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Metal Matrix Composite Materials Wire Electric Discharge Machining

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Abstract: *This chapter describes the SiCp/Aluminum 6061 metal matrix composite's wire electric-discharge machining (WEDM) (MMC). The trials were planned and assessed using response surface methodology (RSM). To investigate the impact of four WEDM input process factors on the cut quality in SiCp/6061 aluminium MMC, MRR and kerf were used as response parameters. The four parameters were servo voltage, pulse-on time, pulse-off time, and wire feed rate. To calculate the value of MRR and kerf theoretically, mathematical links between the WEDM input process parameters and response parameters were created. Analysis of variance (ANOVA) was used to determine the important components for the WEDM process. Confirmation experiments have been performed to confirm the suggested ideal process conditions.*

Key words: *WEDM, MMC, RSM, MRR, kerf*

1. Introduction

Many sophisticated materials have been created thanks to advancements in science and technology. One such material is composite. Engineering now has new dimensions because to composite materials. They are the only means of manufacturing planned multifunctional materials since they may be created to ensure a wide variety of features, able to fulfil the functional and ecological needs of a given application. A composite material is a system made up of two or more micro or macro elements that are fundamentally insoluble to one another due to differences in form and chemical makeup.

In every aspect of life, composite materials are being employed more and more. This expanding utilisation is being driven by the ever growing demand for strong, lightweight materials. By offering a robust, lightweight alternative to steels and aluminiums, these materials are filling gaps in the automotive sector and helping to improve fuel efficiency. The typical lifespan of automobiles can be extended by using these materials, which can also be tailored to be highly corrosion resistant. Military applications for composites range from naval superstructures to lightweight weaponry and body armour. The composite material is used in the aircraft sector for its strength to weight qualities, which increase cargo capacity, as well as its mechanical and thermal capabilities in harsh conditions. The shielding tiles that are employed to safeguard the space shuttle during atmospheric reentry serve as one example. Composite materials are divided into three categories based on their matrix constituents: organic matrix composites (OMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs).

Metal matrix composite is one of the most frequently utilised composite materials. Engineered materials called "metal matrix composites" are made of an elemental or alloy matrix, in which an insoluble second phase reinforcing is spread and implanted to improve some property. In various aspects, MMCs are different from other composite materials. These general distinctions include some of the following:

1. As opposed to a polymer or ceramic, the matrix phase in MMCs is either a pure metal or an alloy.

MMCs have greater ductility and hardness than ceramics or CMCs, according to 2.

3. Like with PMCs, the reinforcement's function in MMCs is to boost strength and modulus. In CMCs, reinforcement typically provides increased damage tolerance.

4. MMCs can withstand temperatures that are typically higher than polymers and lower than PMCs, ceramics, and CMCs.

Due to their expensive reinforcing particles and low cost manufacturing methods like casting or liquid metallurgy, particulate reinforced metal matrix composites account for a significant fraction of these sophisticated materials (Hashim et al., 1999). Metal matrix composites (MMCs) made of aluminium and silicon have drawn interest from all around the world due to its appealing qualities, ease of production, and promise for low price (Hung et al., 1999). MMCs provide a special balance of mechanical and physical characteristics. Due to their characteristics like a high strength-to-weight ratio, great toughness, a low coefficient of thermal expansion, superior wear resistance, and the ability to operate at high temperatures, MMCs have recently found numerous successful industrial uses as high-technology materials .

MMCs are made utilising a variety of techniques, including casting, forging, and extrusion. Unfortunately, little is known about the cutting and polishing processes used by MMCs. Because non-conductive particles are placed into the matrix material, MMCs' applications are limited by their poor machinability. Therefore the main problem is with the MMCs' machining. Both traditional and unconventional techniques have been used to machine MMCs.

Due to the presence of abrasive reinforcing particles, conventional machining of these materials results in significant tool wear and decreased tool life (Yan & Wang, 1993; Monaghan & Reilly, 1992). Although unconventional machining methods like laser beam machining (LBM) and water jet machining (WJM) are possible, their application is limited by the workpiece's height and the poor surface polish they produce (Muller & Monaghan, 2000; Lau & Lee, 1991). However, some methods, such wire electric discharge machining (WEDM) and electric discharge machining (EDM), are quite effective for machining MMCs. EDM only has a few uses because it can only be used for drilling. WEDM appears to be a better option because it can machine complicated and complex shapes and conforms to easy control. To achieve optimal performance, it is essential to set the various process parameters necessary for the WEDM process. A precise and effective machining operation without sacrificing machining performance is possible, claim Patil and Brahmankar for WEDM 2010. New application areas for MMCs will be made possible by efficient and affordable WEDM. MRR and kerf are the two key performance indicators in WEDM. The electrically conductive phase of MMC is melted and/or evaporated in WEDM to remove the substance. The kerf, one of the performance indicators that greatly affects finishing component dimensional accuracy, was not given enough consideration during WEDM of MMC model development. So, in order to understand how the process parameters affect product quality, extensive experimental work is required to examine and optimise the process parameters. One new method that makes it possible to analyse studies with the least amount of experimental work is response surface methodology (RSM) (Montgomery, 1997). To accomplish the best possible selection of process parameters and to produce the best MRR and kerf on the component built of SiCp/6061 Al MMC processed by WEDM process, mathematical models were constructed in the present study. Additionally, verification tests for the developed models were carried out.

The seven sections are contained in this chapter. Why WEDM is crucial for the machining of MMCs is the main topic of Section 1. The brief explanation of WEDM and its operating concept is provided in Section 2. The critical evaluation of prior studies on WEDM of MMCs is found in Section 3. The specifics of the supplies and techniques used throughout the experiments are described in Section 4. Section 5 focuses on the methods for designing experiments using response surfaces. The outcomes of SiCp/6061 Al MMC machinability during WEDM are discussed in Section 6. This section presents a thorough analysis of how process parameters affect response characteristics. The findings from the current research are presented in Section 7, along with suggestions for further investigation.

2. Wire electric discharge machining (WEDM)

Wire electric discharge machining was first introduced to the manufacturing industry in the late 1960s. The development of the WEDM process was the result of seeking a technique to machine the electrodes used in EDM. In 1974, D.H. Dulebohn applied the optical-line follower system to automatically control the shape of the component to be machined by the WEDM process (Jameson et al., 2001). By 1975, its popularity rapidly increased, as the process and its capabilities were better understood by the industry (Benedict, 1987). It was only towards the end of the 1970s, when computer numerical control (CNC) system was integrated with WEDM that brought about a major evolution of the machining process. As a result, the broad capabilities of the WEDM process were extensively exploited for any through-hole machining owing to the wire, which has to pass through the part to be machined.

2.1 Basic principle of WEDM

WEDM, also known as electric discharge wire cutting (EDWC), is a thermo-electric process in which material is eroded from the workpiece by a series of discrete sparks between the workpiece and a wire electrode (tool) separated by a thin film of dielectric fluid (generally deionized water) that is continuously fed to the machining zone to flush away the eroded particles. The movement of the wire is controlled numerically to achieve the desired three-dimensional shapes and accuracy of the workpiece (as shown in Fig. 1).

The wire is guided by sapphire or diamond guide and kept straight by a high value of wire tension, which is important to avoid tapering of the cut surface (Saha et al., 2005). High frequency DC pulses are delivered between the wire and workpiece, causing spark discharges in the narrow gap between the two. A stream of dielectric fluid is directed, usually coaxially with the wire, to flood the gap between the wire and workpiece. The power supply for the WEDM is essentially same as that for conventional EDM. Except that the current carrying capacity of the wire i.e. limited up to less than 20 A. In addition, spark frequencies used are up to 1 MHz, to give a fine surface finish on the workpiece (Linkbeck et al., 1990). There is no mechanical contact between the wire and workpiece in WEDM as shown in Fig. 1, the workpiece is moved under computer numerical control (CNC) relative to the wire, and this enables complex shaped profile to be cut through sheet and plate materials. Many machines incorporate further angular positioning of the wire, thus allowing varying degrees of taper on the cut surface to be obtained. Adaptive control based on gap voltage sensing is necessary to avoid contact between the wire and the work material. Short-circuit must be sensed and the wire is backed off along the programmed path to establish the correct gap for the efficient cutting (Ramasawmy & Blunt, 2003; Krar et al., 2005).

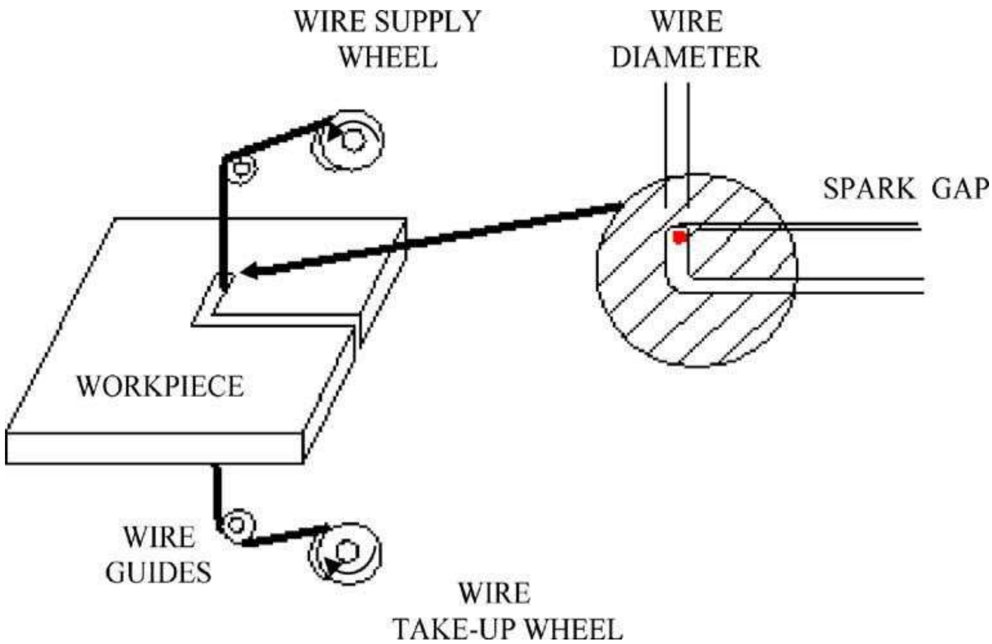

Fig. 1. Detail of WEDM cutting gap (Benedict, 1987)

3. Past research work on WEDM of MMCs

Very few studies have been undertaken in WEDM of MMCs. Further, most of these studies have been done by using one-parameter-at-a-time approach, which may not explain the effects of interaction among various parameters. Some of past studies on WEDM of MMCs are presented as follow.

Gatto and Luliano (1997) performed the WEDM tests under one roughing and two finishing conditions on two composites i.e. 15% SiC_w/2009Al and 20% SiC_w/2009Al. Results show that the WEDM rates (mm/min) of both composites are equal. Rozenek et al. (2001) investigated the effect of machining parameters (discharge current, pulse-on time, pulse-off time, voltage) on the machining feed rate and surface roughness during WEDM of AlSi7Mg/SiC and AlSi7Mg/Al_2O_3 MMCs. Generally machining characteristic of metal matrix composites machined by WEDM is similar to those that occur in the base material (AlSi7Mg aluminium alloy). The machining rate of composites significantly depends on the kind of reinforcement. The maximum cutting speed of AlSi7Mg/SiC and AlSi7Mg/Al_2O_3 composites are approximately 3 times and 6.5 times lower than the cutting speed of aluminum alloy, respectively. Guo et al. (2002) studied the machineability of Al_2O_3 particle-reinforced 6061 Al-alloy by WEDM process. A method of orthogonal design has been used to determine the main factors that affect the machining process. The results show that the electrical discharge energy is closely related to machining stability. A good machining effect can be attained when the electrical parameters are properly selected; otherwise, the machining may be unstable resulting in wire breakage. Yan et al. (2005) used a WEDM in machining of Al_2O_{3p}/6061Al composite. The results show that the cutting speed, the surface roughness and the width of slit of cutting test material significantly depend on volume fraction of reinforcement (Al_2O_3 particles). Test result reveals that in machining Al_2O_{3p}/6061Al composites a very low wire tension, a high flushing rate and a high wire speed are required to prevent wire breakage: an appropriate servo voltage, a short pulse-on time, and a short pulse-off time, which are normally associated with a high current speed, have a little effect on the surface roughness. Sarkar et al. (2006) studied the WEDM of γ titanium aluminide. They also attempted to develop an appropriate machining strategy for a maximum process yield criteria. A feed forward back propagation neural network was used to model the machining process. The three most important parameters the cutting speed, surface roughness, and wire offset- have been considered as measures of the process performance. The model is capable of predicting the response parameters as a function of six different control parameters, i.e. pulse-on time, pulse-off time, peak current, wire tension, dielectric flow rate and servo reference voltage. Ali (2006) investigated on the effect and optimization of machining parameters on the material removal rate (MRR) and surface roughness in the WEDM process of Al-Cu-TiC-Si P/M composite. The settings of machining parameters were determined by using Taguchi experimental design method. The variation of MRR and surface roughness with machining parameters is mathematically modeled by using non-linear regression analysis method. The optimal machining parameters for the objective of maximizing MRR and minimizing surface roughness are performed. Patil and Brahmankar (2006) investigated the effect of various control parameters such as pulse-on time, pulse-off time, ignition pulse current, wire speed, wire tension and flushing pressure on cutting speed and surface finish of Al/SiC_p by using Taguchi methods. Mathematical models relating the machining performance and machining parameters have been formulated. Optimal settings for each performance measure have also been obtained, a comparative study on unreinforced alloy revealed the effect of reinforcement on the machining process. It was found that the cutting speed for unreinforced alloy was higher compared to MMC. Wire breakage was found to pose limitation on the cutting speed of MMC. Saha et al. (2009) studied the machinability of 5% vol TiC/Fe in-situ metal matrix composite. Modeling of WEDM process by normalized radial base function network (NRBFN) with enhanced K-means clustering technique have been done which yields better results than NRBFN with traditional K-means clustering technique. Results show that an increase in the average gap voltage leads to the decrease of the cutting speed. An increase in pulse-on time increases the cutting speed. Shandilya et al. (2010, a) concluded that to achieve higher value of the average cutting speed, lower value of voltage and higher value of pulse-off time should be used during WEDC of SiC_p/6061 Al MMC. In the most recent work, Shandilya et al. (2011, a) studied the effect of input process parameters on surface surface roughness during WEDM of SiC_p/6061 Al MMC. Results show that, voltage is the most significant parameter on surface roughness, where as pulse-on time and pulse-off time has less significant effect.

According to the literature survey it observed that very little work has been reported on WEDM of MMCs. As the SiC_p/ Al MMCs have many industrial applications but their machining by WEDM is still not well understood. There is lack of published literature, to determine the effect of input process parameters on machining of the SiC_p/6061 Al MMC by WEDM. Very few optimization and modeling techniques have been presented for WEDM of SiC_p/6061 Al MMC. In the present work effect of servo voltage, pulse-on time, pulse-off time and wire feed rate on the quality of cut in terms of MRR and kerf has been evaluated during WEDM of SiC_p/6061 aluminum MMC through RSM. This study gives the optimal values of input process parameters in which WEDM of SiC_p/6061 Al MMC is possible with maximum MRR and minimum kerf.

4. Experimentation

The experiments were conducted at ECOCUT WEDM Machine (supplied by Electronica India Pvt Ltd.). A schematic diagram of WEDM system is shown in Fig. 2.

In the present study SiC_p/6061 Al metal matrix composite was used as the workpiece material made by stir casting technique at FENFEE Metallurgical research lab, India. Al 6061 was used as the matrix material and SiC particles were used as reinforcement. Al 6061 alloy has many superior mechanical properties such as low density, low melting point, high strength to weight ratio, good ductility and low cost. Al 6061 alloy is also a heat treatable, weldable and corrosion resistant material (Anon, 1990). The chemical composition of Al 6061 is shown in Table 1. The weight percentage of SiC was used as 10% having size of 10 µm as reinforcement phase in SiC_p/6061 Al MMC. WEDM process parameters that have been fixed during the experiments are listed in Table 2. The four input parameters namely servo voltage (SV), pulse-on time (T_{ON}), pulse-off time (T_{OFF}) and wire feed rate (WF) were chosen as variables to study their effects on the quality of cut in SiC_p/6061 aluminum MMC using MRR and kerf as response parameters. Table 3 gives the levels of various parameters that have been selected on the basis of preliminary experimental investigation and machining constants (Shandilya et al., 2011, b). The following equation is used to determine the MRR value (Nito et al., 2006):

$$MRR = \frac{M_f - M_i}{\rho t} \quad (1)$$

Where M_i, M_f are masses (in gm) of the work material before and after machining respectively, ρ is the density of work piece material and t is the time of machining in minutes. An electronic weighing machine with an accuracy of 0.1 mg was used to measure the initial and final weight of the workpice.

kerf is expressed as sum of wire diameter and twice of wire-work piece gap as given in following equation.

$$kerf = (d + 2\,\mathrm{W}g) \tag{2}$$

Where d is the wire diameter and $\mathrm{W}g$ is the wire workpiece gap in which spark is produced during the machining.

Element	Al	Si	Mg	Cu	Mn	Cr	Fe	Ti
Composition (wt%)	95.83	0.68	1.20	0.61	0.45	0.50	0.27	0.46

Tab. 1. Chemical composition of Al 6061 MMC

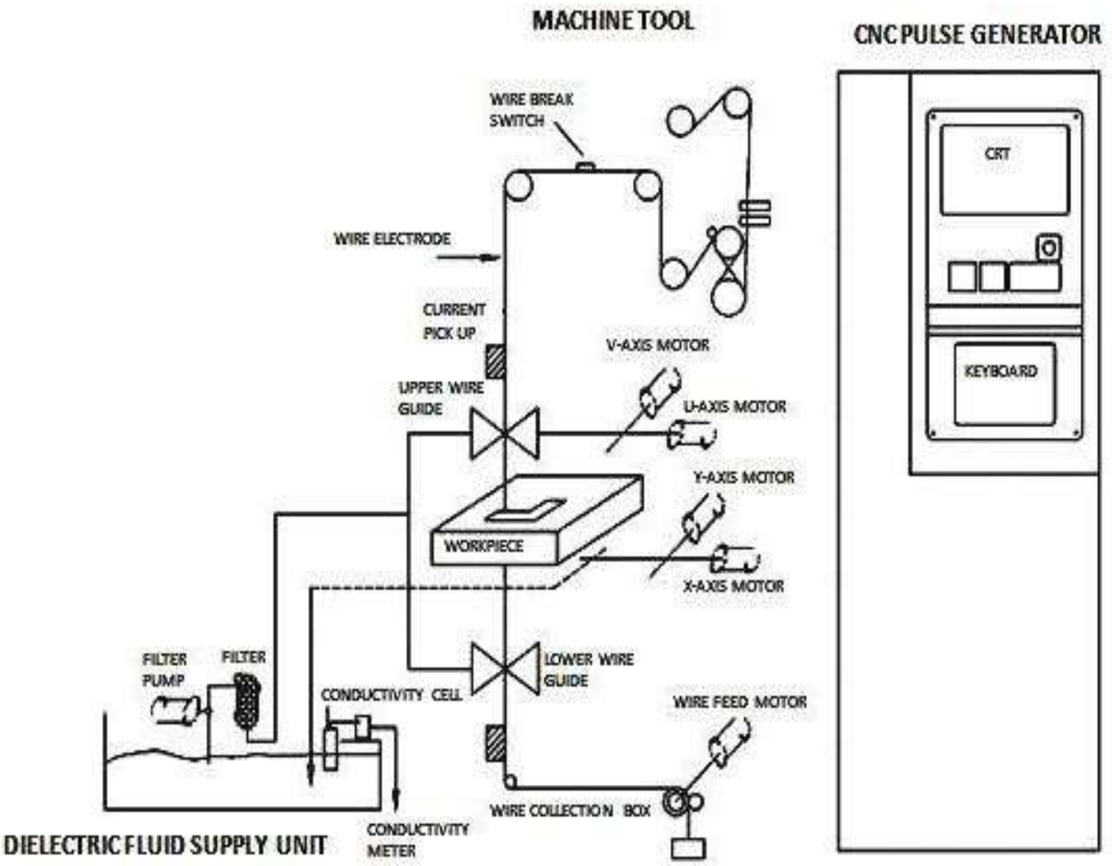

Fig. 2. Schematic representation of the WEDM system (Electronica, India)

S.No	Parameter	Level
1	Wire material	Diffused brass wire
2	Wire size (mm)	Ø 0.25

3	Wire tension (gm)	1600
4	Dielectric	Deionised water
5	Table feed rate (mm/min)	1
6	Workpiece	Al/SiC$_p$
7	Workpiece thickness (mm)	10
8	Room Temperature (ºC)	20

Tab. 2. Machining parameters set up (constant parameters)

Process parameters	Levels		
	-1	0	+1
Voltage (V)	70	80	90
Pulse-on time (μs)	1	2	3
Pulse-off time (μs)	6	8	10
Wire feed (m/min)	5	7	9

Tab. 3. Levels of process parameters

5. Response surface methodology

Response surface methodology approach is the procedure for determining the relationship between various process parameters with various machining criteria and exploring the effects of these process parameters on the coupled responses (Myers and Montgomery, 2002). In order to study the effect of WEDM process parameters of SiC$_p$/6061 Al MMC on MRR and kerf, a second order polynomial response can be fitted into the following equation:

$$Y=b_0+b_1x_1+b_2x_2+b_3x_3+b_4x_4+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2+b_{44}x_4^2+b_{12}x_1x_2+b_{13}x_1x_3+b_{14}x_1x_4+b_{23}x_2x_3+b_{24}x_2x_4+b_{34}x_3x_4 \quad (3)$$

Where Y is the response and x_1, x_2, x_3, x_4 are the quantitative variables. b_1, b_2, b_3 and b_4 represent the linear effects of x_1, x_2, x_3 and x_4 respectively, b_{11}, b_{22}, b_{33} and b_{44} represent the quadratic effects of x_1, x_2, x_3 and x_4. b_{12}, b_{13}, b_{14}, b_{23}, b_{24} and b_{34} represent linear-by-linear interaction between x_1 and x_2, x_1 and x_3, x_1 and x_4, x_2 and x_3, x_2 and x_4, x_3 and x_4, respectively. These quadratic models work quite well over the entire factor space and regression coefficients were computed according to the least-squares procedure (Shabgard and Shotorbani, 2009).

By plotting the expected response of Y, a surface, known as the response surface is obtained. The WEDM process was studied according to the box behnken design (BBD). Levels and values for four factors have been given in Table 3. In this investigation, total 29 experiments were conducted. The 'Design Expert 6.0' software was used for regression and graphical analysis of the data obtained. The optimum values of the selected variables were obtained by solving the regression equations and by analyzing, the response surface contour plots. Analysis of variance was used to analyze the experimental data and the relative importance of the machining parameters with respect to the measure of performance was investigated.

6. Experimental results and discussions

Table 4 illustrates the order, combination and design of experiments based on the coded surfaces and results of the desired response surface.

Analysis of Variance (ANOVA)

ANOVA was used to analyze the experimental data using model summary statistics and lack of fit tests and to determine the relative importance of the machining parameters with respect to the measure of performance. It also shows the value of R^2-statistic and adjusted R^2-statistic. The R^2-statistic is defined as the ratio of variability explained by the model to the total variability in the actual data and is used as a measure of the goodness of fit. The more R^2 approaches unity, the better model fits the experimental data. The adjusted R^2-statistic is a statistic which is adjusted for the ‘size’ of the model; i.e. number of factors (terms). ANOVA tables for SiC_p/6061 Al MMC of MRR and kerf are presented in Table 5 and Table 6 respectively. According to the analysis done by the Design Expert software, if the values of probability (Prob>F) are less than 0.05, it indicated that the factors is significant to the response parameters.

Exp. No.	Voltage, A (V)	Pulse-on time, B (μs)	Pulse-off time, C (μs)	Wire Feed rate, D (m/min)	MRR (mm^3/min)	Kerf (mm)
1	0	1	0	-1	4.200	0.381
2	-1	0	0	-1	9.965	0.266
3	0	0	1	1	4.931	0.328
4	-1	0	1	0	5.188	0.287
5	0	-1	-1	0	4.586	0.359
6	1	0	0	-1	3.679	0.415
7	1	0	-1	0	3.026	0.438
8	0	0	0	0	3.243	0.424
9	0	0	0	0	3.943	0.387
10	1	0	0	1	5.072	0.308
11	0	0	1	-1	3.897	0.407
12	0	0	0	0	3.939	0.394
13	0	-1	0	1	4.740	0.342
14	0	0	0	0	3.170	0.426
15	0	1	0	1	5.075	0.302
16	0	0	0	0	3.293	0.422
17	1	0	1	-1	4.702	0.352
18	0	1	-1	-1	4.974	0.322
19	0	0	-1	1	4.340	0.368

20	0	-1	0	-1	4.251	0.372
21	0	0	-1	-1	4.851	0.334
22	0	-1	1	0	3.901	0.401
23	1	1	0	0	2.590	0.446
24	-1	0	-1	0	11.354	0.261
25	-1	1	0	0	5.991	0.274
26	-1	0	0	1	5.126	0.294
27	-1	-1	0	0	5.325	0.282
28	1	-1	0	0	3.132	0.432
29	0	1	1	0	4.997	0.316

Tab. 4. BBD with four parameters and experimental, MRR and kerf

Table 5 shows that voltage (V), pulse-off time (T_{OFF}), wire feed rate (WF), quadratic effect of voltage (V×V), quadratic effect of pulse-off time (T_{OFF}×T_{OFF}), quadratic effect of wire feed rate (WF×WF), interaction effect of voltage with pulse-off time (V×T_{OFF}) and interaction effect of voltage with wire feed rate (V×WF) have significant effects on MRR. The lack of fit was not significant which satisfy the model to be fitted. The obtained value of 0.8695 for R^2 implies that the model explains approximately 86.95% of the variability in MRR. The value of adjusted R^2-statistic is equal to 0.8173 for MRR indicates that 81.73% of the total variability is explained by the model after considering the significant factors.

For kerf result of ANOVA analysis as given in Table 6 shows that voltage (V), pulse-off time (T_{OFF}), wire feed rate (WF), quadratic effect of voltage (V×V), quadratic effect of pulse-off time (T_{OFF}×T_{OFF}), quadratic effect of wire feed rate (WF×WF), interaction effect of voltage with wire feed rate (V×WF) and interaction effect of pulse-off time with wire feed rate (T_{OFF}×WF) have significant effects. The lack of fit was not significant which satisfy the model to be fitted. The obtained value of 0.8827 for R^2 implies that the model explains approximately 88.27% of the variability in kerf. The value of adjusted R^2-statistic is equal to 0.7655 for kerf indicates that 76.55% of the total variability is explained by the model after considering the significant factors.

Parameters	Sum of Squares	DF	F Value	P value
Voltage *(V)*	*26.86*	*1*	*32.63*	*<0.0001*
Pulse-on time *(T_{ON})*	*0.15*	*1*	*0.18*	*0.6809*
Pulse-off time *(T_{OFF})*	*19.99*	*1*	*24.28*	*0.0002*
Wire feed rate *(WF)*	*12.08*	*1*	*14.67*	*0.0018*
Quad. *V (V×V)*	*11.49*	*1*	*13.96*	*0.0022*
Quad. *T_{ON} (T_{ON} × T_{ON})*	*0.065*	*1*	*0.079*	*0.7823*
Quad. *T_{OFF} (T_{OFF} × T_{OFF})*	*5.73*	*1*	*6.96*	*0.0195*
Quad. *WF (WF × WF)*	*4.90*	*1*	*5.95*	*0.0286*
Interaction *(V× T_{ON})*	*0.36*	*1*	*0.44*	*0.5164*

Interaction *($V\times T_{OFF}$)*	*15.37*	*1*	*18.67*	*0.0007*
Interaction *($V\times WF$)*	*9.71*	*1*	*11.79*	*0.0040*
Interaction *($T_{ON}\times T_{OFF}$)*	*0.13*	*1*	*0.15*	*0.7023*
Interaction *($T_{ON}\times WF$)*	*0.037*	*1*	*0.045*	*0.8346*
Interaction *($T_{OFF}\times WF$)*	*3.915E-003*	*1*	*4.755E-003*	*0.9460*
Standard deviation = 0.79 Mean = 10.34 Predicted residual error of sum of squares = 12.42 R-Squared = 0.8695 Adjusted R-Squared = 0.8173				

Tab. 5. The effect of voltage, pulse-on time, pulse-off time and wire feed rate on MRR

Parameters	Sum of Squares	DF	F Value	P value
Voltage *(V)*	*0.020*	*1*	*25.89*	*0.0002*
Pulse-on time *(T_{ON})*	*3.207E-004*	*1*	*0.41*	*0.5324*
Pulse-off time *(T_{OFF})*	*9.960E-003*	*1*	*12.73*	*0.0031*
Wire feed rate *(WF)*	*0.015*	*1*	*19.37*	*0.0038*
Quad. *V ($V\times V$)*	*0.013*	*1*	*16.07*	*0.0013*
Quad. *T_{ON} ($T_{ON}\times T_{ON}$)*	*3.243E-003*	*1*	*4.15*	*0.0611*
Quad. *T_{OFF} ($T_{OFF}\times T_{OFF}$)*	*4.223E-003*	*1*	*5.40*	*0.0357*
Quad. *WF ($WF\times WF$)*	*6.840E-003*	*1*	*8.74*	*0.0104*
Interaction *($V\times T_{ON}$)*	*2.797E-004*	*1*	*0.36*	*0.5594*
Interaction *($V\times T_{OFF}$)*	*2.553E-003*	*1*	*3.26*	*0.0924*
Interaction *($V\times WF$)*	*5.968E-003*	*1*	*7.63*	*0.0153*
Interaction *($T_{ON}\times T_{OFF}$)*	*1.040E-003*	*1*	*1.33*	*0.2683*
Interaction *($T_{ON}\times WF$)*	*3.216E-004*	*1*	*0.41*	*0.5318*
Interaction *($T_{OFF}\times WF$)*	*4.339E-003*	*1*	*5.55*	*0.0336*
Standard deviation = 0.028 Mean = 0.0558 Predicted residual error of sum of squares = 0.011 R-Squared = 0.8827 Adjusted R-Squared = 0.7655				

Tab. 6. The effect of voltage, pulse-on time, pulse-off time and wire feed rate on kerf

Regression model equations for response parameters

The regression equations for response functions i.e. MRR and kerf in terms of input process parameters are given below. These model equations indicate the individual, interaction and second order effect of input process parameters and can be used for predicting the optimal values of input process parameters. To fit the quadratic model for MRR and kerf, the non-significant terms are eleminated by backward elemination process. After eleminating the non-significant terms, the final response equations for MRR and kerf are found as follow:

$$MRR = +239.04266 - 3.65079 \times V - 12.11592 \times T_{0FF} - 9.42771 \times \mathrm{W}F + 0.013427 \times V^2 + 0.24855 \times T_{0FF}^2 + 0.22835 \times \mathrm{W}F^2 + 0.098025 \times V \times T_{0FF} + 0.077900 \times V \times \mathrm{W}F \quad (4)$$

$$kerf = -6.01628 + 0.097591 \times V + 0.27264 \times T_{0FF} + 0.32573 \times \mathrm{W}F - 4.42028E - 004 \times V^2 - 6.41944E - 003 \times T_{0FF}^2 - 8.16944E - 003 \times \mathrm{W}F^2 - 1.22083E - 003 \times V \times T_{0FF} - 1.86667E - 003 \times V \times \mathrm{W}F \quad (5)$$

Optimization of response parameters

Optimization of responses were performed to determine the optimal values of input process parameters for the desired MRR and kerf based on the developed mathematical models (i.e. equations 4 and 5). The 'Design Expert 6.0' software was used to optimize the responses during WEDM of SiC_p/6061 Al MMC. The target values for the MRR were set as maximum and for kerf as minimum. The optimal values of input process parameters as obtained are listed in Table 7. The process inputs need some modification for machine constraints. The value of composite desirability D, was taken as 1 (Montgomery, 1997).

An experiment was carried out at the optimal parametric settings for MRR and kerf so that targeted value of response parameter can be obtained. Table 8 shows the predicted value of MRR and kerf obatined from the mathematical relationships as given in equations 4 and 5 respectively and experimental results with the parameteric optimal setting as obtained from RSM model. The predicted values of responses were compared with the respective experimental values and the absolute percentage error was computed as follows:

$$\% \text{ Absolute error} = \left| \frac{\mathrm{Fj},pt - \mathrm{Fj},pred}{\mathrm{Fj},pt} \right| * 100 \quad (6)$$

Where *Yj,expt* is the experimental value and *Yj,pred* is the predictive value of the response for the *jth* trail by the RSM model. Prediction are in good agreement with the experimental results for MRR as compared to kerf because the percentage error of the predicted value with respect to the experimentally observed value for MRR is 4.26% whereas for kerf is 10.52%.

Optimize value of input parameters				Modified value of inputs parameters			
SV (V)	T_{ON} (µs)	T_{OFF} (µs)	*WF* (m/min)	*SV* (V)	T_{ON} (µs)	T_{OFF} (µs)	*WF* (m/min)
71.01	1.00	6.04	5.17	70.00	1.00	6.00	5.00

Tab. 7. Optimized input process parameters

Response	Predicted value (µm)	Experimental value (µm)	% error

RR	11.354	11.86	4.26%

Tab. 8. Optimum values of response parameters

Effect of input process parameters on MRR

Fig. 3 depicts the effect of voltage, pulse-on time, pulse-off time and wire feed rate on MRR during WEDM of SiC_p/6061 Al MMC. According to the trend, the value of MRR decreases with increase in voltage because at higher voltage, the dielectric strength of the medium increases and discharge current during machining decreases, resulting to lower melting and evaporation of the workpiece material, as a result the MRR decreases. Increase in pulse-on time, resulting the lower MRR. This figure also shows that pulse-off time and wire feed rate have less significant effect on MRR.

Effect of input process parameters on kerf

Fig. 4 shows the effect of voltage, pulse-on time, pulse-off time and wire feed rate on kerf during WEDM of SiC_p/6061 Al MMC. It can be seen that the value of kerf increases with increase in voltage because as the voltage increases the gap between the wire and workpiece also increases. At the same time when gap between the workpiece and wire electrode increases, the electrode wire tries to maintain the same gap surrounding the wire. This gap corresponds to the set value of voltage, and as a consequence the kerf also increases. The value of kerf increases with increase in pulse-on time.

The pulse-off time has less significant effect on kerf. The kerf increases continuously with increase in wire feed rate upto midium level of wire feed rate and than start decreasing with increase in wire feed rate.

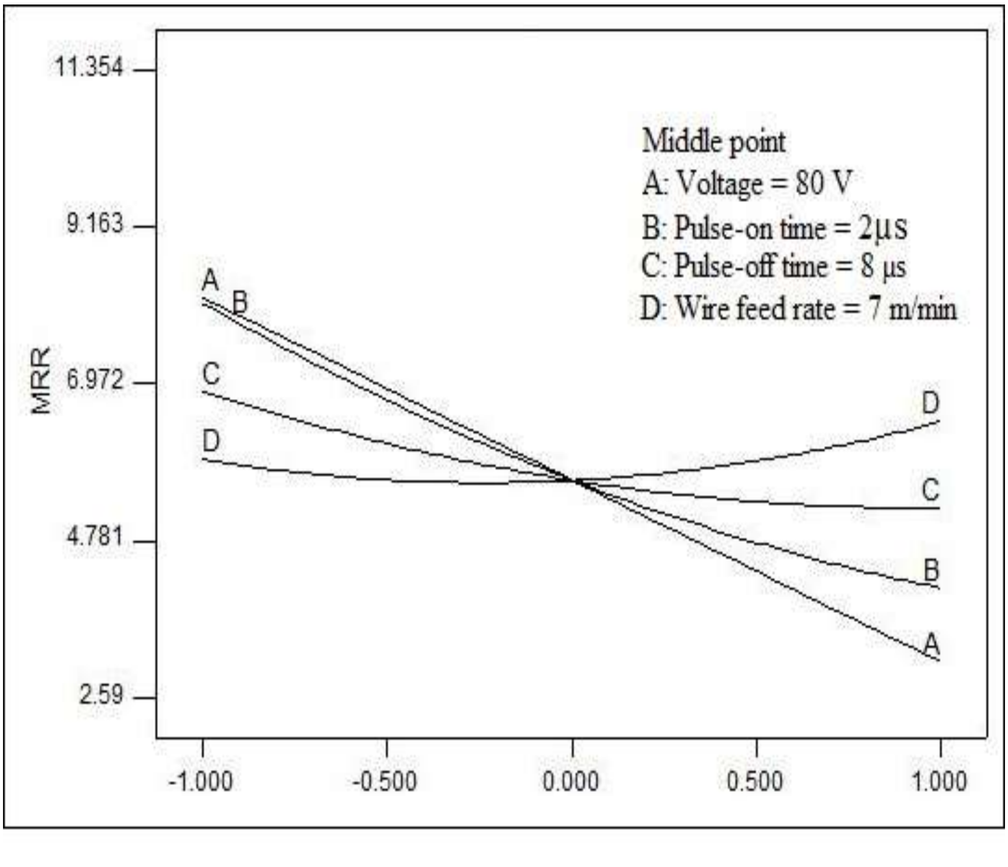

Fig. 3. Effect of voltage, pulse-on time, pulse-off time and wire feed rate on MRR [X-axis in coded value]

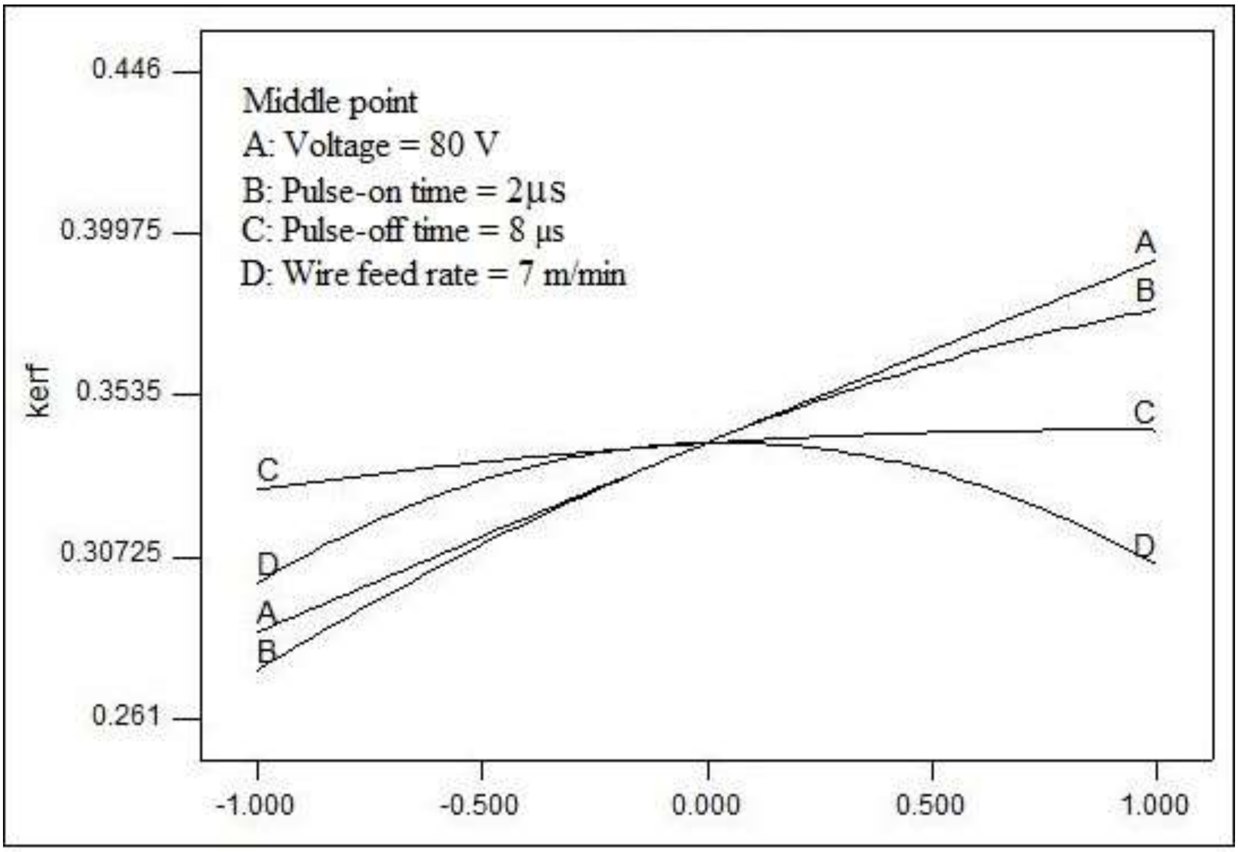

Fig. 4. Effect of voltage, pulse-on time, pulse-off time and wire feed rate on kerf [X-axis in coded value]

7. Conclusions

The basic goal of the WEDM method is to produce accurate and effective machining without compromising machine performance. In this study, an effort was made to take into account the relationship between voltage, pulse-on time, pulse-off time, and wire feed rate on MRR and kerf in SiCp/6061 Al MMC WEDM. The ANOVA results show that voltage has the greatest impact on MRR and kerf, but wire feed rate and pulse-off time have less of an impact. The impact of pulse-on time on MRR and kerf is minimal. According to the results of the optimization, the best conditions for the current study are 71.01 V of voltage, 1.00 s of pulse-on time, 6.04 s of pulse-off time, and 5.17 m/min wire feed rate. At the optimal level of input process parameters, the projected values of MRR and kerf were found to be relatively close to the experimental value. Compared to kerf, where there is a bigger percentage error between the predicted value and the empirically observed value, MRR predictions are in better accord with the experimental data.

Effects of input process parameters demonstrate that greatest MRR and minimum kerf values are attained at lower voltage and pulse-on time levels.

The findings of the current work, which used the RSM approach, can be applied to the efficient and affordable WEDM machining of SiCp/6061 Al MMC. the current

The WEDM of SiCp/6061 Al MMCs with SiC particles up to 10% is the main focus of the work. Future research can be expanded by varying the proportion of SiC particles in MMC and the type of work being done. More research may be conducted to establish the machinability of MMCs during WEDM by varying the levels of various process parameters, such as wire tension, table feed rate, and other variables that have been fixed during this study. The impact of process variables on additional performance indicators, such as features of surface integrity and surface texture of a machined surface, may also be studied.

8. References

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