Optimization of SiC Abrasive Parameters on Machining of Ti-6Al-4V Alloy in AJM Using Taguchi-Grey Relational Method

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ORIGINAL PAPER

Optimization of SiC Abrasive Parameters on Machining of Ti-6Al-4V Alloy in AJM Using Taguchi-Grey Relational Method

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Abstract

In this research, multi response Taguchi-grey relational approach was employed to optimize the machining parameters of Ti-6Al-4V alloy in abrasive water jet process. The main aim of this present investigation was to explicate the role of adding SiC super hard ceramic into the garnet and to find out the optimal input variable, which is influencing the material removal rate and surface finish in the process. The specific input variables such as SiC volume, SiC size and abrasive flow rate were accounted as potential process variables for this present investigation. It is observed that the SiC along with garnet improves the material removal rate. According to the analysis the SiC addition of 0.5 wt.%, SiC size of 80mesh and abrasive flow rate of 2 g/s (A2B1C1) was found to be producing MRR of 48.81 mm^3/s and lower surface roughness of 3.72 μm. From study the particle size was the most influential parameter for producing high MRR with low surface roughness. The confirmation study reveals the improvement of 1.91% in MRR and surface roughness on comparing with predicted mean value.

Keywords AJM · Taguchi · Abrasive size · Abrasive flow rate · MRR · Surface roughness

1 Introduction

Abrasive water jet machining is one of the most common unconventional machining processes used for machining hard materials, which are difficult to machine using conventional methods. In this process a high pressure of water jet is forced on the work piece where the hydraulic energy is converting as mechanical energy [1, 2]. There are lots of studies employed in machining of hard materials and alloys with respect to machining process parameters such as material removal rate, kerf width, taper angle and surface roughness [3, 4]. In recent years researchers have done their investigations on finding the optimal process variable, which is influencing most in the material removal rate in machining process [5, 6]. To find out the optimal process parameter and variable different methods are employed where certain optimization techniques are widely used [7, 8]. Ti-6Al-4V is the alloy of titanium along with other alloying elements such as 6% aluminum, 4% vanadium, 0.25% iron and 0.2% oxygen featuring excellent strength, low modulus of elasticity, high corrosion resistance, weldability and heat treatable nature. Thus it is widely used in light weight applications such as aircraft body frame, jet engines, power transmission devices, automobile parts and power generation components [9]. In recent years lot of research studies are going on to improve the machining parameters of Ti-6Al-4V alloy using abrasive water jet (AJM) process. Many documents have been reported previously in finding out the most supported process parameter to achieve high material removal rate in low abrasive flow and surface roughness. By optimizing the most influential input variable the total machining cost can be reduced with improvement in total life time of equipment [10]. Alberdi et al. [11] analyzed four process parameters such as speed, abrasive mass flow rate,

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stand-off distance and traverse feed rate in machining of titanium alloy. According to authors conclusion the abrasive flow rate and SOD are influenced the MRR of titanium alloy. Jeykrishnan et al. [12] found that the transverse speed of the nozzle was the most significant factor, which is affecting the angle of kerf taper in the titanium alloy. Fowler et al. [13] found that the rate of material removal and surface roughness increased with the increase in the hardness of the abrasive particle. Alberdi et al. [14] found that the standoff distance affects the MRR significantly, while the abrasive flow rate affects the surface roughness. Similarly, Vasanth et al. [15] investigated the process parameters on machining of titanium Ti-6Al-4V alloy using abrasive water jet machining. Author concluded that the abrasive flow rate, type of abrasive and standoff distance is the most promising input variables. Thus based on the previous literatures lot of optimization studies are employed to predict the optimal process variable such as abrasive flow rate, transverse speed, and nozzle diameter and jet pressure. However, the type of abrasive material, shape, size, abrasive flow rate also playing very important role in material removal. Since the abrasives are physically hit the work piece the character of abrasive material is influencing the material removal rate and other output process parameters [16]. Kandpal et al. [17] investigated the effect of using SiC as filler to machine aluminum oxide ceramic material. The author concluded that the addition of SiC particle is capable of machining super hard ceramic material than other abrasives with minimum wear loss in nozzle's inner surface. Moreover, the author confirmed that modifying the abrasive material or its composition also fetches improved results in material removal rate with low energy consumption [18]. Garnet is a so called material, which is being used in almost all abrasive water jet machining process. It is a kind of rock product having silicate, alumina and iron as a main constituent [19]. Similarly, silicon carbide is a very hard man made ceramic, which is used in high hardness material machining and high wear resistance applications. Its hardness is around 23.54 Vickers with almost equal density of 3.21 g/cm^3 as garnet. Its higher thermal conductivity owes this material to be deployed in many engineering applications such as cutting tool and coating material [20].

Taguchi optimization could be an effective tool when more number of input variables and multi responses are employed in any engineering process. In this method different set of optimum level of input process variables could identify at the end of optimization and also used to identify the most influencing process parameter to achieve the required task. The formulation, processing and deriving numerical modeling of Taguchi optimization is narrowed and simple on comparing with existing other optimization methods. The most prominent process variable to produce the required output could identify via multi iterations in the form grey relational coefficient thus the Taguchi optimization is said to be one of the best method over the other methods. Muthuramalingam et al. [21] have done an optimization study for micro machining process to optimize the process variables. According to the author's conclusion the Taguchi optimization could be the effective and fastest tool to find out the optimal set of inputs and determining the most promising input variable. Similarly, Jaykrishnan et al. [22] optimized the process called electrical discharge machining of D_2 die steel and its input parameters using Taguchi. The authors concluded that the Taguchi optimization is the suitable method when multi responses are arrived from the particular process. Thus the previous literatures revealed that there are lot of efforts have been made by many researchers for determining optimum input process parameters in abrasive water jet machining. However, research works presented based on optimizing the abrasive characters are not yet reported.

Based on the research gap the present study was designed. The chief aim of this present research work was to examine and optimize the most influencing input process parameter while machining titanium alloy using activated SiC-garnet abrasive mix in abrasive water jet machining using Taguchi grey relational analysis. These optimized process parameter machined titanium alloys are efficient in both process and energy.

2 Experimental Work

The titanium alloy used for machining investigation was Ti-6Al-4V. Table 1 shows the chemical composition of Ti-6Al-4V. The abrasive water jet machine used in this present study was Maxiem water jets 1515, KENT, USA. The specifications of the machine are as follows. A maximum pressure of 620 MPa, traverse speed of 10 m/min, cutting head movement of 3 m in x-axes and 1.5 m in y-axes and water discharge of 3.2 l/min. Figure 1 shows the experimental setup of this present study. The work piece material was machined carefully without any power interruptions. The machined surface was cleaned with brush and wiped off using a cloth for post analysis. The abrasive particle used in this present investigation was a hybrid pattern of SiC-garnet with selected weight

Table 1 Chemical composition of Ti-6Al-4V alloy

Elements	Composition %
Al	6.325
V	3.712
C	0.006
Fe	0.091
Si	0.010
Mn	0.005
Cr	0.021
Sn	0.001
Ti	Remaining

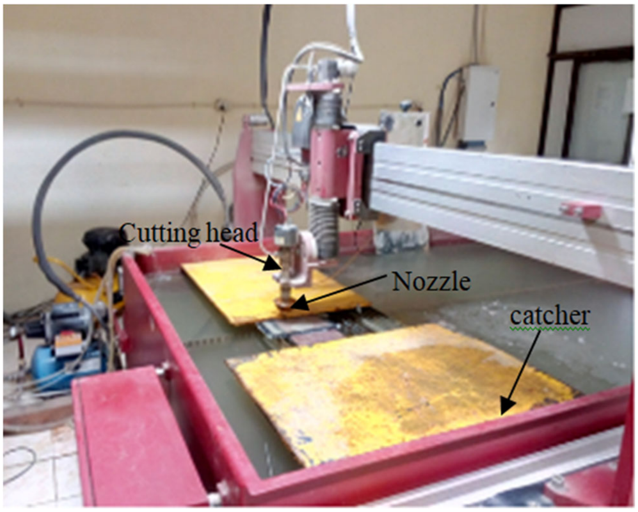

Fig. 1 Abrasive water jet machining setup

percentage and different size. The SiC particle was mixed with garnet gently and there was no heat or mechanical force was applied. Figure 2 shows the SiC particle mixed garnet with suitable EDAX report for confirmation. The EDAX report shows the corresponding peaks of all the basic elements present in garnet and also the added SiC content. For every trial the machine was verified for its accuracy and maintains high repeatability. According to the material removal theories the abrasive particles are the pivoting element in machining. Since the right selection of abrasive particle boost up the machining quality thus the input process parameters are designed such a way. Table 2 shows the process variables involved in the machining process. However, quantity of abrasive addition, size of abrasive particle used and abrasive flow rate during machining are the proposed process variables. In all machining the work piece size was 150 mm in length, 100 mm in width and 10 mm in thickness. The length of cut was maintained as 55 mm with constant feed rate of 285 mm/min, SOD of 4 mm, nozzle diameter of 1.1 mm and jet pressure of 2000 bar with impact angle of 90^{o}. Similarly, the input parameters for this present study was selected as SiC content of 0.25, 0.5, 1 wt.%, SiC particle size of 80, 100, 120 mesh and abrasive flow rate of 2, 4, 6 g/s. Table 3 shows the plan of experiments fixed for this present investigation.

3 Taguchi Method

Taguchi methodology is a systematically organized approach to discover the most favorable amalgamation of input parameters. In this systematic approach a typical customized L_9 orthogonal

Fig. 2 SEM with EDAX report of SiC-garnet mix

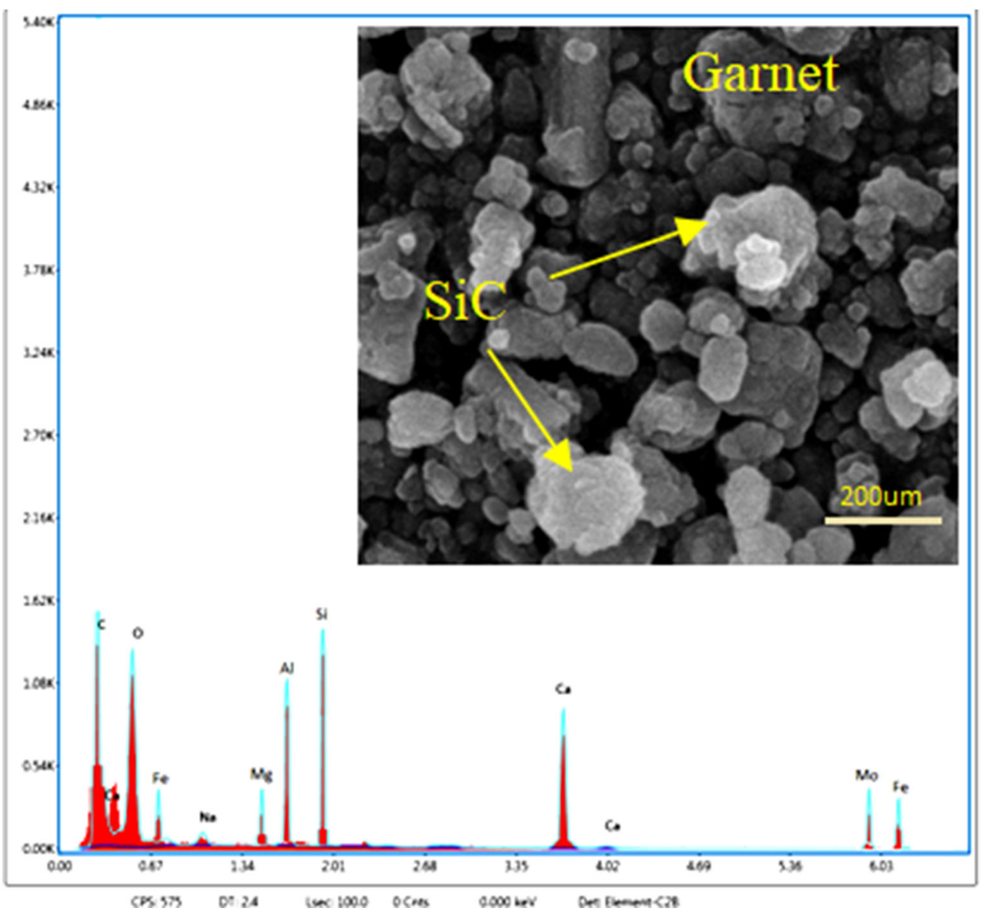

Table 2 Selection of process variables

Process variable	Description
Jet pressure	2000 bar
Traverse speed rate	285 mm/min
Impact angle	90°
Nozzle material	Tungsten carbide
Nozzle diameter	1.1 mm
Stand-off-distance	4 mm
Length of cut	55 mm

array was used to determine the most favorable parameter. In this present investigation the input process variable was three. Thus a customized typical L_9 orthogonal array was utilized to perform the optimization procedure. Henceforth a sum of nine dissimilar machining patterns are selected and performed for revealing its process outcomes in the form of material removal rate (MRR) and surface roughness. The material removal rate was calculated by counting the machining time to achieve the target length to be machined whereas the surface roughness was calculated using the surface roughness tester Mitutoyo version 2.0. The output responses of this nine dissimilar set of input process variables are valued by signal-to-noise ratio (S/N) in the form of larger the better and smaller the better. This (S/N) ratio was measured using the responses via appropriate formulae. Moreover, this present investigation aims to improve the material removal rate with minimal surface roughness. The MRR was considered as larger the better whereas surface roughness (Ra) was considered as smaller the better. Equations 1 and 2 shows the formula for signal to noise ratio values of larger and smaller the better. Table 4 shows the L_9 orthogonal array for response. For this present study material removal rate was larger the better and the surface roughness was smaller the better. This consideration was assumed since for a good machining process the material removal rate should be higher with least surface roughness. Table 5 shows the values of S/N ratio and normalized S/N ratios obtained from the present experimentation. The Eqs. 1 and 2 shows the S/N ratios of two responses similarly, the Eqs. 3 and 4 shows the formulae for finding the set of normalized S/N ratios.

3.1 Grey Relational Approach

It is the numerical approach to analyze the multi response of different input characteristics. In this the multiple performance of various distinctiveness are transformed into a single corresponding grey relational grades (GRGs). In this first the S/N ratios obtained from Taguchi experimentation was been normalized in the range 0 to 1. The weighing factor of 0.5 is equally applied for all experimental trials. The GRG indicates the strongest relational degree between every sequence of variables. Equation 5 shows the formula for calculating the grey relational grade for every sequence done. Similarly Table 6 shows the coefficients and grade of grey relational analysis. A distinguished factor of Ψ = 0.5 was assumed for all experimental trials in this present study. Lastly, the grey relational grade was intended via the obtained grey relational coefficients by using the Eq. 6. In this the term 'm' denotes the number of response variables. In general higher the value of grey relational grades higher the impact of relational grade and it could be the most prominent machining parameter. However, the higher the GRG showed closeness of optimal parameter and value. Table 7 shows the average grey relational grade by level wise. In this the optimum input process parameter was bring into being out of experimentation and optimization. The population in the grey relational grades to the sequence of experimentation was displayed in Fig. 3.

For larger the better

$$\mathrm{S/N\ ratio} = -10\log\left(1/n\right) + \left(1/Y_{ij}^{2}\right) \tag{1}$$

For smaller the better

$$\mathrm{S/N\ ratio} = -10\log\left(1/n\right) + \left(Y_{ij}^{2}\right) \tag{2}$$

where,

n Number of replication for each experiment say '1'
Y_{ij} Response values

For larger the better

$$X_{ij} = \left(Y_{ij} - \min\left(Y_{ij}\right)\right) / \left(\max\left(Y_{ij}\right) - \min\left(Y_{ij}\right)\right) \tag{3}$$

For smaller the better

$$X_{ij} = \left(\max\left(Y_{ij}\right) - Y_{ij}\right) / \left(\max\left(Y_{ij}\right) - \min\left(Y_{ij}\right)\right) \tag{4}$$

where

X_{ij} normalized S/N ratio
Y_{ij} S/N obtained from Taguchi experimentation

$$GC_{ij} = \left(\delta_{min} + \psi\,\delta_{max}\right) / \left(\delta_{ij} + \psi\,\delta_{max}\right) \tag{5}$$

$$Gi = \left(1/m\right) \Sigma\, GC_{ij} \tag{6}$$

Table 3 Plan of experiments

Factor notation	Factor	Level 1	Level 2	Level 3
A	SiC content (wt.%)	0.25	0.5	1
B	SiC size (mesh)	80	100	120
C	Abrasive flow rate (g/s)	2	4	6

4 Results and Discussion

Table 4 shows the signal-to-noise ratio for material removal rate and surface roughness values. These values have been

Table 4 L9 orthogonal array for response

Trial number	A	B	C	A_1	B_1	C_1	MRR (mm^3/min)	Surface roughness (μm)
1	1	1	1	0.25	80	2	39.424	3.437
2	1	2	2	0.25	100	4	33.552	4.721
3	1	3	3	0.25	120	6	42.528	4.283
4	2	1	2	0.5	80	4	47.905	3.815
5	2	2	3	0.5	100	6	38.431	4.662
6	2	3	1	0.5	120	2	44.542	4.331
7	3	1	3	1	80	6	39.175	3.683
8	3	2	1	1	100	2	41.552	3.853
9	3	3	2	1	120	4	35.211	4.512

further converted to equivalent grey relational coefficients and grade using the equations. The distinguishing coefficient of 0.5 was taken for all experimental response. The grey relational coefficient, grade and rank of each experimental setup were calculated using grey relational approach. From the grey relational grade the average grey relational grade was found out. Table 6 shows the rank of each experimental response. Higher the rank indicates better the multi response characteristics. Figure 3 shows the variation of GRG with respect to experiment. It was proved that experiment 4 has higher the rank of 1 with GRG of 0.77, which indicates multi response characteristics for higher material removal rate and lower surface roughness.

Similarly, Table 7 shows the average grey relational grade of each level. This value was calculated by taking average of each response from each level group in all levels. It was observed that higher the level of GRG had very close and strong correlation with optimal value of inputs. The higher the maximum-minimum value in Table 7 explicated the most important determining factor among the responses. Thus it was proved that the size of SiC particle was the most determining factor (0.267) to achieve higher MRR and lower surface roughness in machining of titanium alloy. The other input variables like SiC content and abrasive flow rate has very lower influencing factor of 0.083 and 0.123. From Table 7 the optimal process parameter has been found out. According to the table values the optimal SiC addition of 0.5 wt.% (level 2), SiC size of 80 mesh (level 1) and abrasive flow rate of 2 wt.% (level 1) $A_2B_1C_1$ was identified as optimal process parameters. This large influence in the total performance was attributes to the presence of super hard silicon carbide particle of 0.5 wt.% in garnet, which could effectively remove the material from the hard titanium alloy via localized brittle fracture mechanism. Since the SiC has hexagonal crystal structure its hardness is very high. Thus the high velocity particle hits the work piece specimen and removes the material by brittle fracture [23]. Moreover, the near similar density of both garnet and SiC facilitates high rate of material removal in the process. Due to same density there was no variation in the velocity of abrasives. Almost all the abrasive in same speed and hits the work piece specimen. Thus uniform material removal takes place, which in turn produced lower surface roughness too. Moreover the abrasive flow rate also very less in this pattern thus the inter-particle collision in travel was

Table 5 S/N ratio and normalized S/N ratio for experiments

Trial number	MRR (mm^3/min)		Surface roughness (μm)	
	S/N ratio	Normalized S/N	S/N ratio	Normalized S/N
1	16.02	0.40	−10.25	1
2	15.37	0	−13.44	0
3	16.38	0.62	−12.46	0.30
4	16.98	1	−11.59	0.57
5	15.85	0.29	−13.25	0.05
6	16.57	0.74	−12.66	0.24
7	15.92	0.34	−11.12	0.72
8	16.19	0.50	−11.59	0.57
9	15.52	0.09	−13.06	0.11

Table 6 Grey relational coefficients with grey relational grade

Trial number	GRC		GRG	Rank
	MRR (mm^3/min)	Surface roughness		
1	0.45	1	0.73	2
2	0.33	0.33	0.33	9
3	0.56	0.41	0.49	6
4	1	0.53	0.77	1
5	0.41	0.34	0.38	7
6	0.65	0.39	0.52	5
7	0.43	0.64	0.54	3
8	0.52	0.53	0.53	4
9	0.35	0.35	0.35	8

Table 7 Average grey relational grade by level wise

Input factors	Average grey relational grade			Max-min
	Level 1	Level 2	Level 3	
SiC content (wt.%)	0.516	0.556	0.473	0.083
SiC size (μm)	0.680	0.413	0.516	0.267
Abrasive flow rate (g/s)	0.593	0.483	0.470	0.123
Total mean grey relational grade = 0.522				

significantly less, which resulted less chances of crisscross pattern on the work piece thus lower surface roughness was observed [24]. It was observed that the experimental design 2, 5 and 9 shows relatively very lower GRG values. It indicated that these experimental patterns are produced lower material removal rate with higher surface roughness. In these experimental patterns the volume of SiC particle and abrasive flow rate was typically high thus producing higher surface roughness via more crisscross pattern. When more volume of SiC particle mixed with garnet they may get collision while travel due to neighboring particle hit and produces large crisscross on the work piece. Similarly when large abrasive flow rate was applied more volume of particle are about to travel at a time and there are more chances to self hit with neighboring particles [25].

It is observed that the trials, which contains less abrasive flow rate and low particle dimensions found producing higher material removal rate and lower surface finish. This phenomenon was the cause of high rate of cutting edges approaching the work piece during machining [26]. It was observed further that in trail numbers 1, 4 and 7 the amount of abrasive volume percentage and abrasive flow rate was nominal. Not too low and too high. Thus the amount of active cutting edge SiC particle are high in garnet, which could facilitates higher material removal as well as the flow rate also nominal. Thus the

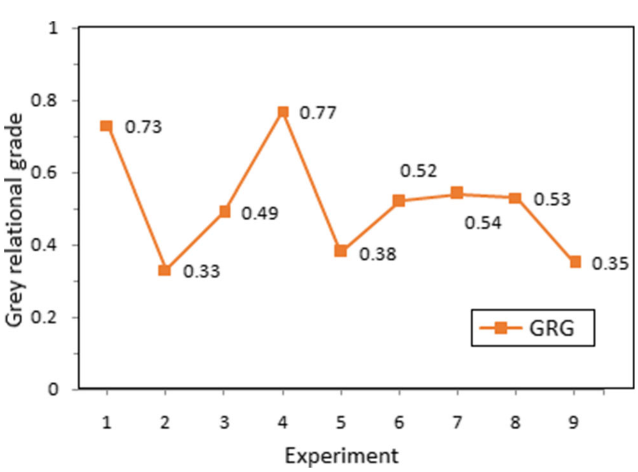

Fig. 3 Grey relational grade for experiments

chances of crisscross patterns and self hit of abrasives in high velocity was significantly less. Thus these set of experimental trials produced significantly good combination of MRR and surface roughness [27, 28].

4.1 Verification Test

To authenticate the present investigated study a numerical confirmation analysis was done subsequently after determining the optimal set of process inputs. A numerical validating trial was conducted with optimal process variables using the grey relational approach. The formula for validating the investigation is provided in Eq. 7.

$$Y = Y_m + \Sigma(Y_n – Y_m) \tag{7}$$

Where m = Mean value of total grey relational grade; n = value of optimum level mean grey relational grade. Based on the verification test using Eq. 7 the predicted GRG of the trial 4 was 0.785. Thus based on the optimum setting of process variables the material removal rate of 48.81mm^3/min and surface roughness of 3.72 μm with grey relation grade value of 0.77 was achieved. There was an improvement of 1.91% on comparing with predicted mean value was observed in obtained grey relational grade.

5 Conclusions

In this present study the hard and high strength titanium based (Ti-6Al-4V) alloy was machined using an abrasive water jet machine in accordance with L9 orthogonal array of experimental patterns. The process variable for producing high material removal rate with low surface roughness in Ti-6Al-4V alloy was identified using Taguchi optimization. The significant of this present investigation was summarized herewith. The process variable like SiC content, SiC particle size and abrasive flow rate were optimized and most influencing parameter was identified using average grey relational grades.

a) The addition of super hard SiC particle into the existing garnet pattern improved the material removal rate. However addition of more particle reduces the surface smoothness.
b) Higher flow rate of abrasive particle for machining the hard Ti-6Al-4V alloy produced higher surface roughness. Thus nominal abrasive flow rate is recommended.
c) The highest maximum-minimum value was found for material removal rate and surface roughness. It is found that the SiC particle size is a most promising influential process parameter among SiC content and abrasive flow rate.

d) The SiC size of 80 mesh is found to be giving high material removal rate with other process variables while maintaining low surface roughness.
e) The maximum material removal of 47.905mm^3/min and surface roughness of 3.815 μm were observed for trial number 4 due to the high active cutting edges of abrasives with nominal abrasive flow rate.
f) The experimental trial 2 ranked 9 among all because of undesirable output in MRR and surface roughness. The particle size of 100 mesh and abrasive flow rate of 4 g/s produced high surface roughness.
g) The confirmation test revealed 1.91% of improvement from predicted mean value. Thus the optimum MRR is 48.81mm^3/min and surface roughness is 3.27 μm.

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Authors' Contributions All have done equal contribution.

Data Availability No data available to deposit as private. There is no rights.

Compliance with Ethical Standards

Yes this article compliance with ethical standards of journal.

Conflict of Interest There is no conflict of interest by any form for this manuscript.

Consent to Participate Yes. All permission granted.

Consent for Publication Yes. All permission granted.

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