Effect of WEDM parameters on selected performance characteristics during machining of newly developed hybrid Al/(SiC + Gr + Fe_2O_3)-MMCs

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ABSTRACT *Wire Electrical Discharge Machining (WEDM) is one of the well known nonconventional machining processes, which is suitable for machining of complex shapes on conducting materials. Aluminium metal matrix composite (Al-MMC) is one of the advanced conductive materials has excellent properties and potential to meet the demand of aerospace, automobile and defense industries. Keeping in view, a series of machining tests has been carried out on CNC wire cut EDM for machining of stir cast hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC and Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3)-MMC with brass wire (diameter 0.25 mm) electrode and water as dielectric fluid. The effect of process control parameters such as pulse-on-time (T_{on}), pulse-off-time (T_{off}), spark gap set voltage (SV), peak current (I_P), wire feed (W_F) and wire tension (W_T) on metal removal rate (MRR, mm^3 /min), surface roughness height (R_a, μm) were investigated and explained with various graphs.ehind the shortage of skills in paint industry.*

Keywords: *Al- MMC, WEDM, MRR, Surface roughness heights.*

Introduction

Metal matrix composites (MMCs) offer high strength to weight ratio, high stiffness and good wear resistance over a wide range of operating conditions, making them an attractive option in replacing conventional materials for engineering applications[1,6]. Typically the matrix materials for MMCs are aluminum alloys, titanium alloys, copper alloys and magnesium alloys, while the reinforcement materials are ceramics in general and added in the form of fibers, whiskers and particles [6]. Out of these Al metal matrix composites are more often used in aerospace industry and these are usually reinforced by Al_2O_3, SiC, C, SiO_2, B, BN, B_4C, AlN, Gr etc. Particulate reinforced MMCs offer higher ductility and their isotropic nature as compared to fiber reinforced composites which makes them an attractive alternative [1]. Increasing number of reinforcements in the MMCs can improve certainly some of properties depending the nature of reinforcement or sometimes it reduces cost without altering the properties too much [1,7]. The MMC material fabricated using two or more than two reinforcements are known as hybrid MMC (hybrid metal matrix composite). MMCs can be fabricated by two basic manufacturing techniques namely casting and powder metallurgy. For simplicity in design and possibility of bulk sizes, the stir casting is emerged as suitable option for the fabrication of composites. The Manna and Bhattacharyya [3] applied the Taguchi design of experiments and Gauss elimination method to determine the optimal WEDM parameters setting and established the mathematical relations respectively for machining of Al/SiC–MMC. Through experimental findings, authors explained that open-gap voltage was found to be the most significant influencing machining parameters, for controlling the MRR followed by pulse-on-time, however, surface roughness was found to be affected significantly by wire tension and spark gap voltage setting as explained by authors [3]. Yan et al. [2005] comprehensively investigated the wire breakage and studied the surface morphologies of the machined surfaces machined by WEDM of Al_2O_3p/6061Al composite. The authors claimed that the increasing the percentage of reinforcing Al_2O_3p particles increased the size of the craters of wire electrode which promoting the wire breakage. Patil and Brahmankar [8] determined the MRR in wire electro-discharge machining of Silicon Carbide particulate-reinforced Aluminium matrix composites using dimensional analysis. This work proposed a semi-empirical model for MRR based on thermo physical properties of the work piece and WEDM parameters such as pulse-on time and average gap voltage. Through experimental findings, authors claimed MRR decreases with increase in percentage of ceramic particulates in the MMC. Shandilya et al.[9] also studied on the wire breakage during WEDM of Al/SiC-MMC. Authors claimed that frequency of wire breakage increases with increase in pulse-on time. Authors also claimed that the frequency of wire breakage increases with increase in volume percentage of SiC in MMC. Some of the researchers have studied the machining behavior of MMCs using WEDM process but still applied research is required to better understanding of this process and parametric optimization for improved machining quality characteristic. In the light of the discussion as mentioned above, the machining experiments were carried out on WEDM for cutting of fabricated hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC. The effect of parameters i.e. wire feed rate (W_F, m/min) and wire tension (W_T, g) on material removal rate (MRR, m^3/min) and surface roughness height (Ra, µm) were investigated. The investigated results acquired during machining were analyzed through various graphs.

Table 1 Chemical composition of AA6061/Al alloy used as Metal Matrix

Matrix Material	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
AA6061	0.6	0.7	0.3	0.15	0.9	0.25	0.15	Balance

Table 2 Physical and mechanical properties of Al-Matrix (AA 6061) and Hybrid Al-MMC

Materials	Density	Hardness	Ultimate tensile strength (MPa)
Metal Matrix: AA6061	2.71	88 BHN	67
S1: Hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC	2.84	97.8 BHN	90.1
S2: Hybrid Al/(15wt.% SiC +5wt.% Gr + 5 wt.% Fe_2O_3)-MMC	2.91	99.4	93.6

2. Preparation of composite material

The hybrid Al/(SiC + Gr+ Fe_2O_3)-MMC workpiece specimens were fabricated using liquid stir-casting. The commercially available Aluminum alloy was selected as matrix material and SiC, Gr, and Fe_2O_3 particles were selected as reinforced particles. Three electric furnaces were used for casting of *hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC and Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3)-MMC*. Three furnaces of capacity 1250°C, 1050°C and 550°C were simultaneously utilized for liquefying Al-matrix, pre-heating of (SiC + Gr + Fe_2O_3) reinforced particles and baking of clay coated metal mold cavity respectively. In stir casting of MMCs, matrix material is required to be liquefied. Commercially available Aluminum alloy (Al-matrix) cut into small pieces and preheated to 450°C for 2 hrs before melting in a furnace of capacity 1150°C. Further, aluminum pieces were made to melt by raising its temperature above its liquid state temperature (660°C) and then allowed to getting cool to just under its liquid temperature to keep slurry in a semi-solid state. Sludge was removed from molten matrix metal during each casting operation to retain its purity. Meanwhile, pre-heating of reinforced (SiC + Gr + Fe_2O_3) particulates was also done to temperature of 1150°C for 2 hrs in another furnace of rating of 1250°C. In third furnace of capacity 550°C, operating simultaneously, the clay coated metal mold made of IS-1079/3.15 mm thick steel sheet was pre-heated at 400°C for 2 hrs. The preheated particulates of (SiC + Gr + Fe_2O_3) were taken out from second furnace and mixed with molten Al-matrix at $700^0 \pm 10^0$C. The mixture was stirred up thoroughly to form a proper heterogeneous mixture. Melt mixture is then poured into the preheated metal mold cavity and allowed it for solidification. Stir cast samples were cleaned and machined to prepare test pieces for property testing and workpiece specimens for machining experiments.

1. Planning for experiments

Electronica Sprincut-734 make Wire Electrical Discharge Machine (WEDM) was used for experiments. The experimental trials were conducted to study the effects of the machining process variable such as pulse-on time (T_{on}), pulse-off, time (T_{off}), spark gap set voltage (SV), peak current (I_P), wire feed (W_F) and wire tension (W_T) on surface roughness height (R_a, µm) and material removal rate.

The work material, electrode and the other machining condition are considered as follows:

(i) Work-piece : S1: Hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC ,and S2: Hybrid Al/(15wt.% SiC +5wt.% Gr + 5 wt.% Fe_2O_3)-MMC (Anode).
(ii) Electrode (Tool) : 250 µm ϕ, Brass wire (Cathode).
(iii) Average voltage gap maintained: 38 to 44 Volts setting (SF) during machining.
(iv) Specific resistance of die-electric fluid: 1 –3 mA
(v) Dielectric fluid: De-ionized water temperature: 22 – 25° C
(vi) Flushing pressure of die-electric fluid: 15 Kg/cm^2

The dimension of the machined workpiece is 5 mm x 5 mm x12 mm. The machined surface roughness height was measured at three different positions and the average values were taken for analyzing the machined surface quality using surface texture measuring instrument Surfcom 130A, Zeiss, Japan. The mean cutting speed data (Vc, mm/min) is calculated from the data displayed in the computer monitor of the Sprintcut WEDM machine and the data recorded from the actual length of cutting during various settings of experimental machining operation. Surface roughness heights (R_a and R_t) µm and the width of cuts (b, mm) were measured using Surfcom 130A and Digimatic Caliper Mitutoyo, Japan respectively. Gap current (Ig, A) is directly recorded from the ammeter of the CNC wire cut-EDM machine. The spark gap (Wg, µm) is calculated from the relation as follows.

$2\,W_g + d = b$ ……………….Eqn. 1

Where, W_g (µm) is the gap width, 'd' is the diameter of wire electrode (250 µm Φ, brass wire); and 'b' (µm) is the width of cut.

The metal removed rate (MRR) is calculated as followed

MRR = $(V_c \,.\, b.\, h)$ mm^3/min …….. Eqn. 2

Where, V_c (mm/min) is the cutting speed, 'b' is the width of cut in mm; and 'h' is the height of the work piece in mm. Equation 1 and 2 were used to analyze the influence of designed variant parameters and designed constant parameters over the material removal rate (MRR). The parameters and their ranges as explained in Table 3 that was considered for experiments.

Table 3 WEDM parameters and their ranges used for experiments

Sl.No.	Symbol	Machining parameters	Ranges	Units
1	A	Peak Current(I_p)	60 A to140A	A
2	B	Pulse-on -Time (T_{on})	0.2 to 1.4	µs
3	C	Pulse-off -Time (T_{off})	12 to 20	µs
4	D	Wire feed rate (W_F)	5 to 9	m/min
5	E	Wire Tension(W_T)	700 to 1450	g
6	F	Spark gap set voltage(SV)	20-40	V

The experiments were carried out based on one factor at a time approach. The plan of experiment for preliminary experimentation with selected parameters and their range was made out and described in Table 4. The thirty experiments with three replications i.e. total ninety experiments were carried out during machining of two categories of hybrid MMC i.e. S1: Hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC and S2: Hybrid Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3)-MMC with brass wire on WEDM.

Table 4 : One factor at a time based experimental plan for preliminary experimentation

Stage of experiment to predict individual parametric effect	Sl. No.	WEDM Parameters and variation of their setting values						Exp No. performed Random
		Pulse Peak Current (I_p)	Pulse-on-Time (T_{on})	Pulse off -Time (T_{off})	Wire feed rate (WF)	Wire Tension (WT)	Spark gap set voltage (SV)	
Stage –I (Peak Current, A)	1	60	Constant Pulse on Time : 0.9 µs	Constant pulse-off-time : 16 µs	Constant Wire feed rate : 7 m/s	Constant Wire Tension : 1000 g	Constant Spark gap set voltage : 30 V	01
	2	80						05
	3	100						03
	4	120						04
	5	140						02
Stage –II (Pulse on Time, µs)	6	Constant Peak Current =100 A	0.2	Constant pulse-off-time :: 16 µs	Constant Wire feed rate : 7 m/s	Constant Wire Tension : 1000 g	Constant Spark gap set voltage : 30 V	10
	7		0.5					6
	8		0.8					9
	9		1.1					8
	10		1.4					7
Stage –III (Pulse-off-	11	Constant Peak	Constant Pulse on	12	Constant Wire feed	Constant Wire	Constant Spark gap	11
	12			14				15

time µs)	13	Current =100 A	Time : 0.9 µs	16	rate : 7 m/s	Tension : 1000 g	set voltage : 30 V	12
	14			18				14
	15			20				13
Stage –IV (Variation of wire feed, m/s)	16	Constant Peak Current =100 A	Constant Pulse on Time : 0.9 µs	Constant pulse-off-time: 16 µs	5	Constant Wire Tension : 1000 g	Constant Spark gap set voltage : 30 V	20
	17				6			18
	18				7			15
	19				8			17
	20				9			16
Stage –V (Variation of wire tension, g)	21	Constant Peak Current :100 A	Constant Pulse on Time : 0.9 µs	Constant pulse-on-time: 16 µs	Constant Wire feed rate : 7 m/s	700	Constant Spark gap set voltage : 30 V	25
	22					850		23
	23					1000		24
	24					1200		22
	25					1400		21
Stage –VI (Spark gap set voltage, V)	26	Constant Peak Current :100 A	Constant Pulse on Time : 0.9 µs	Constant pulse-on-time: 16 µs	Constant Wire feed rate : 7 m/s	Constant Wire Tension : 1000 g	20	27
	27						25	29
	28						30	26
	29						35	30
	30						40	28

4. Results and Discussion

4.1 Material Removal Rate (MRR)

Six machining parameters namely, pulse peak current pulse on-time, pulse off time, wire feed and wire tension and spark gap set voltage were varied by using one-factor-at-a-time strategy. Fig. 1 shows the influence of pulse peak current on material removal rate (MRR). For hybrid specimens, S1(Table 2) i.e. *Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC*, the MRR was found to be increased with increase in pulse peak current. However, for specimens S2 i.e. *Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3)-MMC*, MRR increases with increase in pulse peak current up to 120A but beyond that it decreases with increase in pulse peak current (e.g. 140 A). Fig. 2 shows the influence of pulse-on-time on material removal rate (MRR). From Fig.2, it is clear that the MRR was higher for *Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC* over *Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3)-MMC specimens*. It may be due to comparatively low electrical and thermal conductivities of S2 hybrid MMC specimens over S1 specimens. Again it may be due to higher wt% of SiC presence in S2 i.e. *Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3)-MMC* specimens. On the other hand frequent wire breakages were also noticed during machining of both type of hybrid MMCs at high setting of pulse-on-time. Fig. 3 shows the effect of pulse-off-time on the material removal rate (MRR) which indicates that the MRR continuously decreases with increase in pulse-off-time for both MMCs specimens. The effect of wire feed rate on the MRR is shown in Fig.4. Fig. 5 shows the variation of MRR with wire tension. From Fig.4 and Fig.5, it is clear that the MRR decreases with increase in wire feed rate and wire tension for machining of both types i.e. S1 and S2 specimens. From Figs. 1 to 5, it is clear that the MRR always higher for *Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC* as compared to *Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3)-MMC specimens.* It is also clearly identified that the high value of material removal rate can be obtained at parametric setting value of high pulse peak current, high pulse-on-time, low pulse-off-time, low wire feed rate and low wire tension .

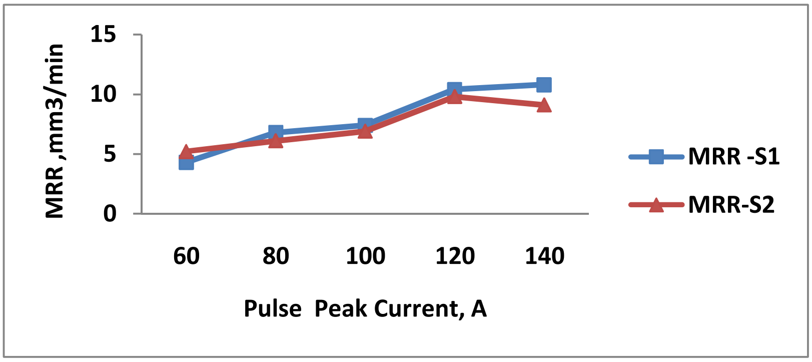

Fig. 1 Variation of Material Removal Rate (MRR, mm^3/min) with Pulse peak current (I_p, A)

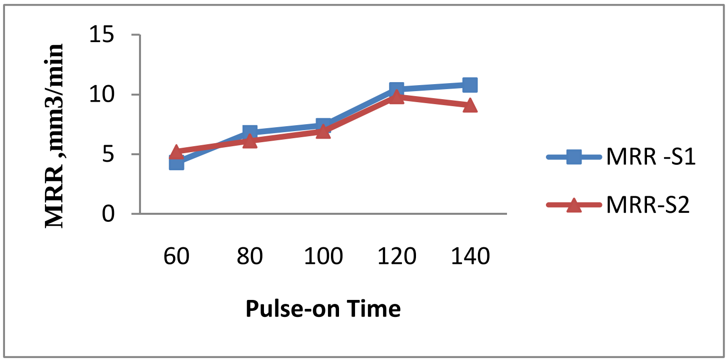

Fig. 2 Variation of Material Removal Rate (MRR, mm^3/min) with Pulse-on-Time (T_{on}, µs)

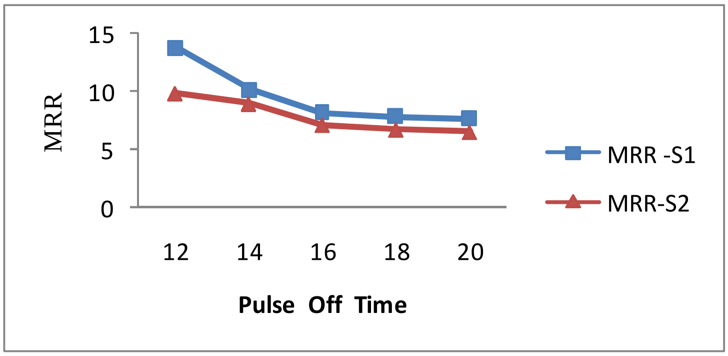

Fig. 3 Variation of Material Removal Rate (MRR, mm^3/min) with Pulse-off-Time (T_{off}, µs)

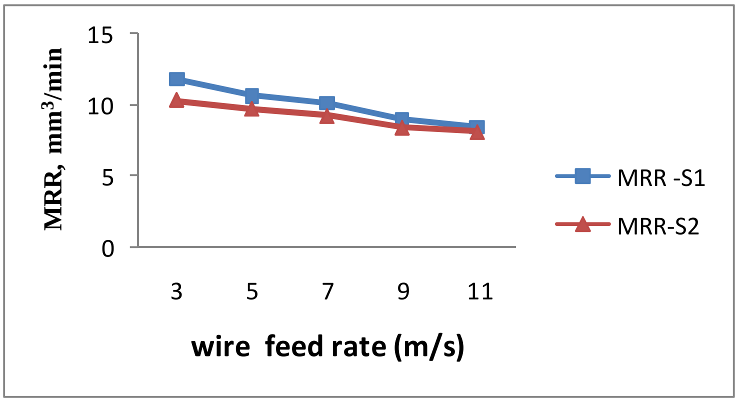

Fig. 4 Variation of Material Removal Rate (MRR, mm^3/min) with Wire Feed rate (W_F, m/min)

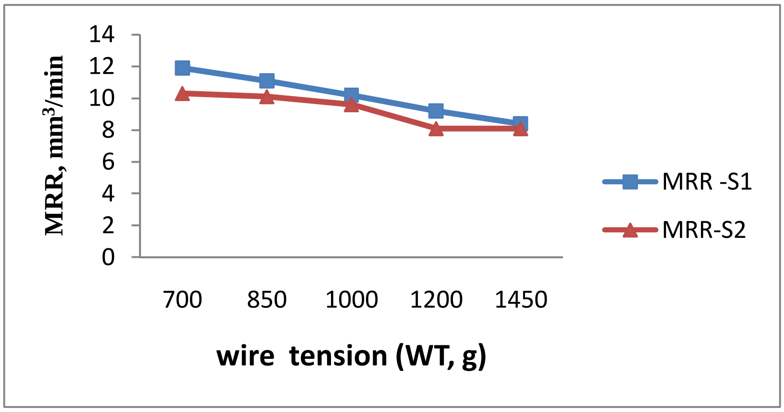

Fig. 5 Variation of Material Removal Rate (MRR, mm^3/min) with Wire Tension (W_T, g)

4.2 Machined Surface Roughness Height

The Effect of WEDM parameters on surface roughness height (R_a) was studied and analyzed through various graphs. Using one factor at a time approach different experiments were carried out and utilized the acquired results draw different graphs. The variation of surface roughness with pulse-on time was explained through Fig.6. From Fig. 6, it is clear that the surface roughness height, R_a (μm) increases with increase in pulse-on-time. Fig. 7 shows the variation of surface roughness height R_a (μm) with pulse-off-time. From Fig.7, it is also clear that the surface roughness height (R_a) slightly decreases with increase in pulse-off-time. Similarly, Fig.8 shows the variation of surface roughness height R_a (μm) with pulse peak current. From Fig. 8, it is clear that the surface roughness height (R_a) increases with increase in pulse peak current. Fig. 9 shows the effect of spark gap set voltage on surface roughness height R_a (μm). From graph Fig.9, it is evident that the surface roughness height R_a (μm) decreases slightly with increase in spark gap set voltage. Fig. 10 shows effect of wire feed rate on surface roughness height (R_a). This graph (Fig.10) depicts that the surface roughness height (R_a) decreases with increase in wire feed rate. The similar trend was noticed when wire tension setting is changed within the selected range. As discussed above from different graphs (Fig. 6 to Fig. 10) that the value of the machined surface roughness height R_a (μm) is always slightly higher for Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3)-MMC as compared to Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3)-MMC specimens. From these graphs (Fig. 6 to Fig. 10), it is clear that the minimum value of surface roughness height R_a (μm) can be obtained at low setting value of pulse peak current, pulse-on time, high setting value of pulse-off-time and wire feed rate. From the experiments and acquired results, it is also observed that the kerf width for higher percentage of particulate reinforced composite was lower. These findings are attributed to the low thermal and electrical conductivities of the hybrid MMC specimens S2 (Table 2) and it may be due to high percentage of SiC presence in the S2 MMC.

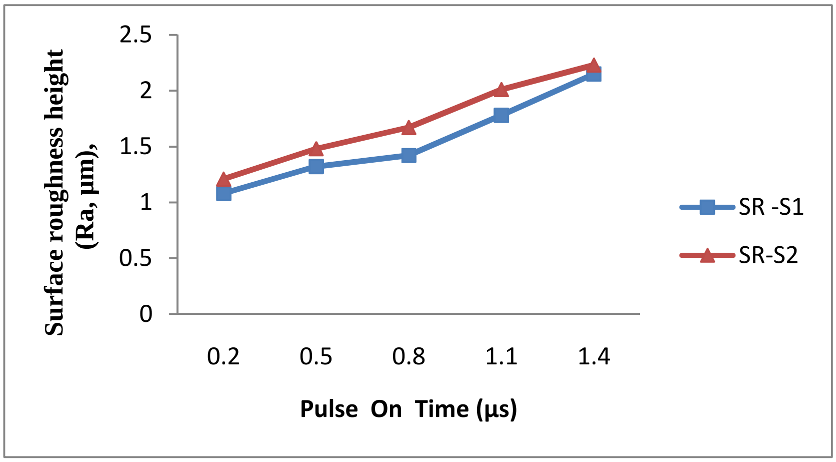

Fig. 6 Variation of Surface roughness height R_a (μm) with Pulse-on-time (T_{on}, μs)

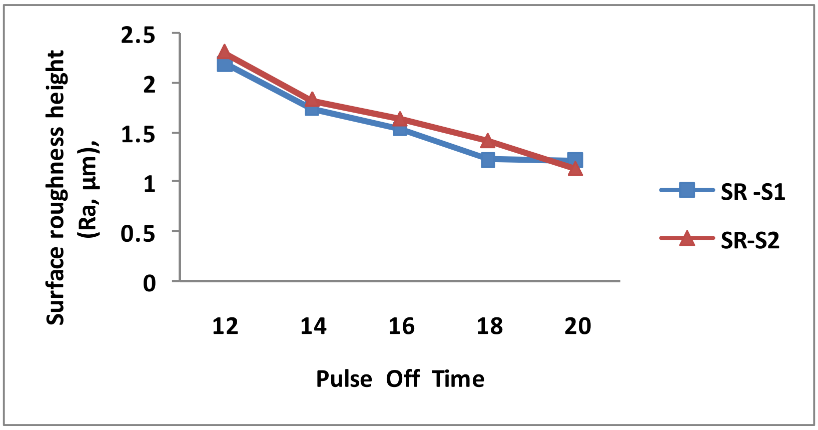

Fig. 7 Variation of Surface roughness height R_a (μm) with Pulse-off-time (T_{on}, μs)

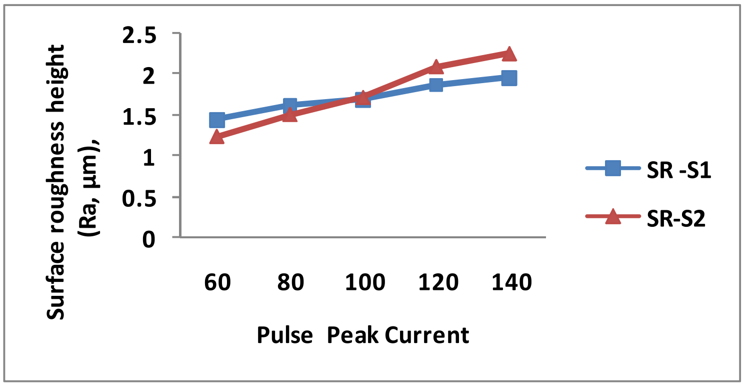

Fig. 8 Variation of Surface roughness height R_a (µm) with Pulse Peak Current ($_{Ip}$, A)

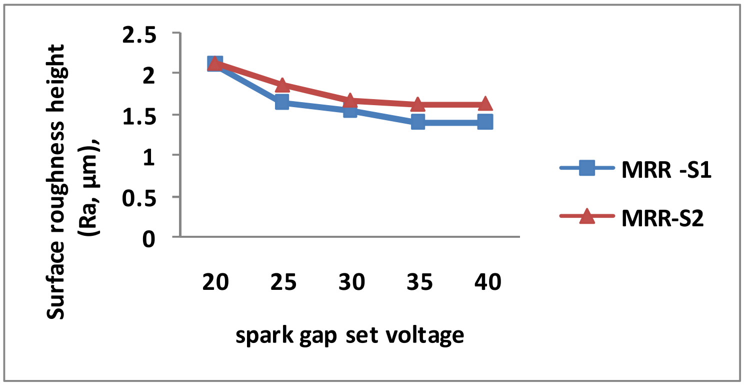

Fig. 9 Variation of Surface roughness height R_a (µm) Spark gap set voltage (SV,V)

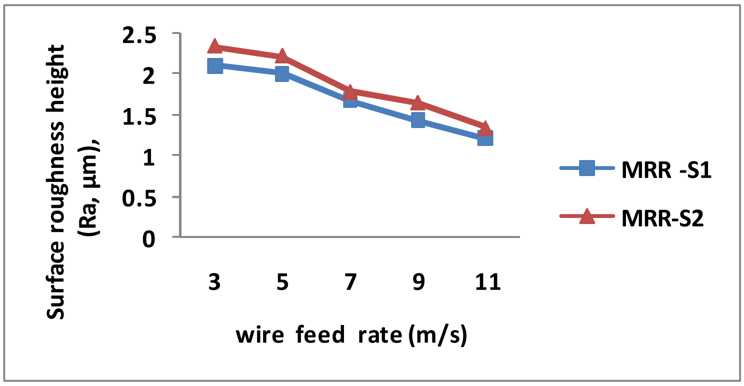

Fig. 10 Variation of Surface roughness height R_a (µm) Wire feed rate (W_F, m/s)

5. CONCLUSIONS

From the experimental investigation during WEDM of hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC and Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3)-MMCs specimens following conclusions were drawn listed as follows:

- The MRR is high at high setting value of pulse peak current and pulse-on time and low setting value of pulse-off-time, wire feed rate and wire tension for machining of both types of hybrid MMC specimens.
- The average MRR is always high for Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC as compared to Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3)-MMC machining, it may be due to high weight percentage of SiC particles presence in the second specimens.
- Frequent wire breakages were noticed during machining of hybrid MMCs when machining operations were carried out at high pulse energy. It may be due to high weight percentage of i.e. 15

wt% SiC_p presences in the hybrid MMC specimens; as SiC has nonconductive characteristics and high melting point over Al-matrix that directly may invites wire breakage.

- The machined surface roughness height R_a (μm) is comparatively low at low setting value of pulse peak current and pulse-on-time, and at high setting value of pulse-off-time, wire feed rate and wire tension. It is for machining of both samples i.e. for hybrid Al/(15wt.% SiC + 5wt.% Gr + 5wt.% Fe_2O_3) and Al/(10 wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC. The machined surface roughness height R_a (μm) was slightly higher in case of Al/(15wt.% SiC + 5wt.%Gr+5wt.% Fe_2O_3) over Al/(10 wt.% SiC + 3wt.% Gr +3wt.% Fe_2O_3)-MMC specimens.

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