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RESEARCH PAPER

Investigation on the Impact of Silicon Carbide and Process Parameters on Wire Cut-EDM of Al/SiCp MMC

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ABSTRACT

In the present work, a model based on Dimensional Analysis (DA) coupled with the Taguchi method to analyze the impact of silicon carbide (SiC) was presented. The Wire Cut Electrical Discharge Machining (WEDM) performance of Aluminium Silicon Carbide (AlSiC) Metal Matrix Composite (MMC) was critically examined. To formulate DA-based models, a total of 18 experiments were conducted using Taguchi's L_{18} mixed plan of experimentation. The input data used in the DA models include a pulse on time, pulse off time, wire feed rate, % SiC, wire tension, flushing pressure, etc. According to these process parameters, DA models for the surface roughness and the material removal rate were predicted. The formulated DA models showed a strong correlation with the experimental data. The analysis of variance (ANOVA) was applied to determine the impact of individual parameters on response parameters.

KEYWORDS: *Al/SiCp MMC; ANOVA; Dimensional; Analysis; Taguchi method; WEDM.*

1. Introduction

Aluminium-based Metal Matrix Composites (MMC) are widely used in very precision applications such as marine sectors, automobile sectors, metal cutting industries, and the aerospace based industries. This is due to the very high strength and the low weight of the Al-based MMC. In recent years, the use of Aluminium-based composites fulfils the basic requirement of machining industries. AlSiC composite is characterized by unique properties that are favorable for all thermal and electronics based industrial applications. AlSiC offers properties such as high strength, high modulus, high wear resistance, and desirable thermal expansion. In addition, it enjoys light weight, brilliant corrosion resistance, and a lower coefficient of thermal expansion.

Bobbili et al. (2015) effectively used dimensional analysis approach to investigate the impact of various process parameters during the EDM of armour material, i.e., Al7017 and RHA steel. The responses were MRR and Ra. The experimental findings show the superiority of the DA models to investigate the engineering system. The basic purpose of using DA approach is to correlate the larger number of parameters during the investigation. Deresse et al. (2019) analyzed the impact of cylindrical grinding process parameters on the Material Removal Rate (MRR) and Surface Roughness (Ra) using Taguchi approach. L_9 orthogonal array was selected for the experimentation. The process parameters include the depth of cut, feed rate, and the work speed. Analysis of variance (ANOVA) was carried out to know the impact of various process parameters on the responses. From the ANOVA, it has been observed that the depth of cut is the most influencing parameter that affects MRR and Ra. The work piece material used for the investigation was steel EN45. Jayson et al. (2016) developed a quartz particulate reinforced AA6063 Aluminium matrix composites using friction Stir Processing. Kadu et al. (2014) analyzed the performance of boring machine environment using DA approach. They used the DA approach to correlate the parameters such as cutting speed, insert material, depth of cut, diameter, and length of the tool and the various

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machining related environmental parameters. Arun Kumar et al. (2014) used the Taguchi's design of experiments (DOE) used for optimizing the process parameters to minimize the surface roughness and maximize the material removal rate. The three input parameters at three levels are considered for the response analysis and the signal-noise ratio is calculated for the material removal rate and the surface roughness. The experimental findings showed the optimum material removal rate at 3-2-3 combination and 1-1-3 for the surface roughness response. From the experimental findings, it can be concluded that the depth of cut is the most influencing parameter for the MRR response and feed is the most influencing parameter for surface roughness response. Li et al. (2019) critically applied the Taguchi method to the analysis of mobile health system. From experimental findings, it was observed that Taguchi approach coupled with the ANOVA was strongly implemented in the analysis process. Liu et al. (2019) investigated the laser powder deposition AlSi10Mg alloy using the Taguchi method. ANOVA was tried to determine the effect of each process parameter on the response variable. The analysis shows the effectiveness of the Taguchi method. Phate et al. (2019) used Dimensional Analysis (DA) and Artificial Neural Network (ANN) for investigating the WEDM performance of Aluminium Silicate Carbide (Al/SiC) metal matrix composite. The WEDM process parameters were pulse on time, pulse off time, and wire feed rate and the input current. Both the modeling techniques have shown a higher value of correlation to model the process parameters. This higher value shows good agreement and reliability of the dimensional models and the overall acceptability of the DA model to analyze the WEDM process in a very effective and efficient way. Phate et al. (2019) effectively and efficiently used the Taguchi method coupled with grey fuzzy approach to analyze the WEDM of Al/SiCp20 MMC. Phate et al. (2019) efficiently and effectively applied dimensional analysis approach to the WEDM of oil hardening nonshrinkage die steel materials (OHNS). Taguchi's L_{27} plan of experimentation was used for the analysis. The process parameters used for the modeling were pulse on time, pulse off time, wire feed rate, servo voltage, and the input current. The DA-based models were formulated for the MRR and Ra responses. Phate et al. (2013) used dimensional analysis approach in the analysis of conventional machining environment. The DA approach was used to correlate a large number of process parameters. There were more than fifty parameters whose effects were analyzed using DA approach.

Rao et al. (2014) adopted and recommended the use of the Taguchi-based parametric analysis of WEDM on residual stresses developed in the machining of Al alloy. Yongfeng Saha et al. (2016) investigated the impact of nano particles in the hard facing materials. The grey relational analysis coupled with the Taguchi method was used for obtaining the experimental findings. Vinod Kumar et al. (2015) worked on WEDM of Monel -400, i.e., nickel copper base alloy. The parameters such as current, pulse on time, pulse off time, and servo voltage were considered to measure the performance of parameters such as surface roughness and the material removal rate. ANOVA was used for the analysis of the WEDM process. The experimental results showed that the current (103 A), Pulse on time (113 micro sec), pulse off time (37 micro sec), and the voltage (50 V) were the optimum combination.

2. Methods

2.1. Preparation of work piece

Aluminium 2124 is an aluminium alloy with high strength and weight ratio. The filler material used for the MMC preparation consists of silicon carbide. It has better thermal conductivity, high melting point, low thermal expansion, high strength, and high hardness value. The geometry of the work piece is shown in Fig.1.

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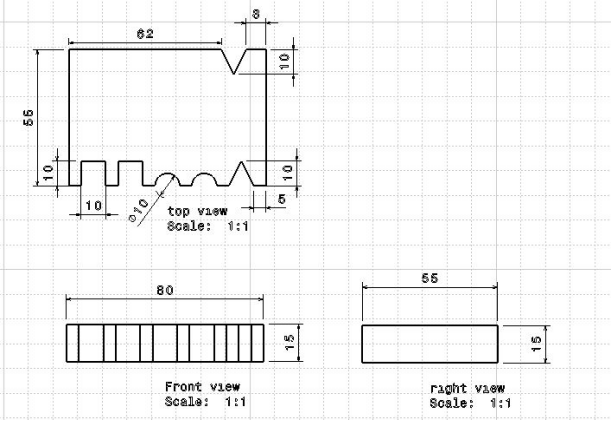

Fig 1 (a)

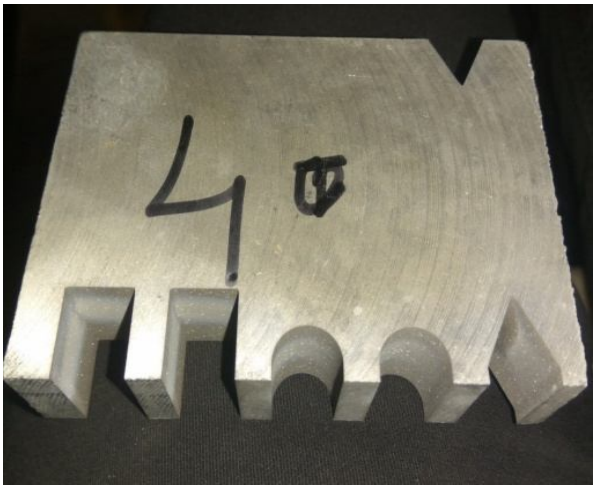

Fig 1 (b)

Fig. 1. (a) and (b): Work piece geometry

2.2. Experimental setup and plan

In the present work, experiments were conducted on Ultracut S0 wire Electronic Discharge Machine (Make : M/S Electronica, Ultracut So Model, Pune, Maharashtra, India). Al SiCp MMC, a rectangular plate of dimension 80 mm × 55 mm × 20 mm, was used for experimentation and was chosen as workpiece material. In WEDM operation, the parameters such as pulse on time, pulse off time, wire feed rate, input current, SiC percentage, Fluid pressure, and wire tension were selected as process parameters. Brass Cutting wire (Diameter of 0.25mm) was chosen as an electrode material. The Wire cut EDM is shown in Fig 2. The levels of various process parameters are shown in Table 1. There are two response parameters: Material Removal Rate (MRR) measure in gm/min and Surface Roughness (Ra). The MRR is calculated using Eq. 1.

$$MRR = [WT_b - WT_a] / [T_m] \quad (1)$$

where WT_b , WT_a are the before and after machining weights of the workpiece (gm), respectively, and T_m is the machining time in minutes. Surface roughness (Ra) was measured in microns using digital surface roughness tester Mitutoyo SJ-201.

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Fig. 2. Wire-Cut EDM set up photograph

Tab. 1. List of Process parameters and their levels.

Levels	Parameters			
	SiC Percentage (%C)	Pulse on Time (PON) Micro-sec	Pulse off Time (POFF) Micro-sec	Wire feed rate (WFR) m/min
1	15	108	52	4
2	20	110	54	5
3	--	112	56	6
Levels	Input current (IP) Amp	Wire tension (WT) Kg	Fluid Pressure (FP) kg/cm^3	
1	1	9	13	
2	2	10	14	
3	3	11	15	

The levels of the various machining parameters are furnished in Table 1. Taguchi's L_{18} plan of experimentation was chosen during the experimentation and the experimental observations are given in Table 3.

2.3. Formation of dimensionless terms

Dimensional Analysis (DA) is a very effective and efficient technique for correlating a large number of parameters. Using the reality that physical quantities correlated with each other must be expressed in terms of the same fundamental quantities such as mass, length, and time. In the present work, a correlation between the independent and dependent or total number of parameters, i.e., n=13, can be stated by Buckingham's pi theorem. Let "n" be the total number of independent and dependent parameters. "m" is the basic dimensions. In this work, pulse on time (TON), Wire Feed Rate (WFR), and Wire Tension (WT) are the basic or primary variables that were selected to formulate the DA model for surface roughness and the material removal rate. The primary dimensions of all enlisted parameters are shown in Table 2. The significant response variables, i.e., material removal rate (MRR) and surface roughness (Ra), can be expressed in Eqs. 2 and 3, respectively.

Tab. 2. List of process parameters

S.N	Process parameters	Symbol	Primary dimensions	Nature
1	Pulse on time	TON	$[L^0 M^0 T^1]$	Independent
2	Pulse off time	TOFF	$[L^0 M^0 T^1]$	Independent
3	Wire feed	WFR	$[L^1 M^0 T^{-1}$	Independent

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	rate		]	
4	% Silicon Carbide	%C	$[L^0 M^0 T^0]$	Independent
5	Power	PW	$[L^2 M^1 T^{-2}]$	Independent
6	Density	P	$[L^{-3} M^1 T^0]$	Independent
7	Wire tension	WT	$[L^1 M^1 T^{-2}]$	Independent
8	Cutting Speed	CS	$[L^1 M^0 T^{-1}]$	Independent
9	Hardness	H	$[L^0 M^0 T^0]$	Independent
10	Flushing Pressure	FP	$[L^{-1} M^1 T^{-2}]$	Independent
11	Servo Feed	SF	$[L^1 M^0 T^{-1}]$	Independent
12	Surface Roughness	Ra	$[L^1 M^0 T^0]$	Dependent
13	Material Removal Rate	MRR	$[L^3 M^0 T^{-1}]$	Dependent

Tab. 3. Observation table

S.N.	%C	PON	POFF	WFR	IP	WT	FP	Ra	MRR
1	15	108	52	4	1	9	13	1.82	33.3
2	15	108	54	5	2	10	14	1.68	27.6
3	15	108	56	6	3	11	15	1.6	26.6
4	15	110	52	4	2	10	15	1.76	31.16
5	15	110	54	5	3	11	13	1.7	28.43
6	15	110	56	6	1	9	14	1.61	26.64
7	15	112	52	5	1	11	14	1.79	32.25
8	15	112	54	6	2	9	15	1.58	25.67
9	15	112	56	4	3	10	13	1.52	24.53
10	20	108	52	6	3	10	14	1.97	36.6
11	20	108	54	4	1	11	15	2.51	58.7
12	20	108	56	5	2	9	13	2.04	38.9
13	20	110	52	5	3	9	15	2.41	56.34
14	20	110	54	6	1	10	13	2.1	44.37
15	20	110	56	4	2	11	14	2.36	55.2
16	20	112	52	6	2	11	13	2.25	50.9
17	20	112	54	4	3	9	14	2.5	57.6
18	20	112	56	5	1	10	15	2.31	54.5

$$MRR = f(TON, TOFF, WFR, IP, \%C, FP, PW, WT, \rho, CS, H) \quad (2)$$

$$Ra = f(TON, TOFF, WFR, IP, \%C, FP, PW, WT, \rho, CS, H \quad (3)$$

Based on the Buckingham's principle, the dependent pi terms are expressed as the product of all independent pi terms. Let PID be the dimensionless term representing the response variable and the Pi1, Pi2, Pi3…….Pi8 are the independent pi terms. These are expressed as

$$PID = f(Pi1, Pi2, Pi3\ldots\ldots Pi8) \quad (4)$$

The basic pi term for the term "Ra" is calculated through Eq. 5 and listed in Table 4.

$$PI = TON^a \ x\, WFR^b x\, WT^c x\, Ra \quad (5)$$

$$[L^0M^0T^0] = [T]^a \times [L^1M^0T^{-1}]^b \times [L^1M^1T^{-2}]^c \times L^1$$

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Solving Eq. 5, we get a = -1, b= -1, and c=0 that are put in Eq. 5.

$$PI = \frac{Ra}{Ton \times WFR} \quad (6)$$

Similarly, the other pi terms are calculated and listed in Table 4.

Tab. 4. Formation of basic dimensionless Terms

Pi term	Equation	a	b	c	Dimensionless term
Ra	$Ton^a \times WFR^b \times WT^c \times Ra$	-1	-1	0	$\frac{Ra}{Ton \times WFR}$
MRR	$Ton^a \times WFR^b \times WT^c \times MRR$	-2	-3	0	$\frac{MRR}{Ton^2 \times WFR^3}$
TOFF	$Ton^a \times WFR^b \times WT^c \times Toff$	-1	0	0	$\frac{Toff}{Ton}$
%C	$Ton^a \times WFR^b \times WT^c \times \%C$	0	0	0	%C
PW	$Ton^a \times WFR^b \times WT^c \times PW$	-1	-1	-1	$\frac{PW}{Ton \times WFR \times WT}$
ρ	$Ton^a \times WFR^b \times WT^c \times \rho$	2	4	-1	$\frac{Ton^2 \times WFR^4 \times \rho}{WT}$
CS	$Ton^a \times WFR^b \times WT^c \times CS$	0	-1	0	$\frac{CS}{WFR}$
H	$Ton^a \times WFR^b \times WT^c \times H$	0	0	0	H
FP	$Ton^a \times WFR^b \times WT^c \times FP$	2	2	-1	$\frac{Ton^2 \times WFR^2 \times FP}{WT}$
SF	$Ton^a \times WFR^b \times WT^c \times SF$	0	-1	0	$\frac{SF}{WFR}$

To formulate the generalized model, the above independent dimensionless pi terms can be grouped into the following pi terms:

$$\Pi_1 = \frac{Toff}{Ton}, \quad (7a)$$

$$\Pi_2 = \frac{Ton^2 \times WFR^4 \times \rho \times \%c}{WT \times H}, \quad (7b)$$

$$\Pi_3 = \frac{P \times CS}{Ton \times WFR \times WT \times SF}, \quad (7c)$$

$$\Pi_4 = \frac{Ton^2 \times WFR^2 \times FP}{WT} \quad (7d)$$

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3. Results & Discussion

3.1. Dimensional models (DA)

According to the Buckingham's pi theorem, the dependent and independent pi terms can be expressed in Eq. 8 :

$$PID = f(\Pi_1, \Pi_2, \Pi_3, \Pi_4) \quad (8)$$

After solving the above Eq. 8, the following expressions (9) and (10) are derived:

$$\text{MRR} = 0.078764 \times \left[\frac{\text{TOFF}}{\text{TON}}\right]^{-18.878417} \times \left[\frac{\text{TON}^2 \times \text{WFR}^4 \times \rho \times \%\text{C}}{\text{WT} \times \text{H}}\right]^{-0.471851} \times \left[\frac{\text{PW} \times \text{CS}}{\text{TON} \times \text{WFR} \times \text{WT} \times \text{SF}}\right]^{1.641771} \times \left[\frac{\text{TON}^2 \times \text{WFR}^2 \times \text{FP}}{\text{WT}}\right]^{-0.057648} \times \text{Ton}^2 \times \text{WFR}^3 \quad (9)$$

$$\text{Ra} = 2.777552 \times \left[\frac{\text{TOFF}}{\text{TON}}\right]^{-0.592761} \times \left[\frac{\text{TON}^2 \times \text{WFR}^4 \times \rho \times \%\text{C}}{\text{WT} \times \text{H}}\right]^{-0.001454} \times \left[\frac{\text{PW} \times \text{CS}}{\text{TON} \times \text{WFR} \times \text{WT} \times \text{SF}}\right]^{0.033839} \times \left[\frac{\text{TON}^2 \times \text{WFR}^2 \times \text{FP}}{\text{WT}}\right]^{-0.505759} \times \text{TON} \times \text{WFR} \quad (10)$$

A generalized DA model of the responses MRR and Ra was formulated with the process variables listed above. The coefficients and the power indices of the formulated models indicate the impact of variables on the response parameter. This study shows that variation in the silicon carbide percentage significantly affects the responses. The correlation coefficient (R^2) values of the MRR and Ra models are 0.99979 and 0.98561, respectively, which shows the acceptability of the DA model to represent the present work. In the present work, higher MRR and good quality surface finish have gained higher significance in the metal industries. The DA-based models of MRR and Ra were formulated using dimensional analysis approach. An analysis was done using the Taguchi approach and the ANOVA.

3.2. Analysis using taguchi method

The machining parameters and their selected levels are tabulated in Table1. Taguchi's L_{18} (2^1 x 6^3) orthogonal array's (OA's) with a mixed plan of experimentation was selected. The effect of various WEDM process parameters was analyzed through the analysis of variance (ANOVA) using MINITAB 16 software. From the ANOVA table for the response MRR and Ra (Table 4 and 5), it was observed that % composition of the silicate carbide was the most influencing parameter followed by the wire feed rate and wire tension. The effect of the order of the process parameters on the response variables is shown in the following Tables 6 and 7, respectively. The "F" values indicate the statistical means between any two groups. There is a significant role of "P" value in the ANOVA. A smaller value of "P", i.e., less than 0.05, shows the insignificant level of the corresponding parameters. This indicates the physically powerful support against the null hypothesis made before the analysis. A larger value "P" indicates the weaker null hypothesis.

Tab. 4. Analysis of variance (ANOVA) for MRR.

Source	DF	Seq. SS	Adj. SS	Adj.MS	F	P
% C	1	2154.52	2154.52	2154.52	73.43	0.001
TON	2	55.16	55.16	27.58	0.94	0.463
TOFF	2	25.58	25.58	12.79	0.44	0.674
WFR	2	206.56	206.56	103.28	3.52	0.131
IP	2	44.46	44.46	22.23	0.76	0.526
WT	2	93.54	93.54	46.77	1.59	0.310
FP	2	88.31	88.31	44.16	1.50	0.326
Error	4	117.36	117.36	29.34		
Total	17	2785.48				

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Tab. 5. Analysis of variance (ANOVA) for Ra.

Source	DF	Seq. SS	Adj. SS	Adj.MS	F	P
% C	1	1.61404	1.61401	1.61401	123.63	0.000
TON	2	0.1174	0.01174	0.00587	0.45	0.667
TOFF	2	0.03974	0.03974	0.03987	1.52	0.332
WFR	2	0.15631	0.15631	0.15631	5.99	0.063
IP	2	0.02308	0.02308	0.02308	0.88	0.481
WT	2	0.06688	0.06688	0.06688	2.56	0.192
FP	2	0.04698	0.04698	0.04698	1.80	0.277
Error	4	0.05222	0.05222	0.05222		
Total	17	2.01096				

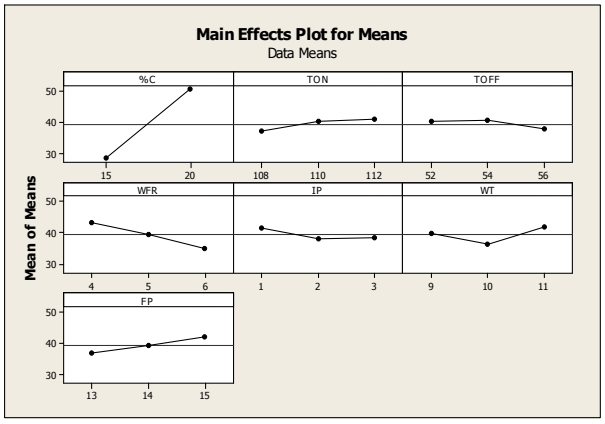

Fig. 3. Main effect plot for the response MRR

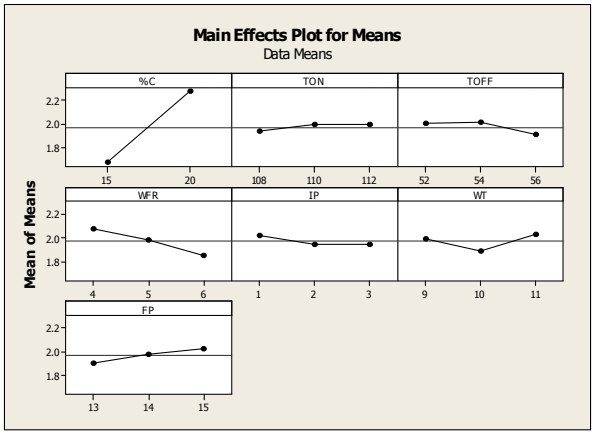

Fig. 4. Main effect plot for the response Ra

From Figs. 3 and 4, it is observed that material removal rate and the surface roughness increase with increase in the silicon carbide percentage, pulse on time, and the flushing pressure, while it is diminished with increase in pulse off time, input current , wire tension and the wire feed rate. Further advance in wire tension from Level 2 to 3 leads to increase in MRR and Ra. The objective of the presented work is to determine the best set of process parameters that maximizes the material removal rate and minimizes the surface roughness. From Figs. 3 and 4, it can be seen that the maximum MRR can be obtained for the process parameters % C (20) –TON (112)-TOFF (54)-WFR (4)-IP (1) – WT (11) and FP (15). Minimum surface roughness is obtained for the process parameters % C (15) –TON (108)-TOFF (56) - WFR (6)- IP (3) – WT(10), and FP (13), respectively. The "larger-the-better" and "smaller-the-better" approaches were adopted to analyze the MRR and Ra responses, respectively.

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Tab. 6. Response table for means MRR

Level	%C	TON	TOFF	WFR	IP	WT	FP
1	28.46	36.95	40.09	43.41	41.63	39.74	36.74
2	50.35	40.36	40.40	39.67	38.24	36.46	39.32
3	--	40.91	37.73	35.13	38.35	42.01	42.16
Delta	21.88	3.96	2.67	8.28	3.39	5.55	5.42
Rank	1	5	7	2	6	3	4

Tab. 7. Response table for means Ra

Level	%C	TON	TOFF	WFR	IP	WT	FP
1	1.673	1.937	2.000	2.078	2.023	1.993	1.905
2	2.272	1.990	2.012	1.988	1.945	1.890	1.985
3	----	1.992	1.907	1.852	1.950	2.035	2.028
Delta	0.599	0.055	0.105	0.227	0.078	0.145	0.123
Rank	1	7	5	2	6	3	4

3.3. Microstructure composition:

The properties of composites depend on the microstructure and interface characteristics between reinforcements and matrix. Trinocular metallurgicalinverted microscope (Model : SuXma-Mat I) was used to test the microscopic structure of the prepared compoistes. The figures below show the microstructure of pure Aluminium 2024 and Al/SiC with 15% and 20% SiC by weight MMC's. Figures 5a, 6a, and 7a show the microstructure of three speciman before etching while the Figures 5b, 6b, and 7b show the microstructure of three speciman after the etching process. The microstructures shown in the figures present evidence of Silicon Carbides. The magnification of the microscope before etching was 100X and 200X after etching. From the microstructural analysis, clustering and non-homogeneous distributions of SiC particles in Al matrix were observed. This was due to the variation of contact time between SiC particles and molten Al during composites processing, high surface tension, and poor wetting behavior of SiC particles in the liquid Al. In the following figures (Fig 5-7), before etching, the microstructures of Pure Aluminium and AlSiC with 15% and 20% are observed. In the figures, after Etching, we can observe black spots which are the impurities like ash, sand particles, etc. The dark green strips are the SiC particles. The part which is light green in colour is pure Aluminium. Porosities were observed in all microstructures. This was because when SiC particles were added to the melt during casting and air was introduced to the melt entrapped between the particles. Therefore, increasing wt. % of SiC particles increased entrapped air and resulted in higher amount of porosity.

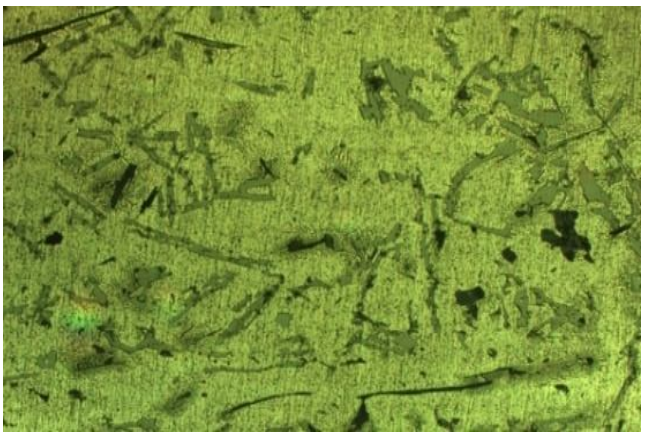

Fig. 5. Al 2124 microstructure after etching.

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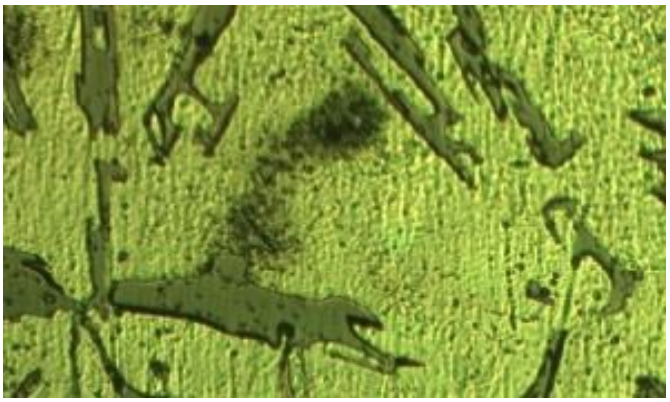

Fig. 6. Al/SiCp15 microstructure after etching.

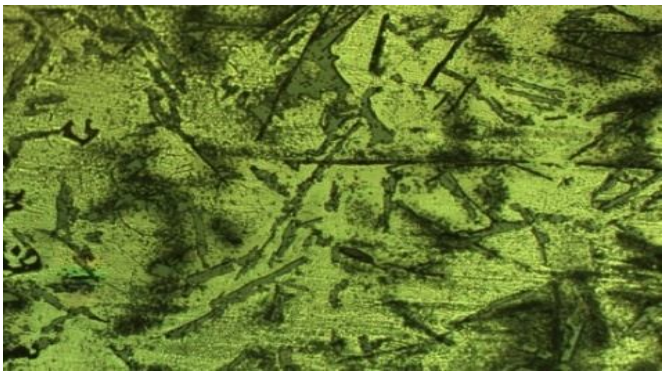

Fig. 7. Al/SiCp20 microstructure after etching

4. Conclusions

This paper discussed the impact of Silicate carbde composution and the WEDm process parameters on the MRR and the Ra responses. The Dimensional Analysis (DA) approach along with the Taguchi method was adopted for the analysis purpose in a very effective and efficient way. The composition of SiC varied in the range of 15-20. The WEDM process parameters considered for the investigation include pulse on time, pulse off time, wire feed rate, input current, wire tension, and the flushin pressure, respectively. Based on the analysis, it was observed that the impact of SiC composition was very significant followed by the wire feed rate and the wire tension. From the Taguchi analysis, the maximum MRR was obtained for the process parameters % C (20) –TON (112)-TOFF (54)-WFR (4)-IP (1) – WT (11) and FP (15). Minimum surface roughness was obtained for the process parameters % C (15) –TON (108)-TOFF (56) - WFR (6)- IP (3) –WT(10) and FP (13), respectively. The presented work concluded that the DA approach was very useful in the modeling of the machining process. In the future, the presented work can be extended to consider a different machining environment. Further, multi-response optimization can be carried out using various advanced optimization techniques. Thus, the presented approach will help the researchers focus on the use of aluminium-based MMC in the industries. The DA-based models were formulated on the basis of some important parameters, and there might be some additional parameters or factors involved in the performance of WEDM process.

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