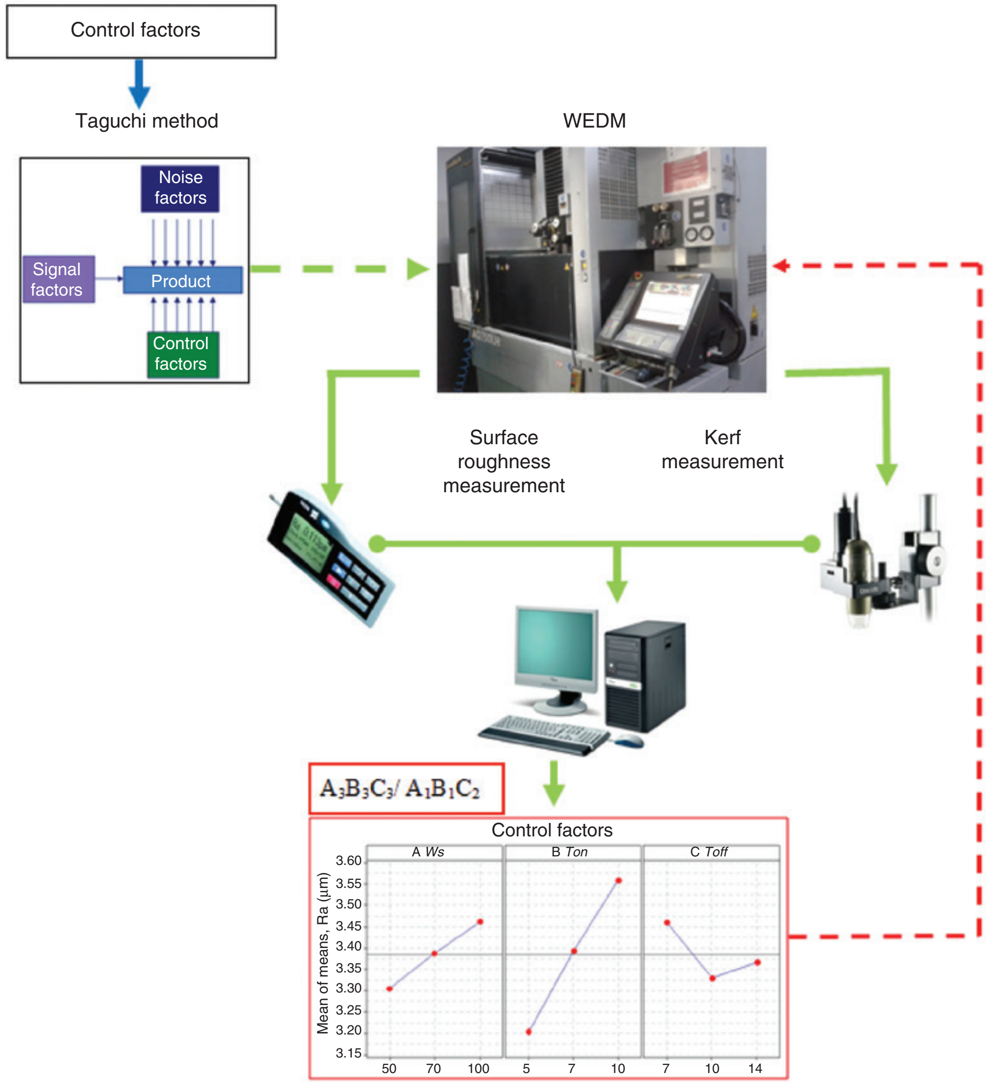

Figure 4 Steps followed in the experimental study.

within the machine shop and laboratory conditions. These kinds of studies are considered to be in the scope of off-line quality improvement [20–23]. The TM is an experimental design technique that decreases the number of tests needed by using orthogonal arrays and also minimizes the effects of out of control factors. The main philosophy of the TM is to provide quality during the course of designing. It is possible to specify the meaningful factors in a short time and decrease the experimental study costs by using the TM [23, 24]. In this study, the TM was used to specify the optimal control factors for maximum MRR and minimum Ra in WEDM because of its higher characteristics for parameter design. In the TM, the process parameters that affect the products are divided into two main groups: the control factors and noise factors [24]. The control factors are used to choose the optimal conditions in the design of production duration, whereas the noise factors are used to specify all of the factors that cause variation. Taguchi aimed to obtain the characteristic data by using orthogonal arrays and from this data to analyze the performance measurements in order to decide on the optimal process parameters [18, 24]. In this method, special designs of orthogonal arrays are used to specify the effect areas of parameters by using a small number of tests.

In this study, three machining parameters were specified as control factors, and each parameter had three levels. Each control factor level was coded as 1, 2 or 3 (Table 1). According to the Taguchi quality design scope the L_{27} (3^3) orthogonal arrays (corresponding to the number of test) consisting of 27 tests was chosen, and the tests were carried out with respect to this design (Table 2).

Table 2 L_{27} (3^3) orthogonal array; experimental results and their S/N ratios.

Exp. No	Designation	Control factors			Observed values		S/N ratio (dB)	
		A	B	C	MRR (g/min)	Ra (µm)	MRR	Ra
1	$A_1B_1C_1$	50	5	7	0.0649	3.307	-23.75	-10.39
2	$A_1B_1C_2$	50	5	10	0.0646	3.109	-23.80	-9.85
3	$A_1B_1C_3$	50	5	14	0.0667	2.916	-23.51	-9.30
4	$A_1B_2C_1$	50	7	7	0.0663	3.438	-23.57	-10.73
5	$A_1B_2C_2$	50	7	10	0.0669	3.289	-23.50	-10.34
6	$A_1B_2C_3$	50	7	14	0.0703	3.295	-23.06	-10.36
7	$A_1B_3C_1$	50	10	7	0.0690	3.535	-23.23	-10.97
8	$A_1B_3C_2$	50	10	10	0.0685	3.300	-23.28	-10.37
9	$A_1B_3C_3$	50	10	14	0.0684	3.547	-23.30	-11.00
10	$A_2B_1C_1$	70	5	7	0.0893	3.175	-20.99	-10.03
11	$A_2B_1C_2$	70	5	10	0.0887	3.123	-21.04	-9.89
12	$A_2B_1C_3$	70	5	14	0.0875	3.302	-21.16	-10.38
13	$A_2B_2C_1$	70	7	7	0.0951	3.612	-20.44	-11.15
14	$A_2B_2C_2$	70	7	10	0.0954	3.224	-20.41	-10.17
15	$A_2B_2C_3$	70	7	14	0.0970	3.273	-20.26	-10.30
16	$A_2B_3C_1$	70	10	7	0.0981	3.457	-20.17	-10.77
17	$A_2B_3C_2$	70	10	10	0.0992	3.761	-20.07	-11.51
18	$A_2B_3C_3$	70	10	14	0.0998	3.557	-20.02	-11.02
19	$A_3B_1C_1$	100	5	7	0.1038	3.177	-19.68	-10.04
20	$A_3B_1C_2$	100	5	10	0.1044	3.351	-19.63	-10.50
21	$A_3B_1C_3$	100	5	14	0.0984	3.360	-20.14	-10.53
22	$A_3B_2C_1$	100	7	7	0.1229	3.491	-18.21	-10.86
23	$A_3B_2C_2$	100	7	10	0.1285	3.484	-17.82	-10.84
24	$A_3B_2C_3$	100	7	14	0.1257	3.428	-18.01	-10.70
25	$A_3B_3C_1$	100	10	7	0.1346	3.942	-17.42	-11.91
26	$A_3B_3C_2$	100	10	10	0.1343	3.314	-17.44	-10.41
27	$A_3B_3C_3$	100	10	14	0.1422	3.614	-16.95	-11.16

3 Analysis and discussion of experimental results

In the TM, the deviation between the experimental and the desired data is defined as the loss function. Afterwards, this loss function is converted to signal-to-noise (S/N) ratio. The S/N ratio characteristics can be divided into three categories as given in Equations (3)–(5) [23]:

"Nominal is the best" characteristic,

$$\frac{S}{N_{NB}}=10\log\left(\frac{\bar{y}}{S_y^2}\right) \tag{3}$$

"Larger is the better" characteristic,

$$\frac{S}{N_{LB}}=-10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{yi^2}\right) \tag{4}$$

"Smaller is the better" characteristic,

$$\frac{S}{N_{SB}}=-10\log\left(\frac{1}{n}\sum_{i=1}^{n}yi^2\right) \tag{5}$$

In this study, the optimum WEDM cutting conditions necessary for the highest MRR were obtained by using Equation (4) "the larger is the better" S/N ratio. Similarly, the optimum WEDM cutting conditions for the lowest Ra were obtained by using Equation (5) "the smaller is the better" S/N ratio. The S/N ratios and level values for MRR and Ra were calculated by using Equations (4) and (5) in the MINITAB 16 program. The S/N ratios obtained from these equations are given in Table 2.

3.1 Analyzing and evaluating experimental results using the Taguchi method

It is highly important to obtain the maximum MRR and minimum Ra values for the development of machining quality and for reducing the costs of the material machined in WEDM. The MRR and Ra values were measured with the test design for each combination of control factors by using the TM, and the optimization of the measured control factors was realized by applying the S/N ratios. Table 2 shows the S/N ratios for the MRR and Ra values. From the cutting tests in WEDM, the average values for MRR and Ra were calculated as 0.0945 g/min and 3.384 µm, respectively. Similarly, the average S/N ratio values for MRR and Ra were found to be -20.77 dB and -10.57 dB.

The level values of the control factors for MRR and Ra according to the TM are given in Table 3. The optimum cutting conditions for the highest MRR values were determined as $A_3B_3C_3$, whereas for the lowest Ra values they were $A_1B_1C_2$. In other words, the highest MRR values were obtained with a wire speed of 100 m/min (level 3), a pulse-on time of 10 µs (level 3) and a pulse-off time of 14 µs (level 3), whereas the lowest Ra values were obtained with a wire speed (level 1) of 50 m/min, a pulse-on time (level 1) of 5 µs and a pulse-off time (level 2) of 7 µs.

Figures 5 and 6 show the graphics of the level values given in Table 3. Figure 5 shows the effect of the control factors on MRR, while Figure 6 shows the effect of the control factors on Ra. It is seen that MRR increases with the increase of all control factor values, and the most effective parameter was wire speed (Figure 5). As seen in Figure 6, Ra values increased depending on the increase in wire speed and pulse-on-time values. Moreover, the most effective parameter on Ra was pulse-on-time, and the most ideal surface roughness values were obtained at 7 µs pulse-off time (level 2).

The average S/N ratio for each level of tests was calculated as shown in Table 4. Wire speed and pulse-on time were two important factors affecting MRR due to the higher differences between their levels of 5.08 dB and 1.31 dB. On the other hand, pulse-on-time, wire speed and pulse-off time were determined to be the three factors affecting Ra with 0.91 dB, 0.41 dB and 0.33 dB values between the levels. According to the TM, the greater difference between S/N levels showed the effectiveness of that factor or factors on MRR and Ra. Hence, from Tables 3 and 4 and Figures 5 and 6, it can be concluded that the MRR and Ra increased with the increase of wire speed and pulse-on time.

The effects of the control factors on MRR and Ra were obtained with the more sensitive technique of variance analysis (ANOVA) [18, 25]. The relative importance of

Table 3 Response table for MRR and Ra.

Control factors	Material removal rate (MRR)					Surface roughness (Ra)				
	Level 1	Level 2	Level 3	Δmax-min	Rank	Level 1	Level 2	Level 3	Δmax-min	Rank
A	0.06728	0.09444	0.12163[a]	0.05435	1	3.304[a]	3.387	3.462	0.158	2
B	0.08537	0.09644	0.10155[a]	0.01618	2	3.202[a]	3.393	3.559	0.356	1
C	0.09376	0.09448	0.09512[a]	0.00136	3	3.459	3.328[a]	3.366	0.131	3

[a]Optimum level, Δ=difference between maximum and minimum.

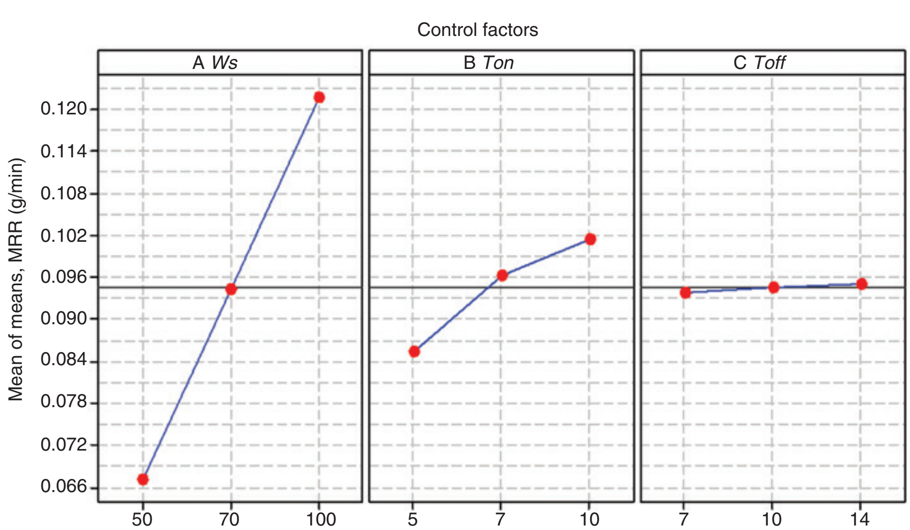

Figure 5 Effect of control factors on MRR.

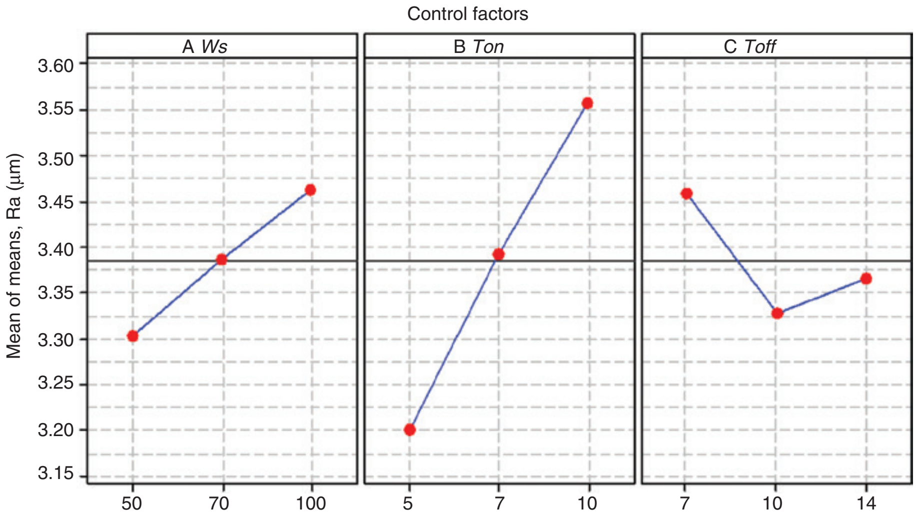

Figure 6 Effect of control factors on Ra.

Table 4 S/N response table for MRR and Ra.

Control factors	Material removal rate (MRR)					Surface roughness (Ra)				
	Level 1	Level 2	Level 3	Δmax-min	Rank	Level 1	Level 2	Level 3	Δmax-min	Rank
A	-23.44	-20.51	-18.37	5.08	1	-10.37	-10.58	-10.77	0.41	2
B	-21.52	-20.59	-20.21	1.31	2	-10.10	-10.61	-11.01	0.91	1
C	-20.83	-20.78	-20.71	0.12	3	-10.76	-10.43	-10.53	0.33	3

Δ=difference between maximum and minimum.

cutting parameters for MRR and Ra was investigated by using ANOVA to determine more accurately the optimum combinations of cutting parameters. The ANOVA results for the cutting tests in WEDM are given in Tables 5 and 6. According to ANOVA analysis results, the most effective parameters on MRR were wire speed and pulse-on-time, whereas pulse-off time did not have any significant effect. Percent contribution shows the relative power of a factor for decreasing the variation. A higher percent contribution for a factor indicates a contribution higher than the performance [18]. The percent contributions of the control factors on MRR are shown in Table 5. As shown in Table 5, wire speed (85.94%) was the most important factor affecting MRR, whereas pulse-on time (7.96%) was the second ranking factor. Pulse-off time had a lower percent contribution (0.05%). The percent contributions of the control factors on Ra are shown in Table 6. Pulse-on time was the most effective factor on Ra with

Table 5 Results of ANOVA for MRR.

Source	Degree of freedom	Sum of squares	Variance	F-Ratio	Prob.>F	Contribution (%)
A	2	0.0132932	0.0066466	142.08	0.000	85.94
B	2	0.0012317	0.0006158	13.16	0.000	7.96
C	2	0.0000084	0.0000042	0.09	0.915	0.05
Residual error	20	0.0009356	0.0000468			6.05
Total	26	0.0154689	–	–	–	100
R^2=93.95%						

Table 6 Results of ANOVA for Ra.

Source	Degree of freedom	Sum of squares	Variance	F-Ratio	Prob.>F	Contribution (%)
A	2	0.11291	0.05645	2.61	0.098	9.41
B	2	0.57228	0.28614	13.23	0.000	47.70
C	2	0.08195	0.04097	1.89	0.176	6.83
Residual error	20	0.43260	0.02163			36.06
Total	26	1.19974		–	–	100
R^2=63.94%						

a 47.70% contribution. The percent contributions of wire speed and pulse-off time on Ra were 9.41% and 6.83%, respectively.

3.2 Analyzing and evaluating experimental results using response surface methodology

RSM is a statistical method using digital data to specify suitable tests and to solve multivariable equations simultaneously [26]. It is used to determine the relation between different independent variables (control factors) and a dependent variable (response) and to find out the effects of machining parameters on the response [16, 27]. If all of the variables can be measured, the response can be expressed as the surface [28]. In RSM, mathematical models are used to specify the relation between the independent variables and the response [29]. The model is based on the examination of the response surface obtained with respect to the results of the design matrix created depending on the parameters between the highest and lowest levels (+1, -1) of the factors. The independent variables are represented by wire speed (WS), pulse-on time (T_{on}) and pulse-off time (T_{off}). In the experimental design, 16 tests were realized (two of them being center points) by using the central composite design technique. The response surface graphics showing the effects of independent variables on MRR are given in Figure 7. In WEDM, although the MRR depends on the thermal diffusion of the material, it is determined by its thermal conductivity and density [30]. With the increase of pulse-on time and pulse-off time no change was observed in MRR, while there was a significant increase with the increase of wire speed (Figure 7A and B). An increased wire speed decreases the contact duration of workpiece and wire. This provides both continuous contact of the wire with the workpiece and more effective usage of the energy transmitted to the workpiece. The transmission of heat to the workpiece with high efficiency increases the amount of melting material and MRR. Similarly, Yan et al. stated that increasing the wire speed increased MRR [8]. It was also seen from the ANOVA results that the most effective parameter on MRR was wire speed with a percent contribution of 85.49% (Table 5). In Figure 7C, it can be observed that there was no explicit variation in MRR depending on pulse-on time and pulse-off time values, although Jangra stated that MRR increased with pulse-on time and decreased with pulse-off time [31].

The response graphics showing the effects of independent variables on Ra are given in Figure 8. From the surface graphic showing the effects of pulse-on time and wire speed on Ra (Figure 8A), it can be seen that the lowest Ra was obtained at 50 m/min wire speed and 5 µs pulse-on time. The Ra values increased noticeably with the increasing of pulse-on time. This was attributed to the deterioration of the surface integrity by the high discharge energy. This energy was created with the increasing of pulse-on time and deepened and extended the surface crater on the workpiece [32]. Likewise, Patil and Brahmankar stated that the most effective parameter on the Ra was pulse-on time [33]. Satishkumar et al. specified that lower pulse-on time values improved the Ra [13]. On the other hand, Ra values increased with the increase of wire speed. In Figure 8B, it can be observed that the Ra values improved with the increase of pulse-off time. Figure 8C shows that the most effective parameter was pulse-on time. From the ANOVA results, it was also specified that the most effective parameter on Ra was pulse-on time, with a contribution rate of 47.7%.

3.3 Predictive equations for metal removal rate and surface roughness

A number of researchers have used linear or nonlinear regression analysis for the determination of the relation between the dependent variable and one or more

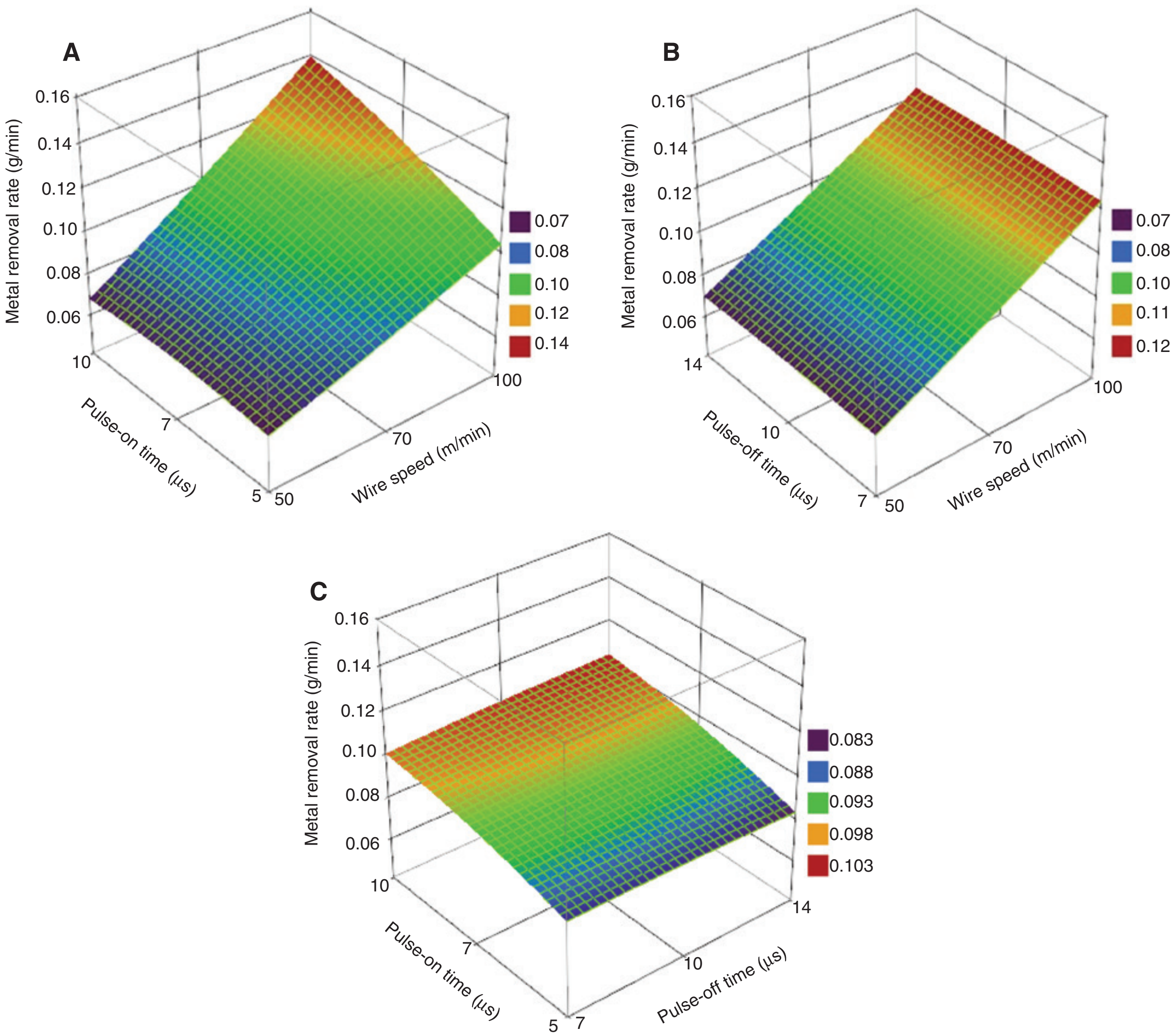

Figure 7 Response surface plots showing the effect of two variables on MRR.

independent variables [33–35]. In the estimation of MRR and Ra, the second-order predictive equations developed with regression analysis are given in Equations (6) and (7).

$$\begin{aligned} MRR = {} & 0.0715 + 0.0208W_s - 0.0239T_{on} - 0.0015T_{off} \\ & - 0.00468W_sT_{on} + 0.000265W_sT_{off} + 0.00065T_{on}T_{off} \\ & + 0.000338W_s^2 + 0.00479T_{on}^2 - 0.00004T_{off}^2 \end{aligned} \tag{6}$$

$$\begin{aligned} Ra = {} & 3.32 + 0.0972W_s + 0.055T_{on} - 0.361T_{off} - 0.0085W_sT_{on} \\ & - 0.0051W_sT_{off} - 0.001T_{on}T_{off} - 0.0031W_s^2 \\ & + 0.0192T_{on}^2 + 0.0842T_{off}^2 \end{aligned} \tag{7}$$

The differences between the actual values measured after the test and the predicted responses calculated by the aid of Equations (6) and (7) are given in Figure 9. It can be seen that the Ra results are more irregular with respect to those of the MRR, and they exhibit significant deviations. The correlation coefficient (R^2=63.8%) for the Ra, which describes the relation between the predicted and actual values, is also an indication of this. The correlation coefficient for MRR was calculated as (R^2=99.2%). The presented quadratic regression models provided a very good statistical performance with high correlation coefficients of 0.992 between the actual and predicted values of MRR.

4 Conclusions

In this study, the effects of the control factors on the material removal rate and surface roughness in WEDM of Al/

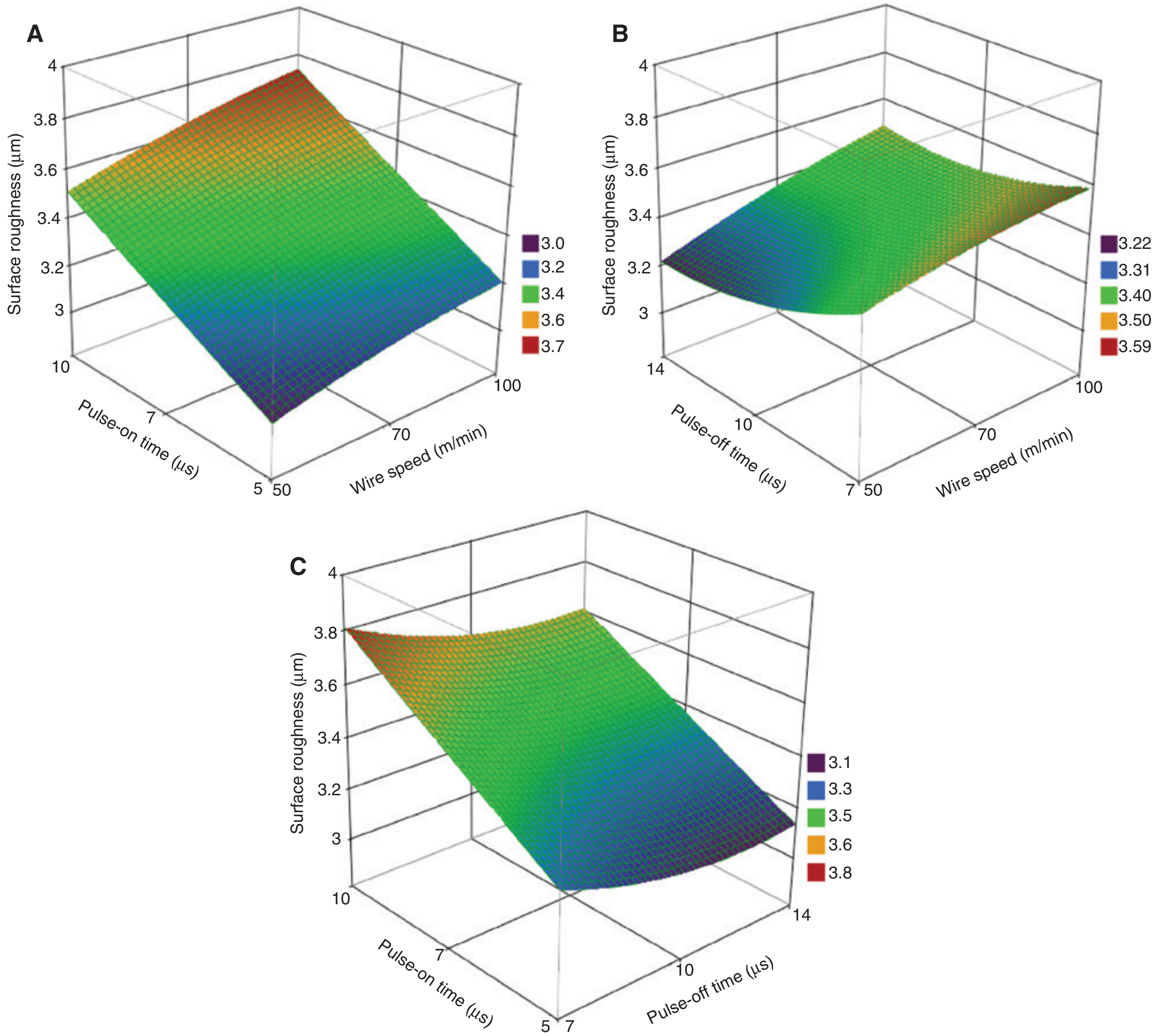

Figure 8 Response surface plots showing the effect of two variables on Ra.

B_4C/Gr composite were investigated via the TM and RSM and the results are given below:

1. The average MRR and Ra were found to be 0.0945 g/min and 3.384 µm in the WEDM of Al/B_4C/Gr composite in the interval of the specified cutting conditions.
2. The optimum levels of the control factors for maximum MRR and minimum Ra were defined by using S/N ratios. The optimum cutting conditions for MRR and Ra were determined as $A_3B_3C_3$ (i.e., wire speed: 100 m/min, pulse-on time: 10 µs and pulse-off time: 14 µs) and $A_1B_1C_2$ (i.e., wire speed: 50 m/min, pulse-on time: 5 µs and pulse-off time: 7 µs), respectively.
3. While the most effective parameter on MRR was wire speed (85.94%), it was followed by pulse-on time (7.96%). No significant effect of pulse-off time was observed. The MRR increased with the increase of cutting parameters. The most effective parameter on Ra was pulse-on time with a 47.70% contribution ratio, while the other cutting parameters had no significant effects. In addition, the Ra increased depending on the increase of wire speed and pulse-on time values; the lowest Ra values were obtained at the pulse-off time of 7 µs.
4. Second-order predictive equations were developed with regression analysis for the estimation of MRR and Ra, and the correlation coefficients of these equations (developed at a 95% confidence interval) for MRR and Ra were calculated as 0.992 and 0.638. These

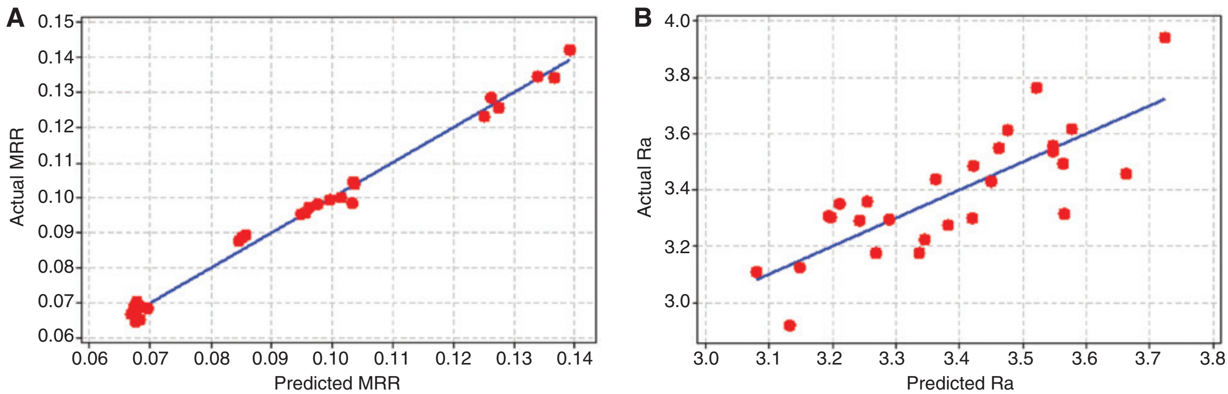

Figure 9 Relationships between actual and predicted response values (A) MRR and (B) Ra.

higher correlation coefficients show a high degree of consistency between the experimental and the estimated values.

5. The experimental results confirmed the validity of applying the Taguchi method in order to increase the machining performance and to optimize the machining parameters in WEDM operations.
6. The relations between MRR, Ra and the machining parameters were determined efficiently by using the Taguchi method together with response surface methodology.

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