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A study on machining parameters for Wire Electrical Discharge Machining of Circular Contouring in Stir Cast AA6063/SiC Composites

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Wire electrical discharge machining (WEDM) is used in machining electric conductive materials for intricate shapes and profiles. This paper presents an experimental investigation on the influence of machining conditions like spark density and voltage cycle time on its performance measures like surface roughness (Ra) and cutting width (Kerf) during machining a circular contour on AA6063/SiC composites. Here, a semi cylindrical piece is removed from a rectangular plate of AA6063/SiC composites plate fabricated with reinforcing SiC in 0%, 5%, 10% and 15% weight fractions through stir casting. The effect of WEDM parameters, spark density is governed by peak current (IP) and sparking rate is governed by voltage cycle time (T) were analyzed for circular contour machining. The experimental results show that increase in SiC content in the composites leads to reduced performance measures. It is observed during the change of spark voltage application time the value of the surface roughness is decreased for the weight fraction of 0% to 5% of SiC and increased for the further inclusion of SiC in the composites.

Keywords: Metal matrix composites, Wire electrical discharge machining, Sparking rate, Spark density, Surface roughness

1 Introduction: With the growth of the mechanical industry, the demand for intricately shaped mechanical components made of composite materials with high hardness, toughness and wear resistance is increasing. However, the machining of such composite materials by traditional machining methods is dimensionally inaccurate. So, non-traditional machining methods like electrochemical machining; sultrasonic machining and wire electrical discharging machining (WEDM) are used to produce accurate components made from such composite materials. In particular, Guitrau (1991), described WEDM is a specialized thermal machining process that uses electro-thermal mechanisms and is capable of accurately machining electrically conductive materials with varying hardnesses and complex shapes [1]. McGeough (1988) explained that WEDM machining process removes material through a sequence of rapid and repetitive discrete spark discharges that occur more than 1,00,000 times per second between a travelling wire electrode and the work piece, without any relative contact between them [2]. Rakwal and Bamberg (2009) discussed that the properties of the work material including density, hardness, and thickness are not limiting factors in machining by this process [3]. The successive discrete spark discharges, with temperatures estimated at 15,000° to 21,000° Fahrenheit, erode the conductive material, and a computerized numerical control moves the work table carrying the work piece transversely along a vertical wire via a predetermined path. Programs are created and written for the required contour with respect to the center wire. These programs can be executed to follow the outline of a part with a servo system. Hsue et.al (1992) developed path programs for a complex contour shape using interactive software and fed to the control unit of a WEDM machine and the path of the wire with respect to the work piece will create the required intricate shapes [4]. A simple schematic diagram explaining the WEDM process is shown in Figure (1).

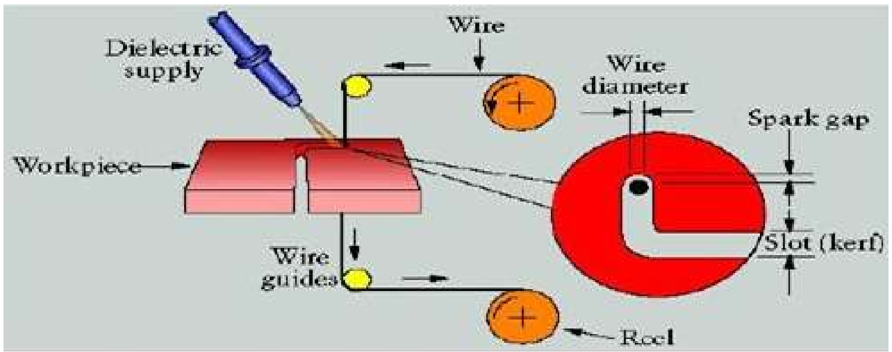

Figure (1): Schematic diagram of the WEDM process [22]

Puertas and Luis (2003) studied the WEDM process and informed that is a vital technique used in the industry for high-precision machining of all types of conductive materials of any hardness, such as aluminum, aluminum bronze alloys, tool steels and Ferro-TiC [5]. Rozenek (2001) reported that the WEDM process has been extended to the machining of conductive metal matrix composite materials, and good results have been arrived [6].

Metal matrix composites (MMCs) have evoked a keen interest in recent times for their potential applications in the aerospace and automotive industries, owing to their superior strength-to-weight ratio and high temperature resistance. Aluminum alloys with good corrosion resistance are commonly used as the matrix materials, along with inexpensive reinforcement particles to synthesize MMCs. Gnjidi (2001) used silicon carbide (SiC), a ceramic material that has a higher hardness has been used as a reinforcement material in the lightweight aluminum metal matrix to form aluminum – silica composite with different weight fractions [7]. Furthermore, under water marine components are subjected to severe corrosion and aluminum alloys are used as raw materials for manufacturing many components are used in marine applications. Bodunrin et al. (2011) syntheses AA6063/SiC composites, in which silicon carbide particulates were used as a discontinuous dispersoid in the AA6063 aluminum matrix to enhance strength, modulus, and corrosion resistance [8]. Pathak et al. (2006) reported that the properties like density and hardness of metal matrix composites with Aluminum as matrix material and SiC as reinforcement material are changing with respect to the weight fraction of the reinforcement material in the matrix materials [9]. The AA6063 aluminum alloy is an Al-Mg–Si based alloy, which comes under the 6xxx series family of aluminum alloy is having properties like lower density, high thermal conductivity, and good wear resistance. Such AA6063 aluminum materials are processed in large quantities at low cost in most of the developing countries. Alaneme et al. (2013) studied the corrosive properties of the composites using AA6063 aluminium alloy matrix and SiC as reinforcement material [10]. Khalifa T.A. and Mahmoud T.S. (2009) developed AA6063/SiC composites through stir casting process by adding SiC particles as reinforcement material in AA6063 aluminum alloy [11]. Kenneth Alaneme (2011) developed such composites which can be used as raw materials for components of engine used in marine application with the addition of different volume percent of SiC particles and studied their corrosion behavior by immersing in NaCl solution. Machining operations are difficult to perform on these composite materials with conventional tools and techniques, because of its low thermal conductivity and the abrasive nature of the reinforcing particles **[12]**. Lau et al. (1995) suggested that among, the un-conventional processing techniques laser and electrical discharge machining have been proved to be effective tools in shaping some of these materials. As there is no contact between tool and work piece material in electrical discharge machining, low tool wear and improved surface finish are observed **[13]**. WEDM is a slightly modified version of the conventional electrical discharge machining and Hochenget al. (1997) studied the machining of advanced MMCs with different compositions of aluminum and silicon carbide through WEDM **[14]**. Sathish kumar and Kanthababu (2011) investigated the WEDM parameters during the machining the samples AA6063/SiC composites with different weight fractions **[15]**. Garg et al. (2010) suggested that WEDM shows higher machining capability for cutting complex shapes in composites **[16]**. Tosun et al (2003) investigated the effect of WEDM parameters such as pulse on time (T_{ON}), pulse off time (T_{OFF}), peak current (*IP*) wire feed (*WF*), flushing pressure (*FP*), wire tension (*WT*), open voltage (*OV*), servo voltage (*SV*), and dielectric pressure (*DP*) on performance measure like surface roughness (R_a), cutting width (*Kerf*) and metal removal rate (*MRR*) **[17]**. Narender singh et al. (2004) optimized the WEDM parameters through grey relational analysis after performing experiments on composites materials **[18]**. Yan et al. (2005) found that T_{ON} has a significant effect on R_a during rough machining through WEDM and for finishing, the cutting feed rate has the significant effect on R_a **[19]**. Nilesh et al. (2010) observed that T_{ON}, T_{OFF} and the volume fraction of ceramic reinforcement in the composites significantly affect the surface finish and cutting width (*Kerf*) **[20]**. Ho et al. (2004) indicated that a significant amount of research have to be conducted to find different methodologies to achieve the ultimate WEDM goals of optimizing the numerous process parameters to minimize R_a and *Kerf* **[21]**. Analyzing the effects of WEDM process parameters on performance measures is an ongoing task and limited study have reported on the circular contour machining of MMC materials through WEDM process. This present work proposes removing a semi cylindrical piece from stir cast rectangular AA6063/SiC composite plates with different compositions through circular contour machining via WEDM. The dimensional accuracy of the machined semicircular contour is compared with a hole machined through the traditional drilling process. Then the effects of parameters T_{ON}, T_{OFF} and *IP* on the performance measures of surface roughness (R_a) and cutting width (*Kerf*) were studied.

2 Wire Electric Discharge Machining (WEDM) Process: WEDM is a thermoelectric process, in which a series of discrete sparks are created between a moving brass wire (cathode) and the conductive AA6063/SiC composite work piece (anode). A negatively polarized brass wire with a diameter of 0.175 mm was used as an electrode: is moved vertically by a servo motor. High frequency pulses of AC current are discharged from the brass wire to the conductive AA6063/SiC composite with a minute spark gap through an insulated dielectric fluid. These electrical discharges melt and vaporize minute amounts of the AA6063/SiC composite plates, that flushed away by the dielectric fluid. During the continuous machining operation, the material removed is continuously flushed with a dielectric fluid by passing through nozzles on both sides of the work piece. Deionized water is used as a dielectric fluid, and the ionization of water is prevented by adding an ion exchange resin to the dielectric distribution system. The brass wire is programmed and controlled by a control unit to travel at a constant tension, along a circular contour corresponding to the work-piece table's movement. The machining power supply unit energizes the wire electrode to produce the spark and melt the material and a separate control unit properly controls the deionized dielectric water supply to flush the melted material.

Three electrical parameters, namely pulse on time (T_{ON}), pulse off time (T_{OFF}) and peak current (*IP*), play a significant role in the WEDM material-removal process. In WEDM, a voltage is applied between the work-piece and the wire for a period of time, measured in microseconds, which is represented by pulse on time (T_{ON}), and a spark is produced and a small amount of material melts and evaporates, which depends on the duration of the sparks produced. The melted part of the AA6063/SiC composite plate forms a small crater in the machining zone. The crater material was removed by the flow of the deionized dielectric fluid and the remaining part of the work-piece re-solidifies rapidly in a period known as pulse off time (T_{OFF}), during which the voltage is absent. Application of consecutive pulses with high frequencies, together with the forward movement of the brass wire towards the AA6063/SiC composite plate results in circular contour shaped according to the path program. The pulse discharge energy depends on the maximum value of current passing through the electrodes in a given pulse cycle, which is represented by peak current (*IP*). The breakdown of the material during the material removal process is due to this high local electric field and this material removal affects the surface finish of the work piece. This study, considers the effects of the parameters T_{ON}, T_{OFF} and *IP* on the performance measures of surface roughness (R_a) and cutting width (*Kerf*) for machining a circular contour in AA6063/SiC composites with different densities.

3 Machining in the WEDM Process: The experiments were carried out on an Electronica 4-axis CNC Sprintcut wire electrical discharge machine and in this machine, all the axes were servo controlled and could be programmed to follow a computer numerical control (CNC) code, which was fed through the control panel. All four axes have an accuracy of 1 μm. The electrode material used was a brass wire with a diameter 0.175 mm. The dimensions of the work piece used in the experiments were 95 × 95 × 10 mm. A photograph of the machine and the WEDM zone with the work piece plate and the brass wire are shown in Figure (7a) and Figure (7b).

Figure (7a): Sprint cut 734 Machine

Figure (7b): Machining zone

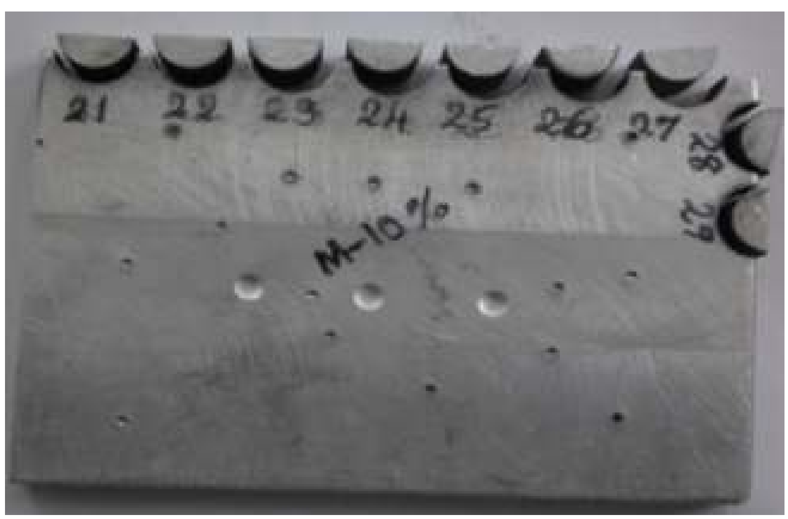

Figure (8): The machined AA6063/10%SiC plate.

The performance measures of surface roughness and cutting width of the resultant pin and the machined work piece for different combinations of electrical parameter settings were analyzed. Four rectangular work piece specimens of AA6063/SiC composite plates with weight fraction of 0%, 5%, 10% and 15% of SiC were machined by similar combinations of the process parameter corresponding to L9 orthogonal array, so that optimum conditions for the process parameters and the wire cut product could be determined. The machined AA6063/SiC plate are shown in Figure (8). In each of the four samples of AA6063/SiC composites plates, nine WEDM passes were made at different settings of T_{ON}, T_{OFF} and *IP*, and the roughness of the inner curved portion of the machined work piece were measured. Similarly, the dimensions of the semi-circular cut pins and the machined work pieces were measured to calculate the cutting width. During the experiment, in one of the samples, one wire cut was rejected due to incorrect settings of gap, and an alternate cut was performed.

4. Experimental Results and Discussions: The material removal process of WEDM can be related to the operations of the band saw in which the cutter intensity is specified by the spark intensity and width of the cut is determined by the length of the spark. The spark energy and sparking rate determine the size of chip and material removal rate of the process. In WEDM machine the spark energy is governed by the parameter peak current (IP) and sparking rate is controlled by voltage cycle time (T). The voltage cycle time is the sum of pulse on time (T_{ON}) during which the material vaporizes from the work-piece and the material is flushed away during pulse off time (T_{OFF}). The performance measures of the WEDM process are studied to determine the effects of inclusions of SiC particles in the AA6063/SiC composite materials by varying the machine parameters governing voltage cycle time and spark energy.

4.1 The Effect of work-piece constituent materials on R_a and *Kerf*:

The inclusion of SiC particles in AA6063 alloy in different weight percent modifies the density and the hardness of the composites; investigations are carried out by machining the composite samples in semi-circular contour at constant spark density and sparking rate. A semi-circular pin with a diameter of 10 mm was removed from all four samples of AA6063/SiC composite plates by keeping the voltage cycle time at 160 microseconds and peak current as 170 amps and the surface roughness (R_a) and cutting width (*Kerf*) were measured and given in Table (5).

Table (5): R_a and *Kerf* at constant *IP* = 170 and *T* = 160

S.No.	Composite Composition		*Ra* (μmm)	*Kerf* (mm)
	AA6063	SiC		
1.	100%	0%	2.26	0.47
2.	95%	5%	2.54	0.52
3.	90%	10%	2.65	0.56
4.	85%	15%	2.76	0.61

In addition to understand the effect, the sparking rate is kept constant at T = 160, the spark intensities were increased two more levels by setting the values of peak current at 190 and 210 amps, the performance measures are found out and given in Table (6) and (7) respectively.

Table (6): R_a and *Kerf* at constant *IP* = 190 and *T* = 160

S.No.	Composite Composition		*Ra* (μmm)	*Kerf* (mm)
	AA6063	SiC		
1.	100%	0%	2.12	0.65
2.	95%	5%	2.20	0.69
3.	90%	10%	2.31	0.69
4.	85%	15%	2.42	0.74

Table (7): R_a and *Kerf* at constant *IP* = 210 and *T* = 160

S.No.	Composite Composition		*Ra* (µmm)	*Kerf* (mm)
	AA6063	SiC		
1.	100%	0%	2.45	0.61
2.	95%	5%	2.67	0.66
3.	90%	10%	2.78	0.65
4.	85%	15%	2.89	0.70

The variations of surface roughness and cutting width of the four samples of AA6063/SiC composites with different weight fractions are shown in the Figure (9a) and Figure (9b).

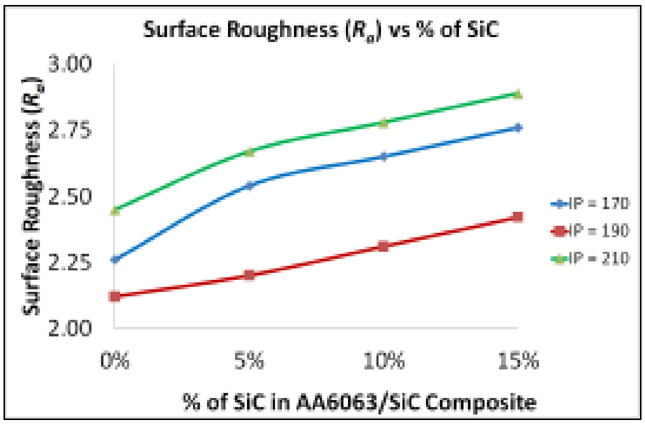

Figure (9a). R_a at constant *T* and *IP*

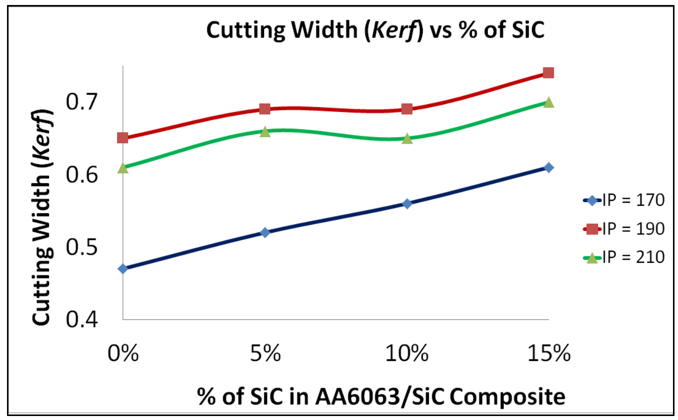

Figure (9b). *Kerf* at constant *T* and *IP*

Figure (11), demonstrates that the surface roughness and cutting width increase with an increase of SiC particles in the composite. It is observed that the inclusion of SiC particles directly affects the performance measures due to its brittle nature at constant sparking rate and spark density.

4.2 The Effect of Spark Energy of WEDM on R_a and *Kerf*: The size and volume of chip material removed in WEDM depends on the spark intensity specified as pulse discharge density and is governed by WEDM machine parameter peak current. Studies have been conducted to investigate the effect of pulse discharge density on the performance of the WEDM process.

Table (8): R_a and *Kerf* at varying Pulse discharge density

S.No.	Composite Composition		*T*	*IP*	*Ra* (µmm)	*Kerf* (mm)
	AA6063	SiC				
1.			160	170	2.26	0.47
2.	100%	0%	160	190	2.12	0.65
3.			160	210	2.45	0.61
4.			160	170	2.54	0.52
5.	95%	5%	160	190	2.20	0.69
6.			160	210	2.67	0.66
7.			160	170	2.65	0.56
8.	90%	10%	160	190	2.31	0.69
9.			160	210	2.78	0.65
10.			160	170	2.76	0.61
11.	85%	15%	160	190	2.42	0.74
12.			160	210	2.89	0.70

In this investigation, the voltage cycle time was kept constant at 160 micro seconds and three WEDM semi-circular contouring was done by keeping the peak current levels at 170, 190 and 210 amps on each AA6063/SiC composites plates and the surface roughness and cutting width were measured. The measured values R_a and *Kerf* are given in the Table (8).

The effects of varying pulse discharge density on R_a and *Kerf* on four different samples of AA6063/SiC composite plates are shown in Figure (10).

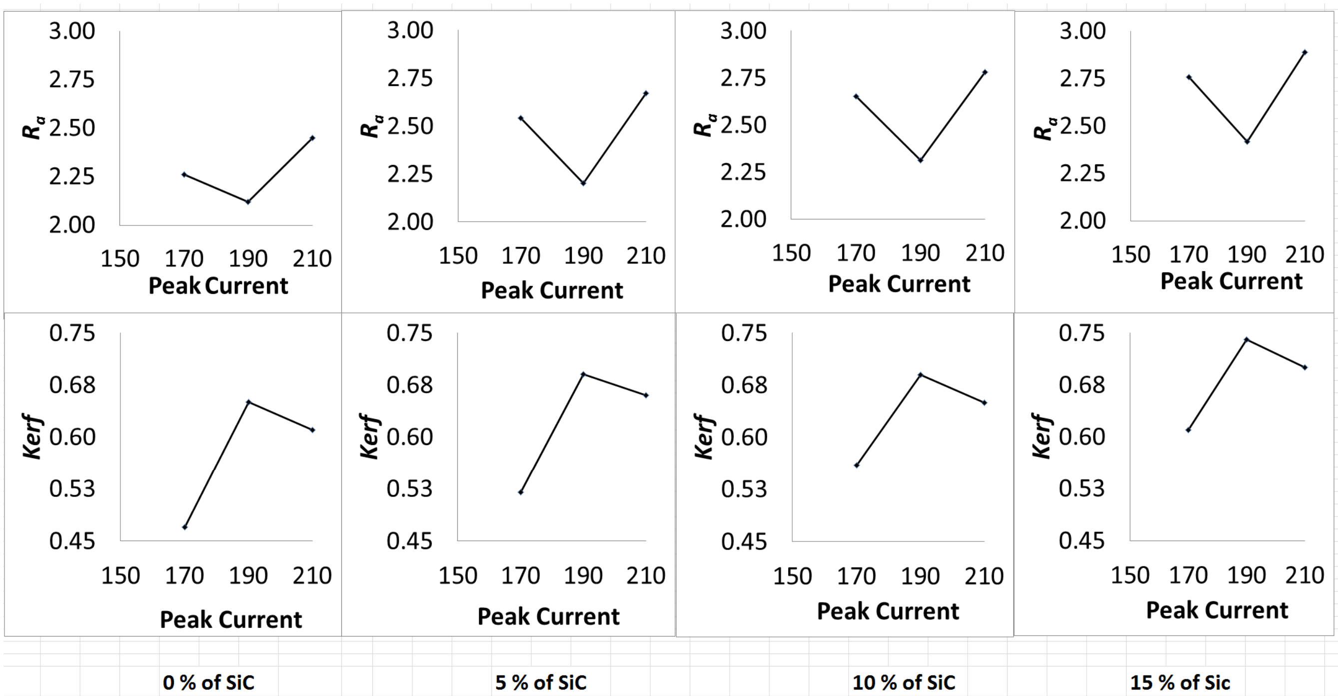

Figure (10). Effect of Pulse Discharge Density on R_a and *Kerf*

The graphs demonstrate that the surface roughness R_a is at a minimum at *IP* = 190 for all the samples, but the *Kerf* is at a maximum. Generally, higher setting of peak current leads to removal of larger chips and produces rough finish and lower setting to smooth surface finish. But, the sparking rate is also, playing a role, it is inferred that, the better surface finish is obtained at *IP* = 190, for the constant voltage cycle time of 160 microseconds.

4.3 The Effect of Sparking Rate on R_a and *Kerf*: The number of chips removed per second in WEDM is determined by the sparking rate described by the voltage cycle time (*T*) which is the sum of pulse on time (T_{ON}) and pulse off time(T_{OFF}). In WEDM, in each cycle, the voltage is applied in microseconds (T_{ON}) during which the current is flowing between the work piece and the electrode and the material is vaporized and melted. Then, the voltage is stopped for certain number of microseconds (T_{OFF}) during which the small melted chips of the work piece are flushed out by the dielectric fluid. Investigations were made to study the effect of sparking rate on the performance measure, 9 semi-circular pins were wire cut from each samples of AA6063/SiC composites plates according to an orthogonal array (L9) machine parameter settings governing sparking rate and spark intensities. Statistical optimization could be performed from these values so that the effect of the process parameter on performance measures from the standard L9 experiments might be analysed but it is not considered in this work. The analysis is based on the statistical averaging and the average performance measures of the four samples at similar combinations of machine setting parameters such as T_{ON}, T_{OFF} and *IP* at different three levels were calculated and given in Table (9).

Table (9). Average performance measures with Varying T_{ON}, T_{OFF}, and *IP*

S No.	T_{ON}	T_{OFF}	*IP*	Average R_a	Average *Kerf*
1.		60	170	2.55	0.54
2.	100	50	190	2.49	0.61
3.		40	210	2.23	0.63
4.		60	190	2.04	0.64
5.	110	50	210	*2.70*	0.66
6.		40	170	2.23	0.67
7.		60	210	2.58	0.62
8.	120	50	170	2.12	0.67
9.		40	190	2.26	*0.69*

Table (9) shows that that the lowest surface roughness was obtained at the parameter settings of T_{ON} = 110, T_{OFF} = 60 and *IP* = 190, and the highest surface roughness was obtained at the parameter settings of T_{ON} = 100, T_{OFF} = 60 and *IP* = 210. Similarly, the lowest cutting width was obtained at the settings of T_{ON} = 100, T_{OFF} = 60 and *IP* = 170, and the highest cutting width was obtained at the setting T_{ON} = 120, T_{OFF} = 40 and *IP* = 190.

4.3.1 The Effect of Vaporizing Time on R_a and *Kerf* : Statistical averaging from the orthogonal array values, investigations have been made to study the effects of T_{ON} on the performance measures. The average value of the performance measures of the four samples are calculated at the three levels of pulse on time (T_{ON}), while keeping all other factors constant, is given in the Table (10) and the variations in the average performance of the four different AA6063/SiC composites materials are shown in Figure (11).

Table (10). R_a and *Kerf* at varying Pulse ON time T_{ON}

S.No	T_{ON}	SiC 0%		SiC 5%		SiC 10%		SiC 15%		Ave.	Ave.
		R_a	*Kerf*	R_a	*Kerf*	R_a	*Kerf*	R_a	*Kerf*	R_a	*Kerf*
1.	100	2.26	0.54	2.37	0.59	2.48	0.61	2.58	0.66	2.42	0.60
2.	110	2.07	0.61	2.23	0.66	2.41	0.65	2.52	0.69	2.31	0.65
3.	120	2.14	0.62	2.26	0.68	2.38	0.65	2.50	0.70	2.32	0.66

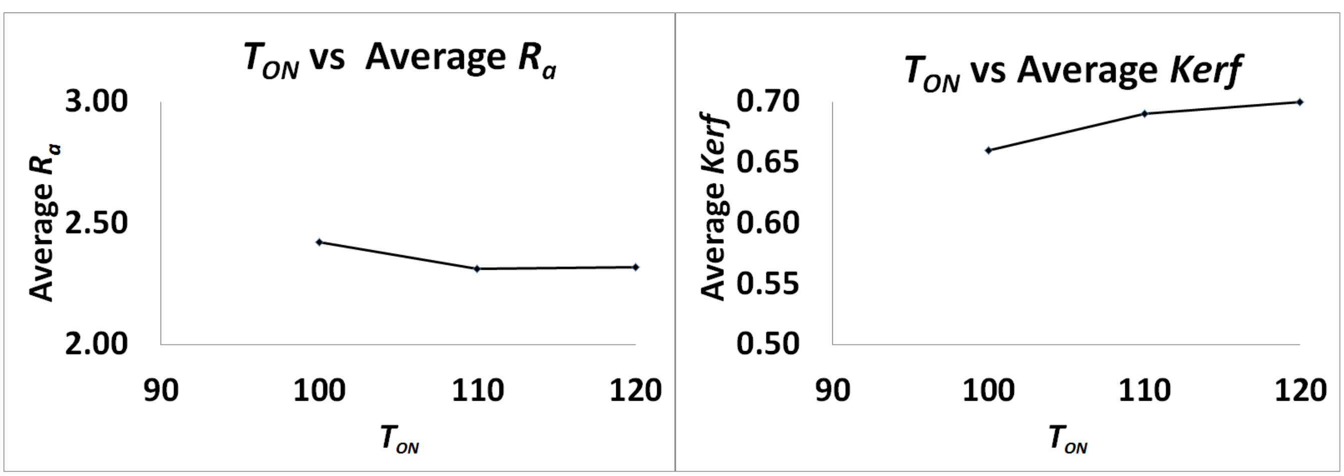

Figure (11): Performance measures at varying T_{ON}

Figure (11) shows that the surface roughness decrease from T_{ON} = 100 to T_{ON} = 110 and increase marginally from T_{ON} = 110 to T_{ON} = 120. However, the cutting width is increasing with the increase in voltage application time. This infers that increase in vaporizing time increases the length of spark and so *Kerf* is higher at T_{ON} = 120. The effects of T_{ON} on the performance measures for different samples of AA6063/SiC composites are shown in Figure (12).

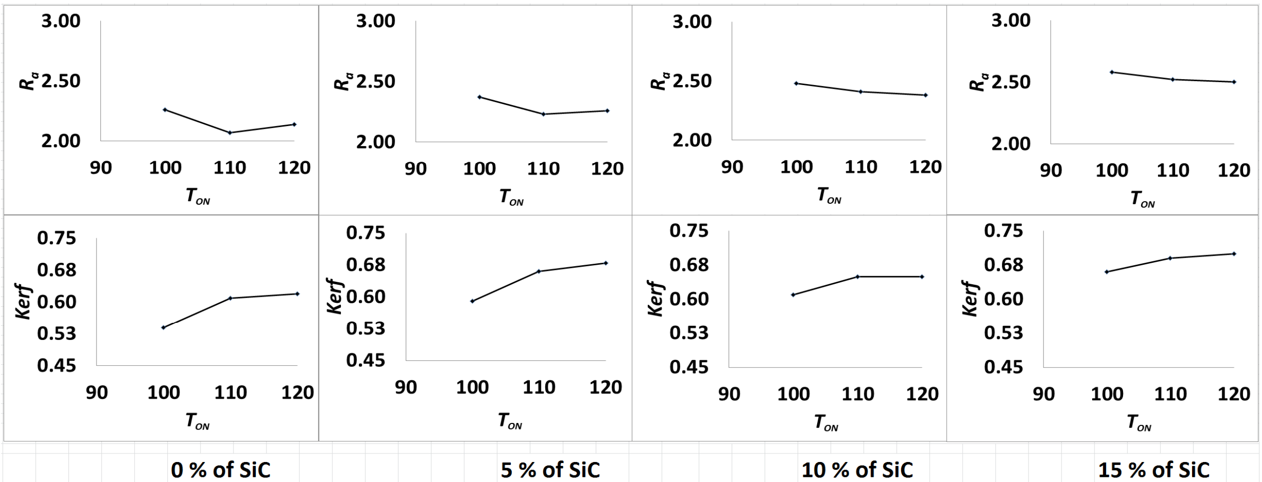

Figure (12). Effect of Pulse ON time T_{ON} on R_a and *Kerf*

Figure (12) shows that the surface roughness decrease from T_{ON} = 100 to T_{ON} = 110 and increase from T_{ON} = 110 to T_{ON} = 120 for the samples having 0% and 5% of SiC. Further, the surface roughness decrease with the increase in the level of T_{ON} for the samples 10% and 15% of SiC. However, the cutting width increases with the increase in level of T_{ON} irrespective of the percentage of inclusion of SiC particles.

4.3.2 The Effect of Flushing Time on R_a and *Kerf* : The effects of T_{OFF} on the performance measures were also analysed by statistical averaging of the values of orthogonal array. The average value of the performance measures of the four samples are calculated at the three levels of pulse off time (T_{OFF}), while keeping all other factors constant, is given in the Table (11) and the variations in the average performance of the four different AA6063/SiC composites materials are shown in Figure (13).

Table (11): R_a and *Kerf* at varying Pulse OFF time T_{OFF}

S.No	*TOFF*	SiC 0%		SiC 5%		SiC 10%		SiC 15%		*Ave.*	*Ave.*
		Ra	*Kerf*	*Ra*	*Kerf*	*Ra*	*Kerf*	*Ra*	*Kerf*	*Ra*	*Kerf*
1.	60	2.16	0.54	2.35	0.65	2.46	0.60	2.58	0.65	2.39	0.61
2.	50	2.24	0.61	2.39	0.66	2.50	0.64	2.61	0.69	2.44	0.65
3.	40	2.06	0.62	2.18	0.67	2.30	0.66	2.41	0.71	2.24	0.67

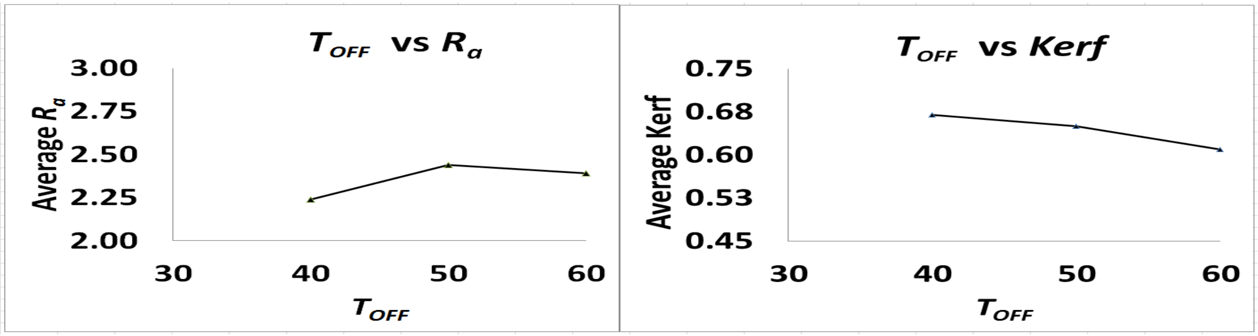

Figure (13): Performance measures at varying T_{OFF}

Figure (13) demonstrates that the surface roughness increase from T_{OFF} = 40 to T_{OFF} = 50, and decrease from T_{OFF} = 50 to T_{OFF} = 60. However, the cutting width decreases with the increase in voltage off time. This infers that increase in flushing time decrease the length of spark and so *Kerf* is lower at T_{ON} = 60. The effects of T_{OFF} on the performance measures of different samples of AA6063/SiC composites are shown in Figure (14).

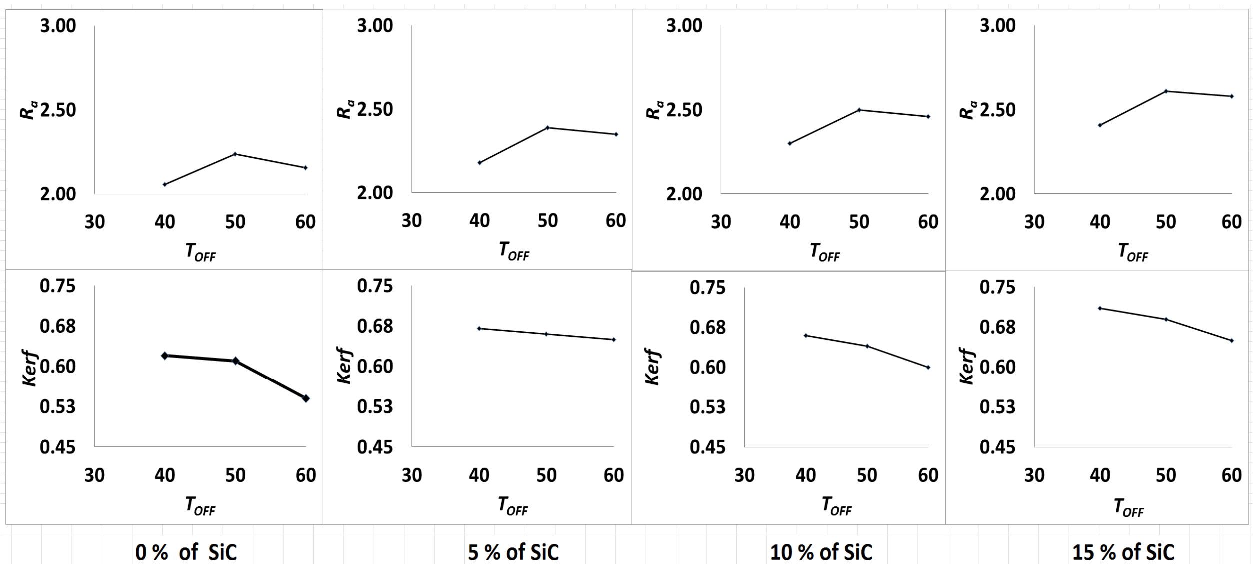

Figure (14): Effect of Pulse OFF time T_{OFF} on R_a and *Kerf*

Figure (14) shows that the surface roughness increases from T_{OFF} = 40 to T_{OFF} = 50 and decreasing from T_{OFF} = 50 to T_{OFF} = 60 for all the samples having 0% and 5%, 10% and 15% of SiC. But the cutting width decrease with the increase in level of T_{OFF}, irrespective of the inclusion of SiC particles.

5 Conclusions: Experimental investigations were performed for the WEDM process on machining AA6063/SiC composites with four different weight fractions. By varying this process parameter in three different levels, it is observed that the values of surface roughness and cutting width increase with the increase of percentage content of SiC particles. Analysing the effect of spark energy, better surface finish is obtained at *IP* = 190, for the constant voltage cycle time of 160 microseconds. Further, the surface roughness decreases from T_{ON} = 100 to T_{ON} = 110 and increases from T_{ON} = 110 to T_{ON} = 120 and increases from T_{OFF} = 40 to T_{OFF} = 50 and decrease from T_{OFF} = 50 to T_{OFF} = 60. However, the cutting width increases with the increase of vaporizing time and decreases with the increase of flushing time. Further, the orthogonal array values of the experiments might be used to optimize the machining parameters and their influences on the performance measure might be studied through design of experiments methodologies.

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