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RESEARCH PAPER

Investigation On Abrasive Water Jet Machining of Al-Al_2O_3 MMC

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ABSTRACT
The present work aims to investigate Abrasive Water Jet Machining parameters for machining of Al-Al_2O_3 Metal Matrix Composite. Plan of experiments, based on Taguchi's analysis technique were performed using L_9 orthogonal array. A correlation was established between concentration of Al_2O_3, Stand-off distance, pressure and Transverse feed with Metal Removal Rate, Surface Roughness, Over-cut and Taper angle by regression analysis. On the basis of experimental results and S/N ratio analysis, ranking of the parameters has been done. The analysis of variance (ANOVA) has been used to find out the impact of individual parameters on response parameters. Al_2O_3 concentration plays a very significant role in determination of MRR and surface roughness. Also overcut is largely influenced by stand off distance. Furthermore, multi-objective optimization can be carried out using advanced optimization techniques. This work helped to generate technical database for industrial applications of MMC.

KEYWORDS: *Al-Al_2O_3 MMC; AWJM; Taguchi method; MRR; Surface roughness; Taper; Over-cut.*

1. Introduction

Aluminium based metal matrix composites (MMC) are widely used in variety of applications such as aerospace and automotive sectors due to their excellent mechanical, physical properties and high strength to weight ratio. Now a days, machining of MMC to high quality, better accuracies and surface finish draws attention in manufacturing industries. Presence of hard abrasive reinforcement particles influence largely on tool life, cutting forces, mechanism of formation of chips, machinability and associated cost in conventional machining [1]. Arun Kumar et al. used the Taguchi's design of experiments (DOE) for the optimization of the process parameters to minimize the surface roughness and maximizing the material removal rate using WEDM. Phate et. al. (2019) has been tried machining of Al/SiCp MMC by wire cut electrical discharge machining (WEDM) process [3]. However; it was observed that Metal Removal Rate (MRR) in EDM and WEDM process is very low and also due to hard and non-conducting abrasive particles make it difficult to machine due to braking of wire in between [2-3]. In order to get maximum Material Removal Rate (MRR) and better surface finish Abrasive Water Jet Machining (AWJM) is being extensively used in many industrial applications.

AWJM is a hybrid machining process makes use of both abrasive jet and water jet. It is used for machining of wide variety of materials irrespective of their hardness. Extensive research reviews from the inception to the current developments in Abrasive Water jet Machining have been done [4-9]. Korat and Acharya (2014) reviewed research related to improving performance measures, optimization of process variables and monitoring and control of AWJM process [5]. A wide range of AWJM industrial applications for materials having different hardness and mechanical properties are also reported [5, 7]. AWJM removes material from the work-piece by striking high pressure jet of water mixed with abrasive particles. Issues relating to Kerf width and drag at high pressure, stand off distance and feed rate needs to be addressed particularly for larger thickness of materials [10-11]. Inaccuracies such as non-circularity and taper were observed in deep hole drilling operations [12]. Wang [13] investigated negative effect on the depth of cut due to nozzle oscillation and improper selection of cutting parameters. Nozzle travel speed and higher water

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pressure has lager impacts on kerf angle and kerf width [14]. Sadhikumar et. al. optimized the process parameters while machining aluminium composites by AWJM and observed that minimum Kerf angle and good surface finish can be achieved at higher water pressure, less standoff distance and low transverse speed [15]. Santhanukumar et. al., [16] while machining Al/SiC/Al_2O_3 composites using AWJM found that the process parameters such as stand-off distance, traverse speed, water pressure and abrasive flow rate have significant effect on striation angle and striation zone length. Wear mechanism while machining Si_3N_4, AlN and ZrB_2 were identified and found wear characterized mainly due to micro-cutting, plastic deformation and erosion [17].

An effect of abrasive water-jet process parameters while machining AA631-T6 alloys were investigated by using various optimization techniques such as genetic algorithm, bee colony, simulated annealing, grey fuzzy logic, fire fly algorithm, particle swarm optimization etc. [18]. An impact of technological factors such as abrasive mass flow rate, abrasive mesh, traverse cutting speed and rotating speed of an alloy Monel K-500 while machining with hydro-abrasive process were analyzed and found that traverse speed of cutting head and abrasive mass flow rate has most significant effect in order to determine material removal rate [19]. Ravi Kumar et. Al., investigated an effect of stand-off distance, transverse distance and percentage of tungsten carbide on MRR and surface roughness using multi response optimization model and set optimum process parameters [20]. Alberdi et. al. [21] was evaluated machinability index for two different CFRP composite materials with two different thicknesses machinability model were developed. According to them, the machinability index of different composite materials varies differently [21]. They found that composite materials have a significantly higher machinability index than that of metals particularly while machining with abrasive water jet [21].

Still machine manufacturers do not have good databases for machining of newly developed composite materials. It is required to generate database through extensive experimental investigations. It has been witnesses that very little research has been carried out on AWJM of metal matrix composites [20]. Also majority of the investigations are limited to the Metal Removal Rate (MRR) and Surface roughness (SR). Hardly any work pertaining to the other inaccuracies produced during machining by AWJM has been addressed so far. The aim of present work is to investigate an effect of process parameters of AWJM on metal removal rate (MRR), surface roughness and accuracies like amount of over-cut and taper.

2. Materials and Methods

2.1. Preparation of work piece

Metal Matrix Composites (MMC) is composed of a metallic matrix (Aluminium) and a dispersed ceramic (Oxides) phase. In this work Al 2124 is used as a matrix and Al_2O_3 ceramics as a filler material. In Stir Casting liquid state MMC manufacturing method, discontinuous reinforcement is stirred into molten metal which is allowed to solidify. By mechanical stirring a dispersed phase is mixed with a molten matrix metal. Figure 1 shows a stir casting process. Powder reinforcement is distributed into molten metal by means of mechanical stirring process. The production of MMC using this process can affect by process variables such as holding temperature, stirring speed, size of impeller and position of impeller in the melt which has impact on mechanical properties. The properties of MMC are strongly depending on the interfacial bonding strength of reinforcement and matrix phase.

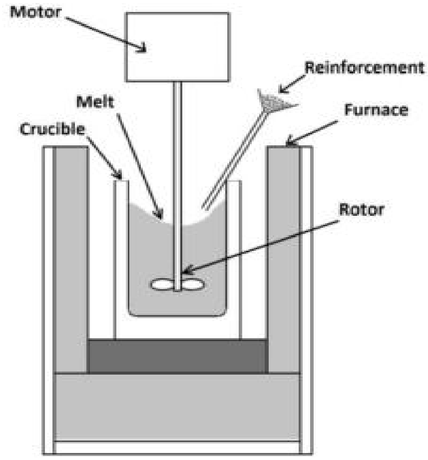

Fig. 1. Stir casting principle

A plate of size 130 mm x 80 mm x 10 mm were cast of Al- Al_2O_3 MMC and finished using on vertical milling machine to brought of cast. Hardness was measured with the Brinell hardness test according for all three plates and found that 73.48 BHN, 76.73 BHN and 78.21 BHN for 10 %, 20 % and 30 % concentration of Al_2O_3 in MMC respectively, this depicts that addition of Al_2O_3 increases hardness.

2.2. Experimental setup

Experiments were conducted on CNC Mach 2B Abrasive water jet machine. Fig. 2 shows schematic of Abrasive Water Jet Machine which removes material from the surface by erosion of fine-grained abrasive particles striking the surface at a high velocity.

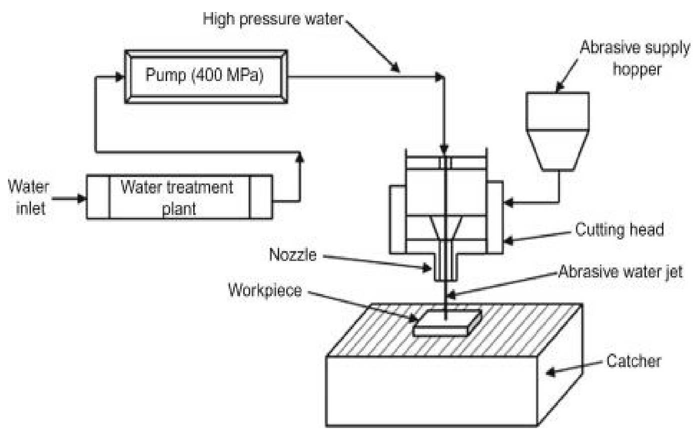

Fig. 2. Schematic of abrasive water jet machine

It is contains reservoir/water tratement plant which is used for storing water. The water is pumped from the reservoir. High pressure intensifier pumps are used to pressurize the water. For the abrasive water jet, the operating pressure capacity of 40,000 PSI HP. At this high pressure the flow rate of the water is reduced greatly. Intensifier is connected to the pump that pressurizes water from the pump to a desired level. Accumulator is used for temporarily storing the pressurized water. It is connected to the flow regulator through a control valve which controls the direction and pressure of pressurized water that is to be supplied to the nozzle. Flow regulator is used to regulate the flow of water. Nozzle renders the pressurized water and abrasives to the work-piece to get desired shape.

2.3. Plan of experiments

Taguchi's design of experiments was used with L_9 Orthogonal Array at 3 levels and 4 factors. Independent parameters are Concentration of Al_2O_3 , Stand-off distance, Pressure and Transverse speed. The levels of various process parameters are as shown in Table 1. There are four response parameters i.e. Material removal rate (MRR), Surface roughness (Ra), Overcut (mm) and Taper (degrees).

Tab. 1. Process parameters and their levels

Parameters	Levels		
	Level 1	Level 2	Level 3
Conc. of Al_2O_3 (%) C	10	20	30
Stand-off Dist. (mm) SD	2	4	6
Pressure (MPa) P	240	310	380
Transverse Feed (mm/rev) F	305	310	315

3. Results and Discussion

3.1. Analysis for metal removal rate

Material removal rate (MRR) is calculated in mm^3/min by using Eq. 1.

$$MRR = \frac{Total\ volumn\ removed\ from\ the\ workpiece}{Time\ taken} \quad \text{Eq. (1)}$$

Using MINITAB, Taguchi Design Software, S/N ratios for MRR, ranking of parameters and ANOVA are calculated. Experimental results, Ranking of Parameters and ANOVA analysis are shown in Table 2, Table 3 and Table 4 respectively. Here, Delta denotes proportionate change in S/N ratio.

Tab. 2. Experimental results for MRR

RUN	C %	SD mm	P MPa	F mm/min	MRR (mm^3/min×10^3)		MRR (mm/min)×10^3 Mean	S/N ratio
					a	b		
1	10	2	240	305	4.5	4.5	4.50	13.06
2	10	4	310	310	4.6	4.6	4.60	13.25
3	10	6	380	315	4.8	4.9	4.85	13.71
4	20	2	310	315	3.3	3.3	3.30	10.37
5	20	4	380	305	3.5	3.4	3.45	10.75
6	20	6	240	310	3.3	3.4	3.35	10.49
7	30	2	380	310	3.2	3.2	3.20	10.10
8	30	4	240	305	2.5	2.4	2.45	7.77
9	30	6	310	315	3.2	3.2	3.20	10.10

Tab. 3. Response table for signal to noise ratios

Level	Conc. Of Al_2O_3	Stand Off Distance	Pressure	Transverse Feed
1	13.344	11.179	10.447	11.307
2	10.541	10.596	11.243	11.285
3	9.328	11.438	11.523	10.621
Delta	4.016	0.843	1.077	0.686
Rank	1	3	2	4

Here in machining operation the metal removal rate is desired to be larger, hence larger S/N ratio as a better condition is considered as an objective function. The main effects plot for the S/N ratios is plotted for the various parameters namely Concentration of Al_2O_3, Stand off Distance, Pressure and Transverse Feed are shown in Fig. 3. From Table 3, the material removal rate is mainly influenced by conc. of Al_2O_3 followed by pressure; stand off distance and transverse feed. Increase in conc. of Al_2O_3 decreases MRR due to its high hardness.

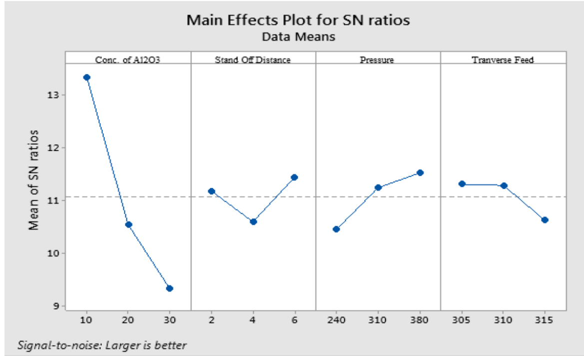

Fig. 3. Main effect plot for S/N ratios (MRR)

Tab. 4. Analysis of variance for MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	4.65208	1.16302	9.12	0.027
Conc. of Al2O3	1	4.33500	4.33500	33.99	0.004
Stand Off Dist.	1	0.02667	0.02667	0.21	0.671
Pressure	1	0.24000	0.24000	1.88	0.242
Transverse Feed	1	0.05042	0.05042	0.40	0.564
Error	4	0.51014	0.12753		
Total	8	5.16222			

Mathematical model for MRR in terms of additive concentration of Al_2O_3 , Stand off distance, Pressure and Transverse speed were obtained from regression analysis using MINITAB19 statistical software. The Eq. (2) obtained was as follows:

$$MRR = 10.02 - 0.0850\ \text{Conc. of}\ Al_2O_3 + 0.0333\ \text{Stand Off Distance} + 0.00286\ \text{Pressure} - 0.0183\ \text{Transverse Feed} \quad \text{Eq. (2)}$$

Where, S= 0.357120, R-sq. 90.12 % and R-sq (adj)= 80.24%

As the R^2 value of regression analysis is more than 70 %, the choice of the process parameters and results obtained seems to be consistent.

3.2. Analysis for surface roughness

Surface roughness (Ra) was measured in µm using digital surface roughness tester Mitutoyo SJ-201 with a cut-off length of 0.8 mm. Experimental results, Ranking of Parameters and ANOVA analysis foe surface roughness are shown in Table 5, Table 6 and Table 7 respectively. Here, Delta denotes proportionate change in S/N ratio.

Tab. 5. Experimental results for surface roughness

RUN	C %	SD mm	P MPa	F mm /min	Surface Roughness (µm)		SR Mean	S/N ratio
					a	b		
1	10	2	240	305	4.88	4.96	4.92	-13.83
2	10	4	310	310	3.76	3.66	3.71	-11.38
3	10	6	380	315	2.29	3.14	2.15	-08.78
4	20	2	310	315	5.20	5.21	5.20	-14.32
5	20	4	380	305	5.58	5.55	5.56	-14.90
6	20	6	240	310	5.67	5.69	5.68	-15.08
7	30	2	380	310	5.93	5.93	5.93	-15.46
8	30	4	240	305	6.22	6.35	6.28	-15.96
9	30	6	310	315	5.34	5.34	5.34	-14.55

Tab. 6. Response table for signal to noise ratios (SR)

Level	Conc. of Al_2O_3	Stand Off Dist.	Pressure	Transverse Feed
1	-11.34	-14.54	-14.96	-14.43
2	-14.77	-14.09	-13.42	-13.98
3	-15.33	-12.81	-13.05	-13.03
Delta	3.99	1.74	1.91	1.41
Rank	1	3	2	4

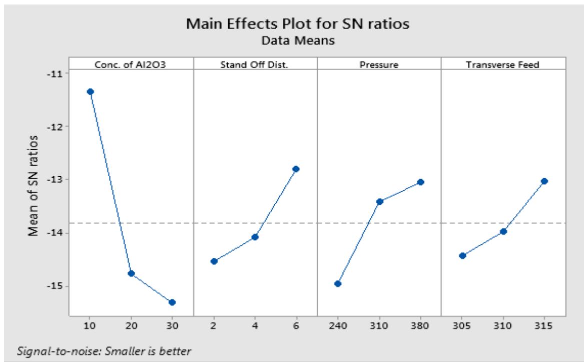

Fig. 4. Main effect plot for S/N ratios (Surface Roughness)

Here in machining operation surface roughness is desired to be smaller, hence smaller is better is considered as an objective function. The main effects plot for the S/N ratios is plotted for the various parameters namely Concentration of Al_2O_3, Stand off Distance, Pressure and Transverse Feed are shown in Fig. 4.

From Table 6, the surface roughness is mainly influenced by conc. of Al_2O_3 followed by pressure; stand off distance and transverse feed. Table 7 depicts Analysis of variance for surface roughness.

Tab. 7. Analysis of variance for Surface Roughness

Source	DF	Adj SS	Adj MS	F- Value	P- Value
Regression	4	8.9544	2.2386	6.49	0.049
Conc. of Al_2O_3	1	6.4274	6.4274	18.64	0.012
Stand Off Dist.	1	0.8971	0.8971	2.60	0.182
Pressure	1	1.1926	1.1926	3.46	0.136
Transverse Feed	1	0.4374	0.4374	1.27	0.323
Error	4	1.3791	0.3448		
Total	8	10.3335			

As increase in conc. of Al_2O_3 increases surface roughness as hard and brittle particles of Al_2O_3 are dislodged from the ductile aluminium . Surface roughness decreases with increase in stand off distance, pressure and transverse feed Eq. (3).

$$\text{Surface Roughness} = 22.5 + 0.1035\ \text{Conc. of } Al_2O_3 - 0.193\ \text{Stand Off Dist.} - 0.00637\ \text{Pressure} - 0.0540\ \text{Transverse Feed} \quad \text{Eq. (3)}$$

Where, S= 0.587169, R-sq.= 86.65 % . As the R^2 value of regression analysis is more than 70 %, the choice of the process parameters and results obtained seems to be consistent.

3.3. Analysis for over-cut

An over-cut was measured by using Mitutoyo non contact type optical profile projector having Protractor screen size of 300mm with projection lenses of 50x and 100x magnification. Experimental results are shown in Table 8.

Tab. 8. Experimental results for overcut

RUN	C %	SD mm	P MPa	F mm /mim	Over-cut (mm) a	b	OC Mean	S/N ratio
1	10	2	240	305	0.36	0.41	0.38	8.272
2	10	4	310	310	0.44	0.41	0.42	7.426
3	10	6	380	315	0.57	0.56	0.56	4.958
4	20	2	310	315	0.41	0.48	0.44	7.006
5	20	4	380	305	0.56	0.53	0.54	5.268
6	20	6	240	310	0.99	1.00	0.99	0.043
7	30	2	380	310	0.57	0.56	0.56	4.958
8	30	4	240	305	0.67	0.70	0.68	3.284
9	30	6	310	315	0.71	0.81	0.76	2.364

Table 8 shows experimental results. In this, an over-cut is inaccuracy hence an objective smaller is better is considered to calculate mean square deviation and signal to noise ratios.

Table 9 depicts the ranking of the parameters based on S/N ratios. Over-cut is largely influenced by Stand off Distance followed by Conc. of Al_2O_3, Pressure and transverse feed.

Tab. 9. Response table for over-cut

Level	Conc. Of Al_2O_3	Stand of Dist.	Pressure	Transverse Feed
1	6.886	6.746	3.867	5.302
2	4.106	5.327	5.599	4.143
3	3.536	2.456	5.062	5.083
Delta	3.350	4.290	1.733	1.159
Rank	2	1	3	4

Fig. 5 depicts the main effects plot for the S/N ratios plotted for the various parameters namely Concentration of Al_2O_3, Stand off Distance, Pressure and Transverse Feed.

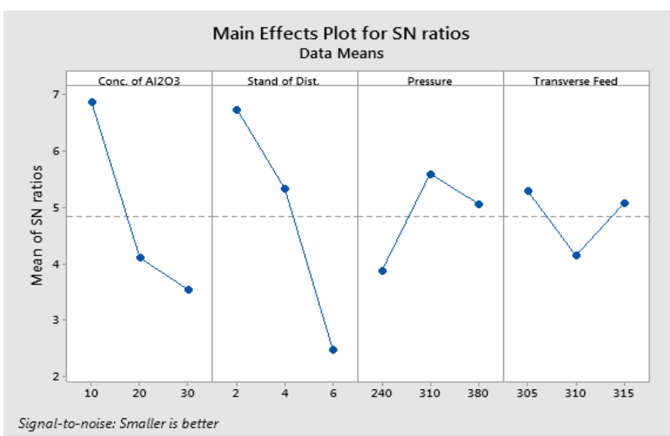

Fig. 5. Main effect plot for S/N ratios (Over-cut)

Table 10 depicts Analysis of variance for an over-cut. From an Eq. (4), Overcut increases with increase in Conc. of Al_2O_3, Stand off distance and Transverse Feed and decresases with pressure. As stand off distance increases, the atmospheric drag leading to spread up water jet causing oversize.

Tab. 10. Analysis of variance for over-cut

Source	DF	Adj SS	Adj MS	F Value	P Value
Regression	4	0.235163	0.058791	3.92	0.107
Conc. of Al_2O_3	1	0.067204	0.067204	4.48	0.102
Stand of Dist.	1	0.142604	0.142604	9.52	0.037
Pressure	1	0.025350	0.025350	1.69	0.263
Transverse Feed	1	0.000004	0.000004	0.00	0.987
Error	4	0.059937	0.014984		
Total	8	0.295100			

$$\text{Over-cut} = 0.31 + 0.01058\ \text{Conc. of } Al_2O_3 + 0.0771\ \text{Stand of Dist.} - 0.000929\ \text{Pressure} + 0.00017\ \text{Transverse Feed} \quad \text{Eq. (4)}$$

Where, S= 0.1224, R-sq.= 79.69 %

As the R^2 value of regression analysis is more than 70 %, the choice of the process parameters and results obtained seems to be consistent.

3.4. Analysis for taper

By using optical profile projector the diameter from top and bottom surface was measured. Plate thickness is 10 mm. Accordingly taper angle was calculated using Equation (5).

$$Taper\ angle\ (\alpha) = tan^{-1}(D - d/2l) \quad \text{Eq. (5)}$$

Where, D, d is diameter measured on profile projector from top and bottom surface, l is total thickness of plate i.e. 10 mm.

Table 11 shows experimental results with an objective function of smaller is better to calculate MSD and S/N ratio. Two replicates were taken. From table 12, ranking of the parameters were done. Concentration of Al_2O_3 contributes largely to produce taper in hole drilling. As Al_2O_3 concentration increases, chipping of hard abrasive may cause increase in diameter at one end than the other, followed by stand off distance, Transverse feed and Pressure.

Tab. 11. Experimental results for taper

RUN	C %	SD mm	P MPa	F Mm /min	Taper angle (degree)		Taper Angle Mean	S/N ratio
					a	b		
1	10	2	240	305	0.20	0.22	0.21	13.54
2	10	4	310	310	0.23	0.25	0.24	12.38
3	10	6	380	315	0.28	0.32	0.30	10.43
4	20	2	310	315	0.54	0.53	0.53	5.43
5	20	4	380	305	1.30	1.54	1.42	-3.07
6	20	6	240	310	1.91	1.86	1.88	-5.50
7	30	2	380	310	0.50	0.71	0.60	4.23
8	30	4	240	305	0.63	0.81	0.72	2.78
9	30	6	310	315	2.34	2.30	2.32	-7.31

Tab. 12. Response Table for taper

Level	Conc. Of Al_2O_3	Stand off Dist.	Pressure	Transverse Feed
1	12.1241	7.7381	3.6083	1.0530
2	-1.0504	4.0325	3.5036	3.7058
3	-0.0960	-0.7929	3.8659	6.2190
Delta	13.1745	8.5310	0.3623	5.1660
Rank	1	2	4	3

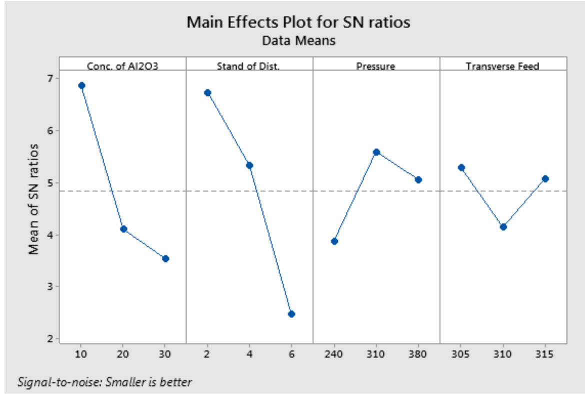

Fig. 6. Main effect plot for S/N ratios (Taper)

Tab. 13. Analysis of variance for taper

Source	DF	Adj SS	Adj MS	F Value	P Value
Regression	4	4.05186	1.01297	5.57	0.062
Conc. of Al_2O_3	1	1.39684	1.39684	7.68	0.050
Stand off Dist.	1	1.65900	1.65900	9.12	0.039
Pressure	1	0.04002	0.04002	0.22	0.663
Transverse Feed	1	0.95600	0.95600	5.26	0.084
Error	4	0.72749	0.18187		
Total	8	4.77935			

$$\text{Taper} = 24.0 + 0.0482\ \text{Conc. of } Al_2O_3 + 0.2629\ \text{Stand off Dist.} - 0.00117\ \text{Pressure} - 0.0798\ \text{Transverse Feed} \quad \text{Eq. (6)}$$

Where S= 0.426464, R-sq=84.75 %

From R-sq value the results obtained are found to be consistent.

4. Conclusions

In the present work the effect of AWJM parameters on the Al- Al_2O_3 metal matrix composites were carried out using Taguchi analysis. An effect of Conc. of Al_2O_3, Stand off distance, Pressure and Transverse Feed on metal removal rate, surface roughness, over-cut and amount of taper was investigated. Parameters were ranks based on S/N ratio and it was observed that for MRR and surface roughness ranking is same as Conc. of Al_2O_3 followed by Pressure, Stand off distance and Transverse Feed; however for overcut and taper stand of distance is influencing more. Empirical relationship between and parameters under consideration and response variables were established by using regression analysis. The adopted model has good adequacy at 95% confidence level. Cracks, brittle fracture were witnesses along the surface of the composites.

The presented work can be extended to optimize the parameters for better MRR and reduced inaccuracies. Furthermore, multi-objective optimization can be carried out using recent optimization techniques.

Thus the presented approach will help the industry to have technical database for the use of AWJM for aluminium based MMC.

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