Int J Adv Manuf Technol (2011) 56:975–986
DOI 10.1007/s00170-011-3242-5

ORIGINAL ARTICLE

Investigation of wire electrical discharge machining characteristics of Al6063/SiC_p composites

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Received: 6 August 2010 / Accepted: 21 February 2011 / Published online: 6 April 2011

Abstract In this investigation, the effect of wire electrical discharge machining (WEDM) parameters such as pulse-on time (T_{ON}), pulse-off time (T_{OFF}), gap voltage (V) and wire feed (F) on material removal rate (MRR) and surface roughness (R_a) in metal matrix composites (MMCs) consisting of aluminium alloy (Al6063) and silicon carbide (SiC_p) is discussed. The Al6063 is reinforced with SiC_p in the form of particles with 5%, 10% and 15% volume fractions. The experiments are carried out as per design of experiments approach using L_9 orthogonal array. The results were analysed using analysis of variance and response graphs. The results are also compared with the results obtained for unreinforced Al6063. From this study, it is found that different combinations of WEDM process parameters are required to achieve higher MRR and lower R_a for Al6063 and composites. Generally, it is found that the increase in volume percentage of SiC resulted in decreased MRR and increased R_a. Regression equations are developed based on the experimental data for the prediction of output parameters for Al6063 and composites. The results from this study will be useful for manufacturing engineers to select appropriate WEDM process parameters to machine MMCs of Al6063 reinforced with SiC_p at various proportions.

Keywords Wire electrical discharge machining · Metal matrix composites · Al6063 · Al6063/SiC_p · ANOVA · Response graph

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1 Introduction

MMCs are materials consisting of two or more constituent parts, in which a metal is reinforced with high strength material such as silicon carbide, aluminium oxide, etc. in various proportions. This leads to MMCs with enhanced properties like high elastic modulus, high specific strength, high wear resistance, improved stiffness, low thermal expansion coefficient, etc. These materials have gained importance in various fields like aerospace, defense, automobiles and sports [1]. However, the reinforcement material in various forms (particulate, whiskers and continuous fibers) makes it difficult to machine using traditional machining methods due to its abrasive nature. Therefore, researchers have made an attempt to machine MMCs using different non-traditional machining methods like abrasive water jet, laser cutting and electrical discharge machining (EDM) [2–4]. However, these processes have certain limitations like linear cutting and elaborate preparation of preshaped electrode (tool). In order to overcome these limitations, few researchers have used wire electrical discharge machining (WEDM) process and it is found to be effective and economical tool in the machining of composite materials [5]. WEDM is considered as one of the most versatile processes for machining intricate, complex shapes and difficult to machine materials [6]. But only limited attempts have been made by researchers to machine different MMCs using WEDM process [7].

In WEDM, the tool is in the form of a continuously moving wire made of either brass or copper of diameter varying from 0.1 to 0.3 mm. The material is eroded from the workpiece by a series of discrete sparks occurring between the workpiece and the wire separated by a stream of dielectric fluid, which is continuously fed to the machining zone [7]. The schematic representation of

WEDM process is shown in Fig. 1. In this process, there is no contact between workpiece and the wire (tool), and therefore, it eliminates the mechanical stress during machining. This process is widely used in the manufacturing of tools, dies, fixtures and gauges [5]. However, WEDM is a complex process controlled by very large number of process parameters. They are broadly classified as workpiece materials, component geometry, dielectric fluids, machining parameter settings, machining characteristics and related [5, 8, 9]. Any small variations in the process parameter will affect the machining performance such as MRR, R_a and dimensional/shape features. Therefore, the selection of appropriate machining parameters for different materials is a difficult task. Mostly it is material specific.

A detailed survey related to machining of MMCs using WEDM process has been presented by Garg et al. [7]. From their studies, it is observed that few researchers have machined different combinations of MMCs using WEDM process. Gatto and Luliano [10] have examined the surface features of aluminium alloy (Al2009) with 15% SiC_w and 20% SiC_p. Rozenek et al. [11] have investigated the WEDM characteristics in $AlSi_7Mg$ with 20% SiC and $AlSi_7Mg$ with 20% Al_2O_3. Similarly, Guo et al. [12] investigated Al6061 with 20% Al_2O_3 particles by WEDM process. Yan et al. [13] machined unreinforced Al6061 and MMCs consisting of Al6061 with 10% and 20% Al_2O_3 in the form of particulate by WEDM process, and the results are compared. Liu et al. [14] studied wire electrochemical discharge machining of Al6061 reinforced with Al_2O_3 particles. Patil and Brahmankar [15] investigated WEDM performance in Al359 with 20% SiC_p. Similarly, Manna and Battacharyya [16] carried out experimental investigation in WEDM to determine the parameters setting for machining Al/SiC_p.

The most commonly used MMCs in different applications are found to be Al/SiC. Aluminium is used as matrix material due to its lesser density, while SiC is used as reinforcement material because of its hardness and temperature-resistant properties [4]. The MMC consisting of aluminium alloy with SiC in different proportions is expected to replace some of the existing material in various applications due to its superior properties. But it has been found that there is no attempt to machine MMC consisting of Al6063 and SiC using WEDM process. WEDM is not only used for machining complex shapes with high accuracy, but improves productivity as well. An attempt has been made by Akshay et al. [17] to machine MMC consisting of Al6063 with SiC by using EDM process. Al6063 is used in a variety of applications such as electrical components, heat sinks and architectural fields. Hence, in this work, it is planned to investigate the effect of WEDM process parameters such as pulse-on time (T_{ON}), pulse-off time (T_{OFF}), gap voltage (V) and wire feed (F) on MMCs consisting of Al6063 with various volume fractions of SiC and to compare the results with that of unreinforced Al6063 considering MRR and R_a.

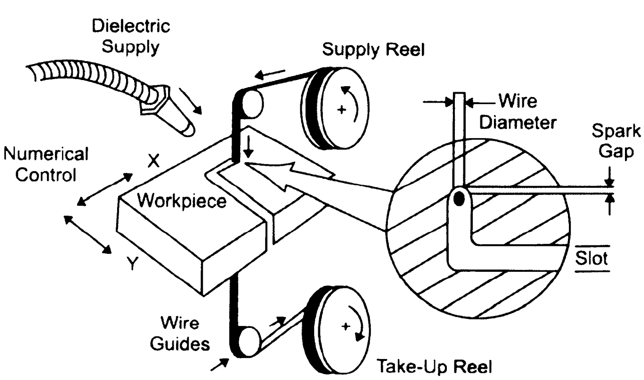


Fig. 1 The schematic representation of WEDM process [8]

2 Experimental details

Machining of unreinforced Al6063 and MMCs are performed in an Electronica make 4-axis CNC Ecocut wire electrical discharge machine. A negatively polarized brass wire of 0.25 mm diameter is used as an electrode. Demineralized water is used as a dielectric fluid. The MMCs used in this investigation consist of Al6063 alloy reinforced with SiC_p particulate of size 25–36 μm range, with various volume fractions such as 5%, 10% and 15%. The chemical composition of the unreinforced Al6063 (directly procured) and MMCs such as Al6063 with 5% SiC, 10% SiC and 15% SiC were studied using optical emission spectrometry as per ASTM E1251 standard and presented in the Table 1. The MMCs are prepared using stir casting process. A special die has been made to prepare the workpiece of size 100×100×6.2 mm. The prepared composites were allowed to cool in the die at room temperature for about 8 h. Photograph of composite material Al6063 reinforced with 5% SiC is shown in Fig. 2. The presence of SiC (acicular morphology) in the composite materials has been identified using microscopic images captured with Dewinter Metallurgical Microscope (Fig. 3). The SEM images were taken with secondary electrons using Hitachi S3400 equipment (Fig. 4). These images show discrete localized pool/agglomeration of SiC particles. EDAX analysis is done for identifying the elemental composition with SiC particle (reinforcement) as an area of interest (Table 2). The hardness of the composites Al6063 with 5% SiC, 10% SiC and 15% SiC has been measured using Brinell hardness tester as per IS 1500–2005 standard at two different locations on the workpiece. The mean hardness value of the composite

Table 1 Chemical composition of unreinforced Al6063 and composites

Chemical	Al6063 (%)	Al6063 with 5% SiC (%)	Al6063 with 10% SiC (%)	Al6063 with 15% SiC (%)
Silicon	0.507	0.546	0.537	0.717
Iron	0.001	0.001	0.001	0.001
Copper	0.018	0.019	0.017	0.067
Manganese	0.009	0.009	0.008	0.008
Magnesium	0.646	0.106	0.106	0.106
Lead	0.005	0.005	0.005	0.005
Zinc	0.010	0.010	0.010	0.010
Chromium	0.001	0.001	0.001	0.001
Nickel	0.013	0.003	0.003	0.003
Titanium	0.019	0.021	0.026	0.028
Tin	0.084	0.083	0.086	0.082
Aluminium	98.634	99.140	99.174	98.973

materials Al6063 with 5% SiC, 10% SiC and 15% SiC are found to be 96.5, 109 and 110.5 HBW, respectively. It is observed that increase in volume percentage of SiC influence the hardness of composites.

Different machine setting parameters such as pulse-on time (T_{ON}), pulse-off time (T_{OFF}), gap voltage (V) and wire feed (F) are varied at three levels (Table 3). The machining parameters at different levels are selected based on the trial runs carried out in such a way to avoid wire breakage during machining of composite materials. The experiments are conducted as per design of experiments (DOE) approach using L_9 orthogonal array (OA) in order to reduce the number of experiments to be performed [18]. By using DOE approach, minimum numbers of experiments are performed and appropriate data are collected to acquire the necessary technical information. The results are analysed by analysis of variance (ANOVA) and response graphs using ANOVA_TM software. Machined workpiece of Al6063 with 5% SiC as per L_9 OA is shown in Fig. 5. Typical machined part of Al6063 with 5% SiC is shown in Fig. 6.

The performances of the WEDM process are evaluated using output parameters such as MRR and R_a. The MRR is calculated using the formula as shown below

$$MRR = \frac{Total\ volume\ removed\ from\ the\ workpiece}{Time\ taken}\ mm^3/\min \quad (1)$$

The surface roughness parameter R_a is measured using Mitutoyo make surface roughness tester with cut off length of 0.25 mm. The regression equations are developed using MATLAB for the prediction of output parameters such as MRR and R_a.

3 Results and discussions

Table 4 shows the allocation of input WEDM process parameters in L_9 OA and experimental results. Data pertaining to MRR and R_a while machining unreinforced Al6063 and MMCs are presented and discussed below.

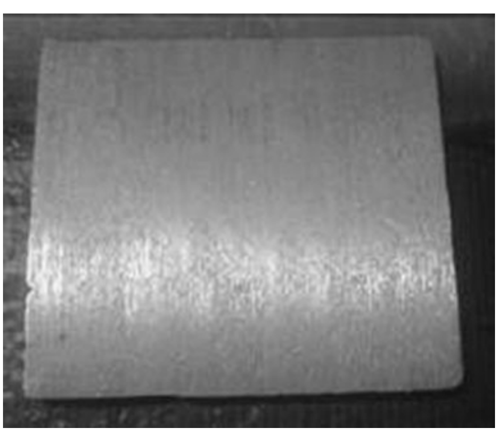
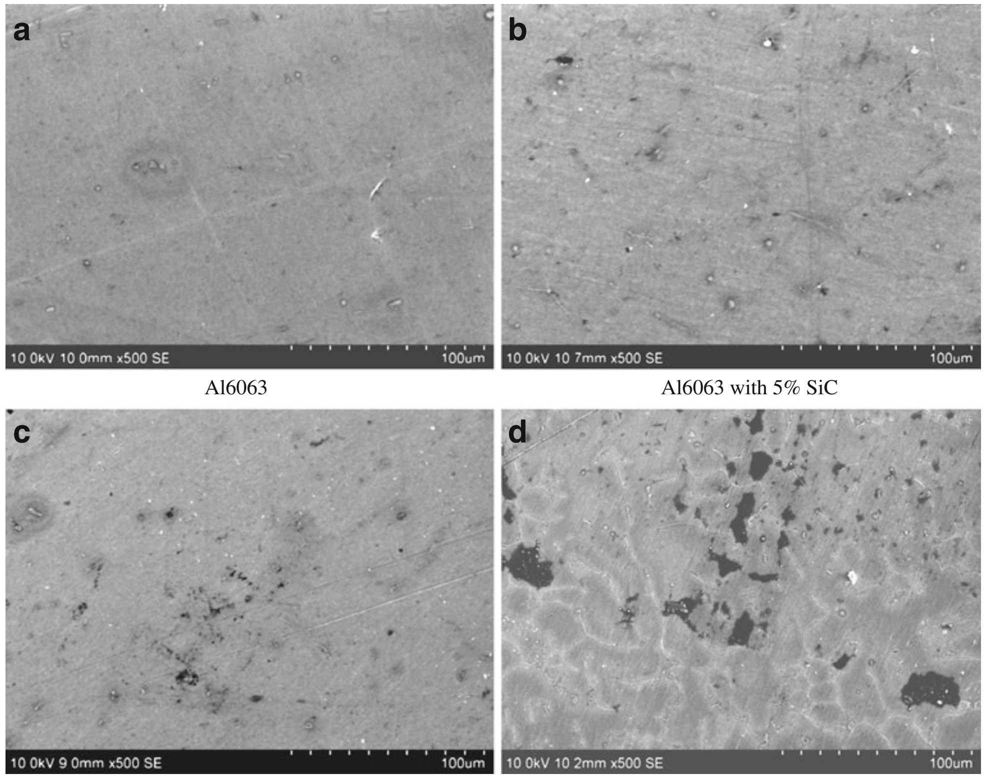


Fig. 2 Photograph of composite material Al6063 with 5% SiC

Fig 3 Typical microscope image (×400 magnification) of the composite material Al6063 with 10% SiC

Fig. 4 SEM photographs of unreinforced Al6063 and MMCs



Al6063 | Al6063 with 5% SiC | Al6063 with 10% SiC | Al6063 with 15% SiC

3.1 Material removal rate

This section deals with analysis on MRR of unreinforced Al6063 and Al6063 reinforced with 5% SiC, 10% SiC and 15% SiC.

3.1.1 Machining of Al6063

ANOVA Table 5a indicates that among the input process parameters considered in this study while machining Al6063, it is observed that pulse-off time (T_{OFF}), gap voltage (V) and wire feed (F) are found to be significant at 99% confidence level. Pulse-on time (T_{ON}) is found to be an insignificant parameter. Voltage (V) is found to be the major influencing parameter with contribution of 82.45%. From the response graph (Fig. 7), it is found that high pulse-on time (T_{ON3}), low pulse-off time (T_{OFF3}), low voltage (V_1) and high wire feed (F_3) resulted in higher MRR. Hence, the above parameters and levels such as high pulse-on time (T_{ON3}), low pulse-off time (T_{OFF3}), low voltage (V_1) and high wire feed (F_3) are recommended for achieving higher MRR for unreinforced Al6063. The regression equation for the above is given below

$$MRR_{Al6063} = 47.8767 + 0.0192\mathrm{T}_{ON} - 0.8392\mathrm{T}_{OFF} - 0.4428\mathrm{V} + 1.1\mathrm{F} \quad (2)$$

3.1.2 Machining of MMCs

ANOVA Table 5b indicates that among the input process parameter considered in this study while machining Al6063 with 5% SiC, it is observed that only gap voltage (V) is

Table 2 Elemental composition based on EDAX analysis (reinforcement as an area of interest)

Chemicals	Al6063 (% wt.)	Al6063 with 5% SiC (% wt.)	Al6063 with 10% SiC (% wt.)	Al6063 with 15% SiC (% wt.)
Carbon	12.28	16.96	26.78	30.31
Oxide	1.11	1.41	4.30	18.51
Silicon	0.14	0.18	0.18	0.70
Aluminium	86.47	81.46	68.74	50.48

Table 3 WEDM process parameters

S. No	Parameter	Symbol	Level 1	Level 2	Level 3
1	Pulse-on time (μs)	T_{ON}	6	8	10
2	Pulse-off time (μs)	T_{OFF}	10	8	6
3	Gap voltage (V)	V	50	60	70
4	Wire feed (mm/min)	F	8	9	10

found to be significant at 99% confidence level for MRR with contribution of 70.35%. Whereas pulse-on time (T_{ON}), pulse-off time (T_{OFF}) and wire feed (F) are found to be insignificant. However, from the response graph of MRR (Fig. 7), it can be observed that with pulse-on time (T_{ON3}), MRR increases. Response graph (Fig. 7) also indicates that the increase in the pulse-on time (T_{ON}) from low level (T_{ON1}) to medium level (T_{ON2}) as well as from medium level (T_{ON2}) to high level (T_{ON3}), there is an increase in the MRR. The rate of increase of MRR is found to be higher when the pulse-on time (T_{ON}) increases from low level (T_{ON1}) to medium level (T_{ON2}) than that of medium level (T_{ON2}) to high level (T_{ON3}). In the case of pulse-off time (T_{OFF}), it is found that low pulse-off time (T_{OFF3}) results in higher MRR. WDEM being a discontinuous sparking process, it is necessary to restrict/constrain pulse-off level to a minimum, to sustain the process, i.e. it is seen that with reduced pulse-off duration, the MRR is found to increase. In the case of voltage, low voltage (V_1) resulted in higher MRR. The rate of MRR decreases as the gap voltage (V) increases from low level (V_1) to medium level (V_2) as well as from medium level (V_2) to high level (V_3). Increasing voltage across the gap will tend to produce arcing and leads to wear of wire, deposition of resolidified/recast layer on workpiece resulting in reduced MRR. In the case of wire feed, low wire feed (F_1) resulted in higher MRR. The rate of MRR decreases proportionally as the wire feed increases from low level (F_1) to medium level (F_2) and also from medium level (F_2) to high level (F_3). Therefore, high pulse-on time (T_{ON3}), low pulse-off time (T_{OFF3}), low gap voltage (V_1) and low wire feed (F_1) are recommended for achieving higher MRR in MMC consisting of Al6063 with 5% SiC.

From ANOVA Table 5c, for MRR it is seen that the voltage (V) is found to be significant at 90% confidence level with Al6063 with 10% SiC. While pulse-on time (T_{ON}), pulse-off time (T_{OFF}) and wire feed (F) are found to be insignificant parameters. From the Table 5c, it is also observed that the voltage is the major influencing factor for achieving higher MRR with a contribution of 71.45%. From Fig. 7, it is observed that high pulse-on time (T_{ON3}) resulted in higher MRR. MRR is found to increase as pulse-on time (T_{ON}) increase from medium level to high level rather than that of low level to medium level. In the case of pulse-off time (T_{OFF}), low pulse-off time (T_{OFF3}) resulted in higher MRR. While in the case of voltage (V), low voltage (V_1) resulted in higher MRR. The rate of MRR is found to decrease proportionately as the gap voltage (V) increases from low level (V_1) to medium level (V_2) and as well as from medium level (V_2) to high level (V_3). In the case of wire feed (F), the rate of MRR increases significantly as the wire feed increases from low level (F_1) to medium level (F_2) than that of medium level (F_2) to high level (F_3). From response graph (Fig. 7), it is observed that high pulse-on time (T_{ON3}), low pulse-off time (T_{OFF3}), low voltage (V_1) and high wire feed (F_3) resulted in higher MRR. Hence, the above parameters and their levels are recommended for achieving higher MMR in MMC consisting of Al6063 alloy with 10% SiC.

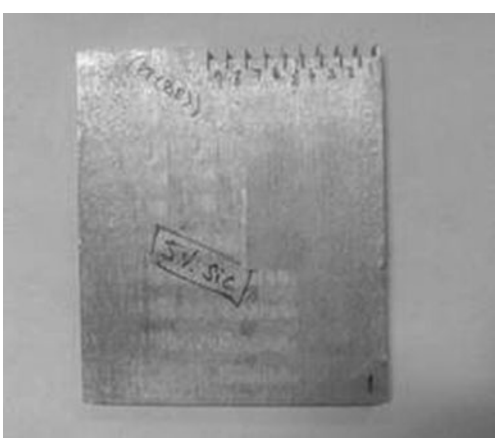


Fig. 5 Photograph of machined workpiece of Al6063 with 5% SiC as per L_9 OA

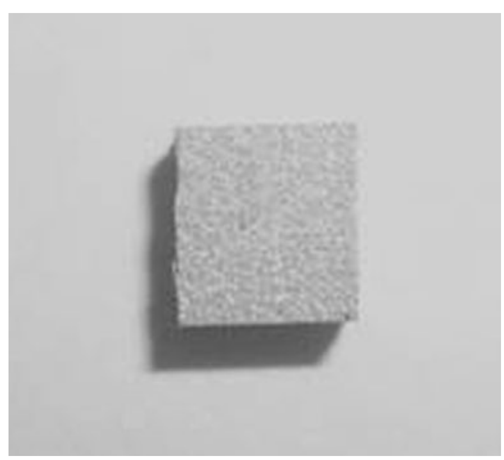


Fig. 6 Photograph of typical machined part of Al6063 with 5% SiC

Table 4 Allocation of input process parameters and experimental results for MRR and R_a

Ex. No.	Process parameters				Output parameters							
					MRR, mm^3/min				R_a, μm			
	Pulse-on time, μs (T_{ON})	Pulse-off time, μs (T_{OFF})	Gap Voltage, V (V)	Wire feed, mm/min (F)	Al6063	Al6063 with 5% SiC	Al6063 with 10% SiC	Al6063 with 15% SiC	Al6063	Al6063 with 5% SiC	Al6063 with 10% SiC	Al6063 with 15% SiC
1	6	10	50	8	26.21	25.71	24.11	24.12	0.82	0.76	1.12	1.67
2	6	8	60	9	24.99	18.42	20.85	21.28	1.29	1.41	1.99	1.71
3	6	6	70	10	22.91	15.80	20.15	15.28	1.14	1.48	1.60	1.48
4	8	10	60	10	25.54	19.60	21.64	20.29	1.45	1.93	1.21	1.85
5	8	8	70	8	18.06	17.26	15.56	13.91	1.43	1.16	1.24	1.78
6	8	6	50	9	29.77	32.01	27.15	20.82	0.94	1.36	1.82	1.71
7	10	10	70	9	17.88	17.49	20.27	14.19	1.31	1.50	1.76	1.99
8	10	8	50	10	29.44	28.46	27.09	22.94	0.98	0.96	1.49	1.20
9	10	6	60	8	27.02	28.09	23.95	22.82	1.06	1.06	1.17	1.34

Table 5 ANOVA of MRR

Parameter		Pool	*df*	*S*	V_e	*F*	*S*′	*ρ*	Remarks
(a) Al6063	T_{ON}	–	2	0.17	0.09	–	–	–	NS
	T_{OFF}	–	2	17.95	8.98	104.82	17.780	11.82	99%
	V	–	2	124.18	62.09	725.05	124.01	82.45	99%
	F	–	2	8.11	4.05	47.32	7.93	5.27	99%
	(e)	–	2	0.17	0.09	–	0.69	0.46	–
	Total	–	8	150.41	18.80	–	–	–	–
(b) Al6063 with 5% SiC	T_{ON}	–	2	33.97	16.99	3.91	25.28	8.72	NS
	T_{OFF}	–	2	34.63	17.32	3.99	25.95	8.95	NS
	V	–	2	212.71	106.36	24.49	204.03	70.35	99%
	F	Y	2	8.69	4.34	–	–	–	NS
	(e)	–	2	8.69	4.34	–	34.75	11.98	–
	Total	–	8	290.01	36.25	–	–	–	–
(c) Al6063 with 10% SiC	T_{ON}	–	2	9.72	4.86	1.76	4.20	3.85	NS
	T_{OFF}	–	2	10.42	5.21	1.89	4.90	4.49	NS
	V	–	2	83.52	41.76	15.14	78.00	71.45	90%
	F	Y	2	5.52	2.76	–	–	–	NS
	(e)	–	2	5.52	2.76	–	22.07	20.22	–
	Total	–	8	109.17	13.64	–	–	–	–
(d) Al6063 with 15% SiC	T_{ON}	–	2	6.32	3.16	60.03	6.21	4.89	97.5
	T_{OFF}	Y	2	0.11	0.05	–	–	–	NS
	V	–	2	117.01	58.55	1,112.36	116.99	92.13	99%
	F	–	2	3.47	1.73	32.93	3.36	2.65	95%
	(e)	–	2	0.11	0.05	–	0.42	0.33	–
	Total	–	8	126.99	15.87	–	–	–	–

Values in percent indicate confidence levels

T_{ON} pulse-on time (μs), T_{OFF} pulse-off time (μs), *V* voltage (V), *F* wire feed (mm/min), *(e)* pooled error, *Y* pooled factor, *df* degrees of freedom, *S* sum of square, V_e error variance, *F* variance ratio, *S*′ pure sum of square, *ρ* contribution ratio, *NS* not significant

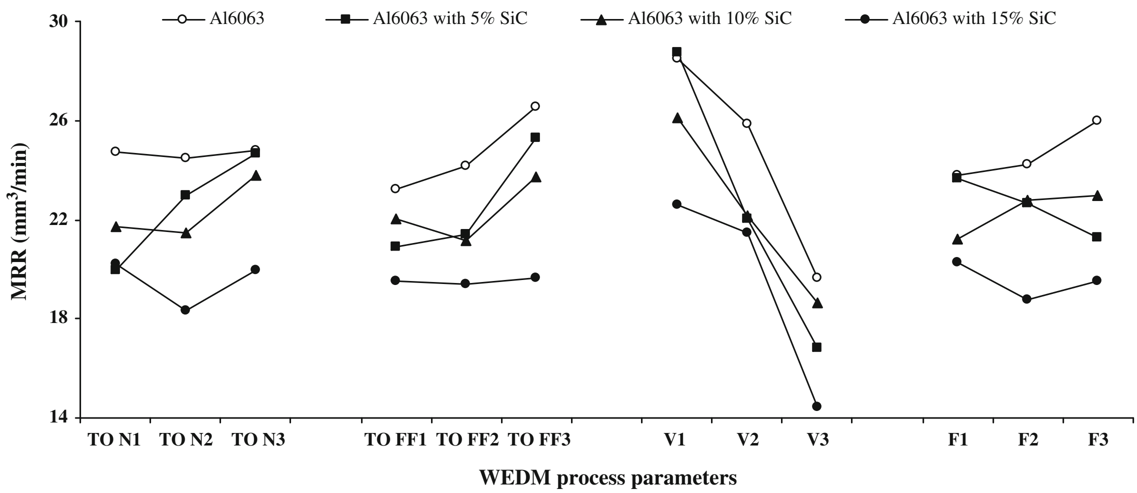


Fig. 7 Response graph of MRR

ANOVA Table 5d indicates that among the input process parameters considered in this study, the pulse-on time (T_{ON}), gap voltage (V) and wire feed (F) are found to be significant at 97.5%, 99% and 95% confidence levels respectively for MRR while machining Al6063 with 15% SiC. Whereas pulse-off time (T_{OFF}) is found to be an insignificant parameter. From Table 5d, it is also observed that the gap voltage (V) is found to be the major influencing factor with 92.13% contribution followed by pulse-on time (T_{ON}) and wire feed (F) with 4.89% and 2.65%, respectively. From the response graph (Fig. 7), it is observed that low pulse-on time (T_{ON1}), low voltage (V_1) and low wire feed (F_1) resulted in higher MRR. Even though pulse-off time (T_{OFF}) is not a significant factor, from the response graph (Fig. 7), it is observed that the low pulse-off time (T_{OFF3}) resulted in higher MRR. Therefore, high pulse-on time (T_{ON1}), low pulse-off time (T_{OFF3}), low gap voltage (V_1) and low wire feed (F_1) are recommended for achieving higher MRR while machining Al6063 with 15% SiC. The regression equations for the MMCs considering MRR are given below

$$MRR_{Al6063/5\%SiC} = 68.2944 + 1.1758\mathrm{T}_{ON} - 1.0917\mathrm{T}_{OFF} - 0.5938\mathrm{V} - 1.2\mathrm{F} \quad (3)$$

$$MRR_{Al6063/10\%SiC} = 36.1411 + 0.5167\mathrm{T}_{ON} - 0.4358\mathrm{T}_{OFF} - 0.3728\mathrm{V} + 0.8767\mathrm{F} \quad (4)$$

$$MRR_{Al6063/15\%SiC} = 48.2267 - 0.0608\mathrm{T}_{ON} - 0.0267\mathrm{T}_{OFF} - 0.4083\mathrm{V} - 0.39\mathrm{F} \quad (5)$$

It is seen that with higher order volume fraction (15% SiC) both pulse-on time (T_{ON}) and pulse-off time (T_{OFF}) influence MRR only marginally. Also it is seen that excess in matrix material (Al6063) and higher volume fraction of reinforcement material (SiC) constrain the significance of feed rate on MRR.

From the above study, it is observed that the average MRR for the unreinforced Al6063 is found to be 24.65 mm^3/min (Fig. 7). In the case of MMCs Al6063 with 5%, 10% and 15% SiC, the average MRR are found to be 22.54, 22.31 and 19.52 mm^3/min, respectively (Fig. 7). This shows that with the increase in percentage volume of SiC particles in the MMCs, it is found that the MRR decreases. This may be due to the presence of harder SiC particles in the MMC. The SiC particles will enhance the thermal characteristics of aluminium, with consequent reduction in MRR. From Fig. 7, it is observed that MRR is found to increase generally with increase in pulse-on time (T_{ON}). This is because due to the intensity of the spark in the WEDM process, which depends on the pulse-on time (T_{ON}). High pulse-on time (T_{ON3}) produces discharge pulses with higher intensity creating deep craters on the workpiece with higher material removal. This is also observed similarly by Rozenek et al. [11], Ramulu and Taya [19], Hung et al. [20], Mohan et al. [21], Tosun et al. [22] and Sushant et al. [23]. Figure 7 shows that low pulse-off time (T_{OFF3}) resulted in higher MRR. Garg et al. [7] observed that, if the interval is too short, the ejected workpiece material will not be flushed away with the flow of the dielectric fluid and also the dielectric fluid will not be deionized. Therefore, minimum pulse-off time (T_{OFF}) has to be maintained for effective machining. From Tables 5 and 7, it is generally found that low gap voltage (V_1) is the most influencing factor to achieve higher MRR in all the materials studied in this work. It also observed similarly by Manna and Bhattacharyya [16]. It is seen that pulse-on time (T_{ON}) and pulse-off time (T_{OFF}) time are non-significant parameters. It is obvious that both pulse-on time (T_{ON}) and pulse-off time (T_{OFF}) time influence the effective sparking. The observation of non-significant contribution can be attributable to the range of values for the input parameter. Pulse-on time (T_{ON}) was found to be influencing parameter as the percentage volume of SiC increases (Table 5d). It is seen that the order of significance of individual WEDM machining parameters on MRR are voltage (V), pulse-on time (T_{ON}), wire feed (F) and pulse-off time (T_{OFF}) with increase in percentage volume fraction of SiC (Table 5d).

3.2 Surface roughness

The following section presents data on R_a of machined unreinforced Al6063 and Al6063 reinforced with 5% SiC, 10% SiC and15% SiC particles.

3.2.1 Machining of Al6063

ANOVA Table 6a indicates that among the input process parameter considered in this study, only gap voltage (V) is found to be significant at 95% confidence level for R_a while machining Al6063. From Table 6a, it is also observed that the gap voltage (V) is the major influencing factor with 63.61% contribution. The other machining parameters such as pulse-on time (T_{ON}), pulse-off time (T_{OFF}) and wire feed (F) are found to be insignificant. However, from the response graph (Fig. 8), it is observed that low pulse-on time (T_{ON1}), low pulse-off (T_{OFF3}), low gap voltage (V_1) and low wire feed (F_1) resulted in lower R_a. Unlike the case of MRR, it is preferable to constrain the spark energy to attain good machined surface texture. Hence, the above parameters and their levels are recommended for achieving lower R_a in Al6063. The regression equation for the above is given below

$$\mathrm{R}_{aAl6063} = -0.7322 + 0.0083\mathrm{T}_{ON} + 0.0367\mathrm{T}_{OFF} + 0.019\mathrm{V} + 0.0433\mathrm{F} \quad (6)$$

Table 6 ANOVA of R_a

Parameter		Pool	*df*	*S*	V_e	*F*	*S'*	*ρ*	Remarks
(a) Al6063	T_{ON}	–	2	0.06	0.03	4.58	0.05	11.97	NS
	T_{OFF}	–	2	0.06	0.03	4.30	0.04	11.03	NS
	V	–	2	0.27	0.14	20.01	0.26	63.61	95%
	F	Y	2	0.01	0.01	–	–	–	NS
	(e)	–	2	0.01	0.01	–	0.05	13.38	–
	Total	–	8	0.40	0.05	–	–	–	–
(b) Al6063 with 5% SiC	T_{ON}	–	2	0.17	0.08	2.32	0.10	9.92	NS
	T_{OFF}	Y	2	0.07	0.04	–	–	–	NS
	V	–	2	0.33	0.16	4.49	0.25	26.12	NS
	F	–	2	0.40	0.20	5.49	0.33	33.83	NS
	(e)	–	2	0.07	0.04	–	0.29	30.13	–
	Total	–	8	0.97	0.12	–	–	–	–
(c) Al6063 with 10% SiC	T_{ON}	–	2	0.03	0.02	3.52	0.02	2.90	NS
	T_{OFF}	–	2	0.07	0.04	7.77	0.06	7.80	NS
	V	Y	2	0.01	0.00	–	–	–	NS
	F	–	2	0.71	0.35	74.56	0.70	84.70	NS
	(e)	–	2	0.01	0.00	–	0.04	4.61	–
	Total	–	8	0.82	0.10	–	–	–	–
(d) Al6063 with 15% SiC	T_{ON}	–	2	0.11	0.06	1.48	0.04	7.06	NS
	T_{OFF}	–	2	0.18	0.09	2.46	0.11	21.62	NS
	V	Y	2	0.07	0.04	–	–	–	NS
	F	–	2	0.14	0.07	1.82	0.06	12.13	NS
	(e)	–	2	0.07	0.04	–	0.30	59.18	–
	Total	–	8	0.51	0.06	–	–	–	–

Values in percent indicate confidence levels

T_{ON} pulse-on time (μs), T_{OFF} pulse-off time (μs), V voltage (V), F wire feed (mm/min), (e) pooled error, Y pooled factor, df degrees of freedom, S sum of square, V_e error variance, F variance ratio, S' pure sum of square, ρ contribution ratio, *NS* not significant

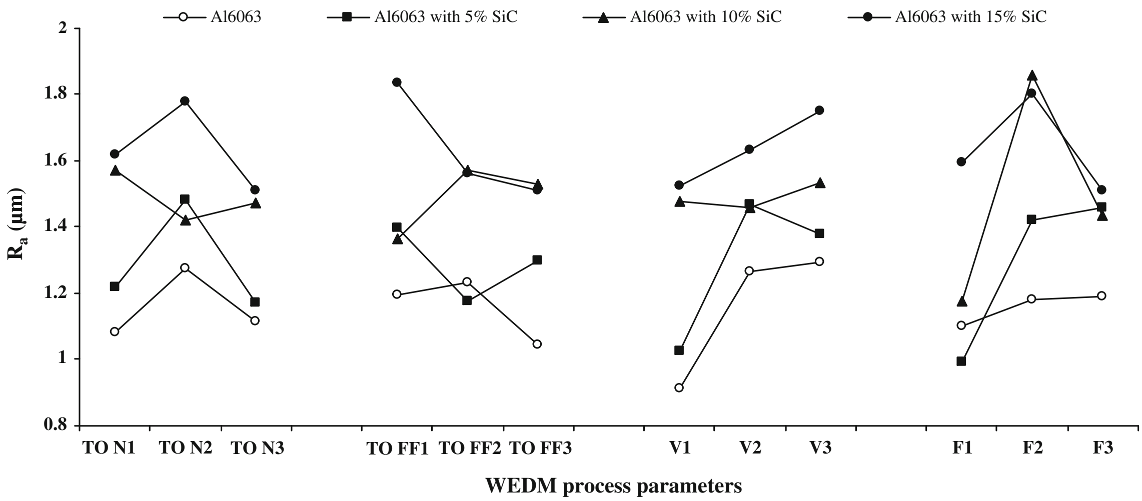


Fig. 8 Response graph of R_a

3.2.2 Machining of MMCs

From ANOVA Table 6b, it is observed that there is no single WEDM process parameter is significant for R_a while machining Al6063 with 5% SiC. Similar observation can be seen for Al6063 with 10% SiC and 15% SiC reinforcements (Table 6c and d). It becomes difficult to identify the significant parameters for R_a because of the presence of harder SiC particles and also due to the formation of recast/ resolidified layer of low melting aluminium dominating the surface texture during machining. Most of the parameters are non-significant, attributable to the range of values and the consequent influence on surface texture. These indicate that combination of all input process parameters are involved in the machining of MMCs for achieving lower R_a. Hence, higher levels of experimentation are required to identify the significant WEDM process parameters for R_a in MMCs.

However, from the response graph (Fig. 8), the trend can be observed for achieving smaller R_a. In the case of Al6063 with 5% SiC, it is found that high pulse-on time (T_{ON3}), medium pulse-off time (T_{OFF2}), low voltage (V_1) and low wire feed (F_1) resulted in smaller R_a. Hence, these combinations of input process parameters and their levels are recommended for achieving lower smoother texture in MMC consisting of Al6063 with 5% SiC. In the case of Al6063 with 10% SiC, it is observed that medium pulse-on time (T_{ON2}), high pulse-off time (T_{OFF1}), medium voltage (V_2) and low wire feed (F_1) resulted in lower R_a (Fig. 8). Hence, these combinations of input process parameters and their levels are recommended for achieving smaller R_a for MMC of Al6063 with 10% SiC. In the case of Al6063 with 15% SiC, from Fig. 8, it is observed that high pulse-on time (T_{ON3}), low pulse-off time (T_{OFF3}), low gap voltage (V_1) and high wire feed (F_3) resulted in smaller R_a. Hence, these combinations of input process parameters and their levels are recommended for achieving lower R_a in MMC consists of Al6063 with 15% SiC. The regression equations for the MMCs considering R_a are given below

$$\mathrm{R}_{aAl6063/5\%SiC} = -1.9606 - 0.0108\mathrm{T}_{ON} + 0.0242\mathrm{T}_{OFF} + 0.0177\mathrm{V} + 0.2317\mathrm{F} \quad (7)$$

$$\mathrm{R}_{aAl6063/10\%SiC} = 0.6906 - 0.0242\mathrm{T}_{ON} - 0.0417\mathrm{T}_{OFF} + 0.0028\mathrm{V} + 0.1283\mathrm{F} \quad (8)$$

$$\mathrm{R}_{aAl6063/15\%SiC} = 0.9233 - 0.0275\mathrm{T}_{ON} + 0.0817\mathrm{T}_{OFF} + 0.0112\mathrm{V} - 0.0433\mathrm{F} \quad (9)$$

From the above study, it is observed that the average R_a obtained for the unreinforced Al6063 is found to be 1.16 μm (Fig. 8). In the case of MMCs Al6063 with 5%, 10% and 15% SiC, the average value of R_a are found to be 1.29, 1.49 and 1.64 μm, respectively. It is seen that the machining of composite materials results in higher order roughness, due to the possible presence of reinforced particles (SiC) in the surface. It is found that the surface roughness R_a values increases with an increase in the percent volume of SiC particles. From Fig. 8, it is generally observed that low pulse-on time (T_{ON}) results in smaller R_a. This is because at high pulse-on time (T_{ON3}) the spark intensity is high, which remove the workpiece material at higher depth (creates large crater size) and results in higher surface roughness. This is similarly observed by Liao et al. [24]. The R_a is found to increase as the pulse-on time (T_{ON}) increases from low level (T_{ON1}) to medium level (T_{ON2}). This is similarly observed by Muller and Monaghan [4] and Narender Singh et al. [25]. However, different trend is observed as the pulse-on time (T_{ON}) is increased from medium level (T_{ON2}) to high level (T_{ON3}). This may be due to interaction among input parameters such as pulse-off time (T_{OFF}), voltage (V), and wire feed (F) and material properties. In the case of pulse-off time (T_{OFF}), higher pulse-off time (T_{OFF1}) resulted in smaller R_a. High pulse-off time (T_{OFF1}) is required in WEDM process in order to flush the eroded materials by the dielectric fluid effectively before it gets resolidified. In the case of voltage (V), it is observed that in most of the cases with the increase in voltage, the surface roughness parameter R_a value increases. This is also similarly observed by Tosun et al. [22]. In the case of wire feed (F) for Al6063 and MMCs Al6063 with 5% and Al6063 with 10% SiC, it is observed that low wire feed (F_1) resulted in lesser R_a. However, for MMC consisting of Al6063 with 15% SiC, the high wire feed (F_3) resulted in lesser R_a. Wire feed (F) play a major role in the case of machining MMCs using WEDM process. The contribution percentage of wire feed (F) is found to be more than that of other parameters in the case of Al6063 with 5% and 10% SiC (Table 6). The WEDM process parameter influencing the R_a according to the relative importance as the percentage volume of SiC increases are pulse-off time (T_{OFF}), wire feed (F), pulse-on time (T_{ON}) and voltage (V).

The comparison between the experimental and the predicted values for both MRR and R_a are shown in Figs. 9 and 10, respectively. Better relationship is found with MRR than that of R_a. The consolidated results from the study are shown in Table 7 indicating the significant WEDM parameters and their levels to achieve higher MRR (Table 7a) and smaller R_a (Table 7b) for ready reference to the user. Confirmation experiments have been carried out as per the suggested significant WEDM parameter for achieving higher MRR and smaller R_a (Table 7). It is found that maximum variation of 7.5% and 9.5% were observed for MRR and R_a, respectively. The variations in the values are evaluated based on the experimental results and the values obtained using regression equations from this study (Table 7).

4 Conclusions

WEDM of Al/SiC$_p$ MMCs in various volume fractions (5%, 10% and 15% of SiC) prepared through stir casting process has been studied considering MRR and R_a. The following conclusions are drawn.

- The microstructure of stir cast composite shows discrete localized pool/agglomeration of SiC particles indicating constrain of the process for attaining uniform microstructure.
- The mean hardness of the cast composites varied in the range of 96–111 HBW, influenced by the percentage volume fraction of SiC reinforcement.

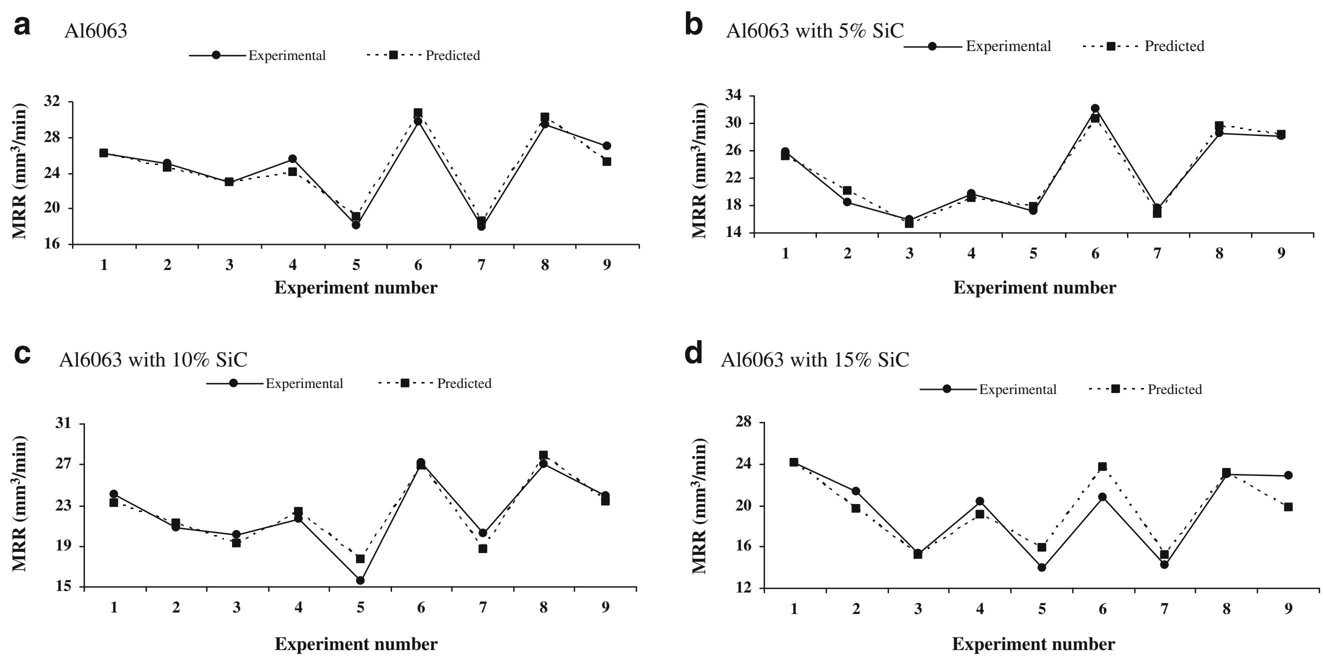


Fig. 9 Comparison between experimental and predicted values for MRR

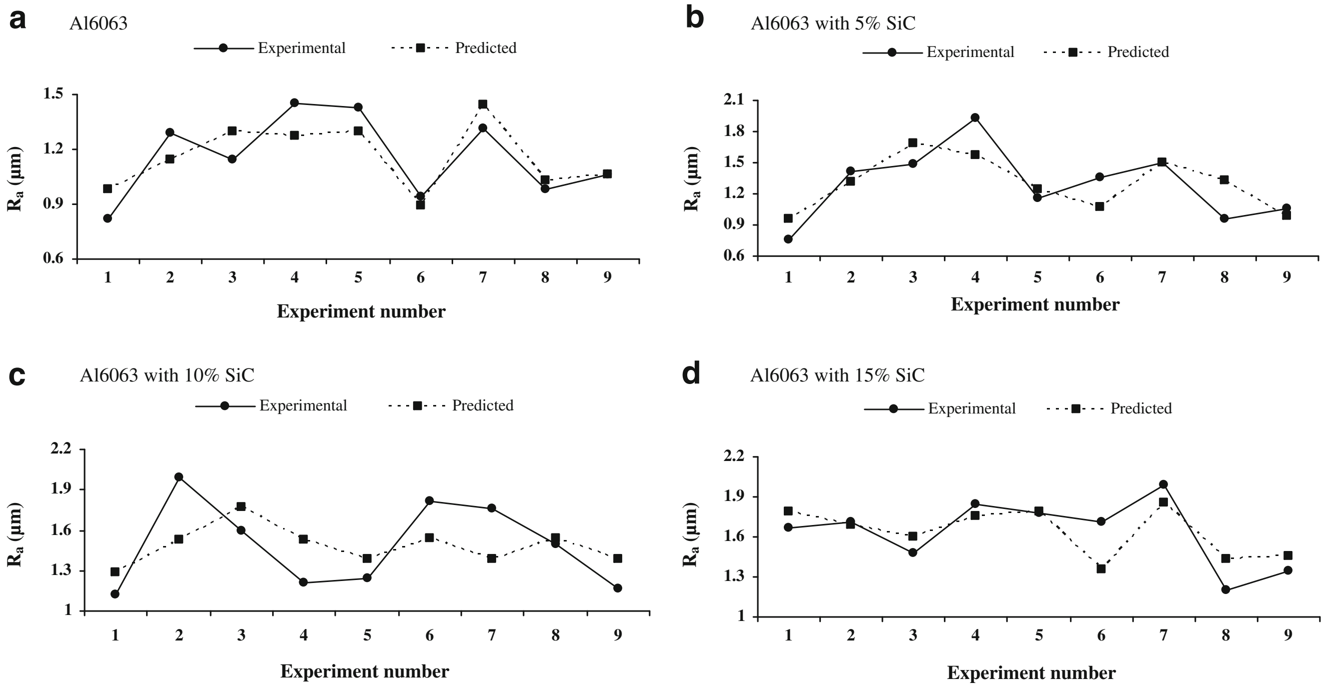


Fig. 10 Comparison between experimental and predicted values for R_a

- It is generally observed that the MRR is found to decrease with increase in the percentage volume fractions of SiC particles in the MMCs. Whereas, the surface roughness parameter R_a increases with increase in the percentage volume fractions of SiC particles in the MMCs.
- Surface texture of wire eroded aluminium matrix composites is relatively insensitive to parametric influence. This is attributable to the occurrence of recast/resolidified layer of aluminium.

From machining of Al/SiC$_p$, it is found that the influence of gap voltage (V) is more significant than that of other parameters for MRR. Voltage (V), pulse-on time (T_{ON}), wire feed (F) and pulse-off time (T_{OFF}) are found to be the order of influence as the percentage of SiC increases in the MMCs for achieving higher MRR. However, based on the trend from the response graphs the significant WEDM process parameters are identified for Al/SiC$_p$ to achieve higher MRR and smaller R_a and presented (Table 7).

Table 7 Predicted values vs experimental values for MRR and R_a

Output parameters	Material	WEDM parameters				Experimental values	Predicted values	Variation (%)
		Pulse-on time (T_{ON})	Pulse-off time (T_{OFF})	Voltage (V)	Wire feed (F)			
(a) MRR, mm^3/min	Al6063	High	Low	Low	High	31.26	31.89	−2.0
	Al6063 with 5% SiC	High	Low	Low	Low	36.12	34.21	5.3
	Al6063 with 10% SiC	High	Low	Low	High	30.15	28.82	4.4
	Al6063 with 15% SiC	High	Low	Low	Low	25.86	23.92	7.5
(b) R_a, µm	Al6063	Low	Low	Low	Low	0.88	0.83	6.0
	Al6063 with 5% SiC	High	Medium	Low	Low	0.94	0.86	8.8
	Al6063 with 10% SiC	Medium	High	Medium	Low	1.32	1.27	4.0
	Al6063 with 15% SiC	High	Low	Low	High	1.39	1.26	9.5

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