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OPTIMIZATION OF PROCESS PARAMETERS OF AWJM ON AA6061-7.5% SiC MMC FOR LOWER SURFACE ROUGHNESS AND HIGHER MRR

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Abstract - **Metal matrix composites (MMCs) have evoked a keen interest in recent times for potential applications in aerospace and automotive industries. Hardness and strength are the prime requirements of MMCs used in structural applications. In general, these properties are exhibited by Al-SiC MMCs. But major restraints are material cost, heterogeneous distribution of reinforcement in matrix during manufacturing and inaccurate dimensions of final product after machining. Subduing the limitations, an attempt has been made to fabricate AA6061-7.5%SiC using two step stir casting method and machine it using Abrasive Water Jet Machining (AWJM) technique. The present investigation targets to optimize the AWJM process parameters while machining AA6061-7.5%SiC MMC. The variable process parameters of AWJM are considered as abrasive feed, stand-off distance and traverse speed. Using the L9 orthogonal array by Taguchi method for design of experiments and analysis, the liaison between these parameters and their responses is explored by ANOVA and Response Surface Methodology (RSM). The results are developed in accordance to a quality control factor and a machinability factor which are surface roughness (SR) and material removal rate (MRR) respectively. Optimal parameters are obtained with respect to lower SR and higher MRR.**

Keywords - **Abrasive Water Jet Machining (AWJM), Metal Matrix Composite (MMC), Taguchi method, ANOVA, Response Surface Methodology (RSM), Two step stir casting, Traverse speed, Abrasive feed, Stand-off distance, Hardness, Strength, Material Removal Rate (MRR), Surface Roughness (SR).**

I. INTRODUCTION

Aluminium alloys are very promising for structural applications in aerospace, military and transportation industries due to their light weight, high strength-to-weight ratio and excellent resistance to corrosion [Dharmpal Deepak et al. (2013)]. AA6061 is a wrought heat treatable aluminium alloy. It has Mg & Si as major constituent elements. It is widely used in construction of aircraft and marine (ship building) structures. It has commendable corrosion resistance, workability, machinability, weldability and brazability but medium strength and low hardness. In marine applications, surface transport like yachts are completely manufactured using AA6061. Yachts need high strength to balance various forces acting on them. The desire to achieve high hardness and high strength leads to the evolution of composites. Therefore, the need of composites is justified. Composites are composed of a combination of distinctly different two or more micro or macro constituents that differ in the form of composition and it is insoluble in each other [Sijo M T et al. (2016)]. According to matrix constituent, composites are classified into organic-matrix composites, Metal Matrix Composites (MMCs) and ceramic-matrix composites [Sijo M T et al. (2016)]. Metallic matrix composites are combinations of two or more different metals, intermetallic compounds or second phases in which dispersed phases are embedded within the metallic matrix [Md. Habibur Rahman et al. (2014)].

The majority of composites are metallic matrices reinforced with a high strength, high modulus, and often brittle second phase, in the form of a fibre, particulate, or whiskers embedded in a ductile metal matrix [M.Ramachandra et al. (2006)]. In order to tailor the existing properties of AA6061, reinforcements like Silicon Carbide (SiC), Boron Carbide (B_4C), Titanium Carbide (TiC), Alumina (Al_2O_3), silver nano particles, carbon nano tubes, fly ash or combination of any two reinforcements can be added to the matrix. Usually non-metallic and ceramic particles like SiC, Al_2O_3, B_4C, graphite etc. are used as reinforcements in Aluminium Matrix Composites (AMCs) [Md. Habibur Rahman et al. (2014)]. Silicon carbide as such, because of its high hardness, has got a number of applications such as cutting tools, jewellery, automobile parts, electronic circuits, structural materials, nuclear fuel particles, etc [Sijo M T et al. (2016)]. Thus, SiC when reinforced in matrix upgrades the hardness and strength of the composite. For applications (like ship building) requiring high strength and hardness, the MMC AA6061-SiC can be used.

Dharmpal Deepak et al. (2013) studied the wear behavior and microhardness of the friction stir processed sample of AA5083 and SiC. Observations revealed that hardness increased significantly but wear resistance reduced when compared to AA5083. According to an investigation carried out by M.Ramachandra et al. (2006), aluminium alloy LM25 is reinforced with 5%, 10% and 15% (by weight) micro-sized SiC particles using vortex method. Bulk hardness, slurry erosive wear resistance and sliding wear resistance increased whereas corrosion resistance decreased with increase in SiC content. Md. Habibur Rahman et al. (2014) evaluated AMCs of varying SiC content (0, 5, 10 and 20 wt. %) manufactured by stir casting. It is concluded that Vickers hardness, wear resistance and tensile strength increased with increase in SiC content. Also 20 wt. % SiC in aluminium matrix corresponded to maximum tensile strength, Vickers hardness and wear resistance. But the cost of reinforcement, manufacturing time and cost increase with increase in SiC content. Many experimental investigations disclosed that 5%, 10%, 15%, and 20% (by weight) of SiC is used to analyze various properties of composite. Hence by optimizing the cost of reinforcement, cost of manufacturing and time for fabrication without compromising in achieving appreciable strength and hardness, 7.5% (by weight) SiC is considered to be added to AA6061 in this experiment. M.T.Sijo et al. (2016) revealed stir casting is a better technique when compared to powder metallurgy, diffusion bonding, spray casting, compo casting, rheo casting, in situ processes and infiltration of liquid matrix into the reinforcements to fabricate Al-SiC MMCs because it is simple, economical, flexible, applicable for large quantity production and causes no damage to reinforcement during manufacturing. Also limitations of stir casting like heterogeneous distribution of reinforcement particles, decrease in fracture toughness and poor wettability can be curbed by employing two step stir casting method and adding 1% magnesium (Mg) to the molten matrix. Ergo, stir casting is the manufacturing method utilized to fabricate AA6061-7.5%SiC MMC in this experiment. As the hardness of the composite increases, it becomes brittle in nature. Due to anisotropic and non-homogeneous nature of composites, their machining behavior differs in many aspects from metal machining [M. A. Azmir et al. (2007)]. It is difficult to machine brittle materials using conventional methods because of formation of chatter, damage of work material such as delamination, fibre pull out, poor hole quality in case of drilling, development of thermal stress and generation of heat [M. A. Azmir et al. (2007), G. Selvakumar et al. (2018)]. Hence, unconventional methods like Abrasive Jet Machining (AJM), Water Jet Machining (WJM), Electrical Discharge Machining (EDM), laser machining and ultrasonic machining has drawn much interest [D. Sidda Reddy et al. (2014), M. A. Azmir et al. (2007)]. Abrasive Water Jet Machining (AWJM) is an amalgamation process of abrasive jet and water jet machining in which the abrasives are entrained into the mixing chamber at suitable proportion through a side tube and mixed with water [G. Selvakumar et al. (2018)]. The metal removal takes place by impact erosion of pressurized water jet passing through the nozzle with high velocity abrasives striking the work piece [G. Selvakumar et al. (2018), B. Arul kumar et al. (2015)]. Among these processes, AWJM is the only method used in industry today for trimming fibre reinforced composite materials as laser machining suffers from the problem of a large heat-affected zone, poor machinability of plates of thickness more than 3mm and incapability of machining the components with least slot width, while EDM suffers from extremely low cutting rates [D. Sidda Reddy et al. (2014), M. A. Azmir et al. (2007)]. AWJM offers several advantages over conventional cutting techniques as it is environment friendly, is best choice for machining complicated contours, has ability to cut metals & non metals, has capability to machine brittle and ductile materials, high flexibility, is less sensitive to material properties and high versatility [M. A. Azmir et al. (2007), G. Selvakumar et al. (2018), B. Arul kumar et al. (2015)]. In this experiment, Abrasive Water Suspension Jet Machining (AWSJM) is employed to machine the MMC AA6061-7.5%SiC because M. Hashish (1991) reported that slurrying (pumping directly premixed abrasive slurry to the nozzle) helps in consistent entrainment to increase velocity of abrasive stream for effective performance in comparison with dry powder.

The disadvantages of AWJM are poor surface finish, low Metal Removal Rate (MRR), loud noise, messy working environment, inefficient machining of water degradable materials. Among the disadvantages, SR and MRR are the prime concern because standardization aims at interchangeability and perfect quality. Surface roughness is one of the most important quality control parameters for assessing a production process [D. Sidda Reddy et al. (2014)]. M. Hashish (1991) identified the process parameters in AWJM as hydraulic parameters, abrasive parameters, mixing parameters, traverse rate, number of passes, standoff distance, rotational speed, lateral feed increment and dwell time. The optimization criteria include maximum surface area generation, minimum cost, maximum cutting speed and maximum surface finish value. The observations revealed that less coherent jets are apt for hard materials, surface waviness is reduced and MRR is increased by increasing the pressure, increasing abrasive flow rate reduces burr height at the exit side of the cut, coarser size abrasives result in the fastest but the roughest cut whereas fine abrasives result in increased surface waviness due to the reduced cutting capability, etc. Upon summarizing the results, the surface waviness and roughness are significantly affected by particle diameter, water jet pressure, water jet orifice diameter, abrasive flow rate, and work piece properties.

K. Ravi Kumar et al. (2017) analyzed the effect of AWJM parameters (stand-off distance, traverse speed and %WC) on MRR and SR of stir casted AA6082-(2%, 4%, 6%, 8%, 10%)WC MMCs using Taguchi Method, Response Surface Methodology (RSM) and Analysis of Variance (ANOVA). SR is mostly influenced by % WC whereas MRR is influenced significantly by traverse speed. G. Selvakumar et al. (2018) developed a technology table for AWJM of stir casted AA5083 in different job thicknesses by optimizing stand-off distance, abrasive flow rate and jet diameter to scrutinize MRR, SR and taper error using Taguchi, Artificial Neural Networks (ANN) and PARETO analysis. The investigation carried out by D. Sidda Reddy et al. (2014) concentrates on optimizing the process parameters (traverse rate, abrasive flow rate and stand-off distance) of AWJM to analyze MRR and SR for Inconel 800H using Taguchi and ANOVA. The conclusion reveals that traverse speed plays a major role on influencing MRR whereas standoff distance influences SR to a greater extent. Abrasive flow rate is sub-significant in both the cases. B. Arul Kumar et al. (2015) focused on optimizing pressure, traverse speed and stand-off distance for AWJM of stir casted Al-(2%, 4%, 6%) SiC MMCs using Taguchi method. The results stated that SR is primarily influenced by traverse speed. M. A. Azmir et al. (2007) tried to optimize hydraulic pressure, abrasive mass flow rate, stand-off distance and traverse rate in AWJM of Kevlar composite for better surface finish using Taguchi methodology and Grey Relational Analysis (GRA). Rajkamal Shukla et al. (2016) conducted experiments on AWJM to obtain the influence of the parameters such as traverse speed, stand-off distance and mass flow rate on the kerf top width and taper angle. AA6351 is machined by AWJM and the results are developed using Taguchi, ANOVA and seven advanced optimization techniques (particle swarm optimization, firefly algorithm, artificial bee colony, simulated annealing, black hole, biogeography based and non-dominated sorting genetic algorithm). Based upon literature survey, three parameters are selected by observing their significance and frequency of selection in various experimental studies. They are abrasive feed, traverse speed and stand-off distance. The optimization is carried out by Taguchi method, RSM and ANOVA for better surface finish and higher MRR.

II. EXPERIMENTAL WORK

A. Materials

AA6061 is used as matrix material and 7.5% (by weight) SiC particles of mesh size 80 are added as reinforcement to fabricate the composite. The chemical composition of AA6061 is given in Table 1.

1% Mg is added to the molten matrix material during casting. Table 2. provides the mechanical properties of AA6061.

Table 1. Chemical composition of AA6061 by weight percentage

Element	Amount (wt%)
Aluminium	96.8
Magnesium	0.9
Silicon	0.7
Iron	0.6
Copper	0.3
Chromium	0.25
Zinc	0.2
Titanium	0.1
Manganese	0.05
Others	0.05

Table 2. Mechanical properties of AA6061

Yield strength	302 MPa
Ultimate strength	334 MPa
Elongation (%)	189
Reduction in cross-sectional area	12.24
Hardness (VHN)	105

B. Preparation of composite

According to two step stir casting technique discussed by M. Sambathkumar et al. (2017)], 6 kg of AA6061 in a graphite crucible placed in a furnace is heated above liquidous temperature 652°C at which 1% (by weight) Mg is added and 0.2 kg slag is removed within 5 minutes. Then cooled to 600°C (between solidous-582°C and liquidous-652°C temperatures) at which 0.5 kg of preheated SiC is added. The reinforcement SiC is preheated to 250°C to remove moisture and improve the compatibility with molten aluminium. At a temperature of 1250°C, the mixture is stirred at 10,000 RPM for 25 minutes. Around 600°C, thermodynamically unstable SiC reacts with molten aluminium to form Al_4C_3 according to the reaction $4Al + 3SiC \rightarrow Al_4C_3 + 3Si$. Al_4C_3 is formed by degradation of reinforcement strength and the interfacial strength. Thus, it increases the corrosion susceptibility and changes the composition of composite. As discussed by D. J. Lloyd et al. (1988), this reaction can be avoided by carrying out the experiment at a temperature beyond 600°C. Finally the melt is poured into mould and left for solidification. The dimensions of the composite specimen are 120 x 100 x 15 mm^3. Figure 1. shows the casted component.

Figure 1. Casted component

C. Design of experiments

Taguchi's experimental design is employed to contrive the design of experiments. The variable process parameters used are abrasive feed (gm/min), stand-off distance (mm) and traverse speed (mm/min). Using Taguchi methodology for design of experiments in MINITAB 19.3.1, L9 orthogonal array is selected with three levels and three factors. Table 3. gives the L9 orthogonal array with machining parameters. Each sever is set to the pre-defined values of process parameters according to the orthogonal array.

Table 3. L9 orthogonal array

JOB	Traverse speed (mm/min)	Abrasive feed (g/min)	Stand-off distance (mm)
1	50	400	3
2	50	750	4
3	50	1100	5
4	70	400	4
5	70	750	5
6	70	1100	3
7	90	400	5
8	90	750	3
9	90	1100	4

D. Machining

The major components of AWSJM are water pressurizing unit, abrasive storage, suspension nozzle and work piece fixture. The pressurized water is directed into two channels; one towards the abrasive storage and the other towards the suspension nozzle. In abrasive storage, pressurized water and abrasive particles mix together to form slurry. The slurry flows out of abrasive storage, mixes with second channel in the suspension nozzle (to avoid choking of the slurry in the nozzle) and impinges on to the work piece. The material removal takes place due to impact erosion. The MMC AA6061-7.5%SiC is machined using AWJ-S3015 of Water jet Germany Private Limited. The nozzle diameter is 1.1mm and operating pressure lies in the range: 10-1000 MPa. In general, abrasive particles like sand (SiO_2), glass beads, aluminum oxide, and silicon carbide are used. In this study, sand of mesh size 80 is used as abrasive material. Table 4. gives the specifications of AWJ-S3015. Figure 2. shows machined specimens.

Table 4. AWJ-S3015 specifications

Specification	Dimension/ Description
Nozzle diameter	1.1mm
Abrasive particle	Sand-80 mesh (garnet)
Orifice diameter	0.35mm
Water pressure	3800 bar
Machine size	3 m (x-axis) 1.5 m (y-axis)
Cutting fluid	RO-purified water
Water consumption	2000 lt/hr
Software for CNC	Item CAD
Nesting software	Most 2D

Figure 2. Machined specimens

E. Calculation of MRR and measurement of SR

After machining the casted component according to the L9 orthogonal array using MOST 2D for sequencing of operations, MRR and SR are calculated and measured respectively. MRR is calculated using MRR = $(W_b - W_a) / (t * \rho)$ where W_b = Weight of work piece before machining (g), W_a = Weight of work piece after machining (g), t = Machining time (sec) and ρ = Density of work piece (g/mm^3). SR is measured in terms of mean absolute deviation (Ra) using Surftest SJ-210. Table 5. gives calculated values of MRR and Table 6. gives surface roughness values.

Table 5. Calculated values of MRR

JOB	$(W_b - W_a) / (t * \rho)$	MRR (mm^3/sec)
1	(53.5-51.9) / (0.00269*15)	39.7
2	(48.9-47.63) / (0.00269*14.8)	32.7
3	(50.1-48.8) / (0.00269*16.1)	30
4	(49.4-47.91) / (0.00269*15.1)	36.9
5	(49.8-48.2) / (0.00269*15.3)	38.9
6	(49.8-48.5) / (0.00269*15)	32.2
7	(51.1-49.9) / (0.00269*15.4)	28.97
8	(51.5-50.2) / (0.00269*15.1)	32
9	(51.6-50.7) / (0.00269*16)	21

Table 6. Observed values of surface roughness

JOB NO.	Surface roughness (Ra in µm)
1	5.16
2	5.22
3	5.93
4	5.48
5	5.58
6	5.86
7	5.78
8	5.92
9	5.24

III. RESULTS AND DISCUSSION

To analyze the responses and optimize the process parameters, again MINITAB 19.3.1 is used. Taguchi analysis is applied for Taguchi design of experiments and signal to noise ratio is developed for individual machining characteristics separately. Figure 3. shows the Taguchi results for higher MRR and Figure 4. shows the Taguchi results lower SR.

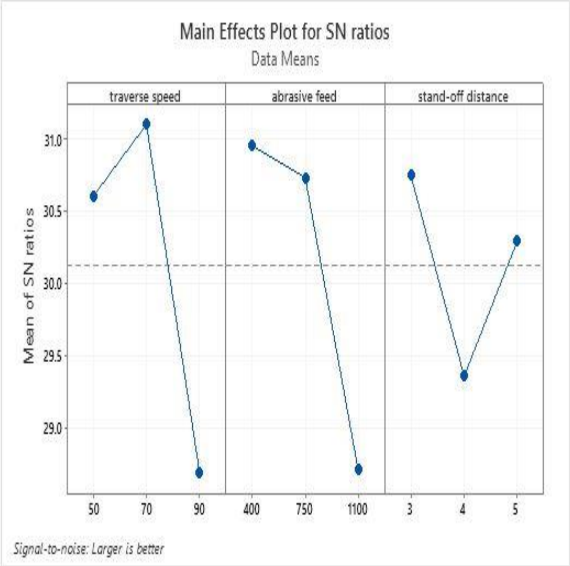

Figure 3. Taguchi results for higher MRR

From Figure 3. It is revealed that 70 mm/min of traverse speed, 400 g/min of abrasive feed and 3 mm of stand-off distance correspond to maximized MRR. Similarly from Figure 4. it is revealed that 50 mm/min of traverse speed, 400 g/min of abrasive feed and 4 mm of stand-off distance correspond to minimized SR.

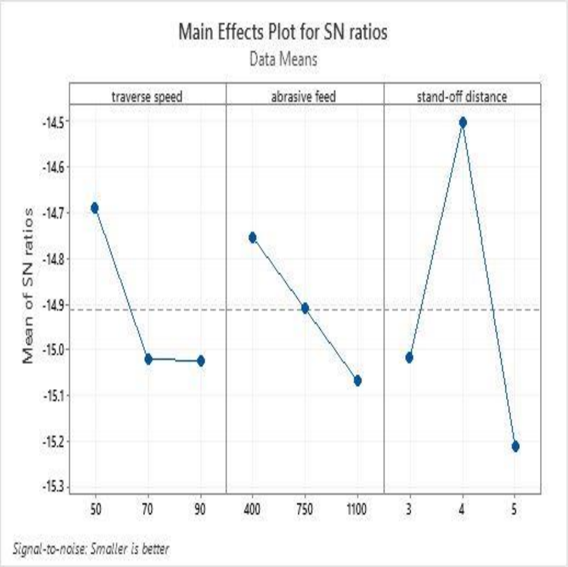

Figure 4. Taguchi results for lower SR

Using the signal to noise ratio the optimized values are identified for a particular machining characteristic whereas Response Surface Methodology (RSM) is used to analyze multiple responses. RSM is applied for Taguchi design of experiments and a regression equation with a PARETO graph generate the optimized set of process parameters which can produce higher MRR and lower SR together. Eq 1. and Eq 2. give the regression equations for SR and MRR. Figure 5. depicts the PARETO graph. The regression equations are quadratic which reveal that MRR and SR vary according to their respective equation. The optimal process parameters from PARETO graph are 50 mm/min of traverse speed, 400 g/min of abrasive feed and 4.7172 mm of stand-off distance. The surface roughness and material removal rate corresponding to optimal factors are 5.1584 µm and 39.7920 mm^3/sec.

MRR = 46.25 + 1.725*traverse speed – 0.001467*abrasive feed – 30.24*stand-off distance – 0.01276*(traverse speed*traverse speed) – 0.000018*(abrasive feed*abrasive feed) + 4.383*(stand-off distance*stand-off distance) + 0.000225*(traverse speed*abrasive feed) – 0.06717*(traverse speed*stand-off distance) (1)

SR = 4.049 + 0.1024*traverse speed + 0.002020*abrasive feed – 1.5*stand-off distance – 0.000246*(traverse speed*traverse speed) + 0.000001*(abrasive feed*abrasive feed) + 0.2450*(stand-off distance*stand-off distance) – 0.000042*(traverse speed*abrasive feed) –

0.007833*(traverse speed*stand-off distance) (2)

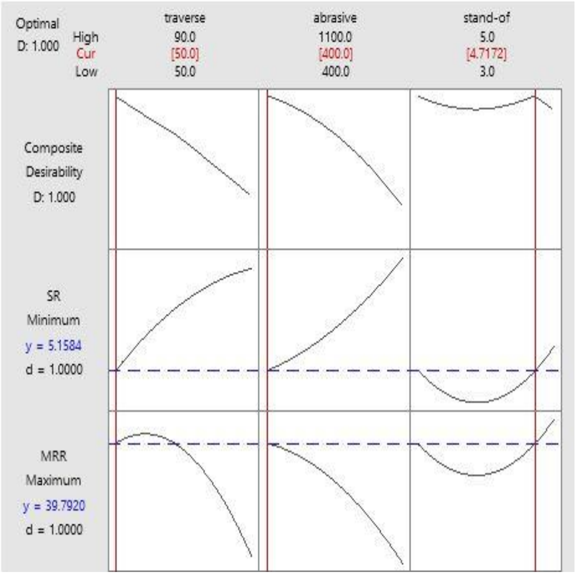

Figure 5. PARETO graph

Apart from optimization, contribution of each factor towards response is calculated using analysis of variance (ANOVA). Contribution of each process parameter towards any particular response helps in identifying the significance of a factor. Table 7. gives the result of ANOVA for MRR and Table 8. gives the result of ANOVA for SR. From the results of ANOVA, it is clear that all the process parameters affect the responses. For surface roughness, abrasive feed has a significant contribution of 83.5% while traverse speed and stand-off distance have sub-significant contribution of 78.6% and 48.9% respectively. In case of material removal rate, the effect of stand-off distance is significant with a contribution of 12.6% while traverse speed and abrasive feed are sub-significant with contribution of 3.6% and 3.9% respectively.

Comparatively, the process parameters influence surface roughness to a greater extent than material removal rate. The effect of process parameters on MRR can be neglected also.

Table 7. Analysis of variance for MRR

Source	DF	Adj SS	Adj MS	F-value	P-value
Traverse speed	2	115.043	57.521	26.48	0.036
Abrasive feed	2	107.904	53.952	24.83	0.039
Stand-off distance	2	30.065	15.032	6.92	0.126
Error	2	4.345	2.172		
Total	8	257.357			

Table 8. Analysis of variance for SR

Source	DF	Adj SS	Adj MS	F-value	P-value
Traverse speed	2	0.08549	0.04274	0.27	0.786
Abrasive feed	2	0.06202	0.03101	0.2	0.835
Stand-off distance	2	0.32722	0.16361	1.05	0.489
Error	2	0.31309	0.15654		
Total	8	0.78782			

IV. CONCLUSION

The aim of this experimental study to manufacture the AA6061-7.5%SiC MMC using two-step stir casting method and to machine the casted component using AWJM technique by optimizing the process parameters (traverse speed, abrasive feed and stand-off distance) to obtain lower surface roughness and higher material removal rate is achieved.

1. Manufactured AA6061-7.5% SiC MMC using two step stir casting technique.

2. Machined using AWJ machine, according to the design of experiments developed by Taguchi method.
3. Optimized process parameters using Taguchi & RSM and ranked the contribution of factors using ANOVA.
4. Higher material removal rate is possible when traverse speed is 70 mm/min, abrasive feed is 400 g/min and stand-off distance is 3 mm. Stand-off distance has a significant effect on MRR where as abrasive feed and traverse speed are sub-significant.
5. Lower surface roughness corresponds to 50 mm/min of traverse speed, 400 g/min of abrasive feed and 4 mm of stand-off distance. Abrasive feed has a significant contribution for surface roughness where as traverse speed and stand-off distance are sub-significant.
6. 50 mm/min of traverse speed, 400 g/min of abrasive feed and 4.7172 mm of stand-off distance constitute the optimal set of process parameters that lead to surface roughness of 5.1584 μm and material removal rate of 39.792 mm^3/sec.
7. The influence of factors on MRR is negligible when compared to the influence of factors on SR.

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