

Process parameter optimization of Al/SiC metal matrix composites during ultrasonic machining process

Bikash Banerjee^{1*}, Arindam Chakraborty², Somnath Das², Debabrata Dhupal¹

¹Department of Production Engineering, Veer Surendra Sai University of Technology, Odisha 768018, India

²Mechanical Engineering Department, Swami Vivekananda Institute of Science and Technology, Kolkata 700145, India

Abstract: Metal matrix is highly acceptable composites providing good strength for industrial use. In many field of industries, especially aerospace industry metal matrix composites of type Al/SiC is used because of its superior properties. In this research work, experimental analysis has been done for producing through hole on metal matrix composites with suitable quality ultrasonic machining (USM) process. Three unconstrained process parameters are chosen, like abrasive slurry concentration, power rating sand tool feed rate. Material removal rate (MRR) is considered as response parameter. The effects of each parameter have been analyzed here. Analysis of variance (ANOVA) has also been applied to identify the most significant factor. Response surface methodology (RSM) has been utilized to developed empirical model for determine the performance of ultrasonic process. Optimization technique has been used to find out the maximum process MRR. Confirmation verification test has been done to improve optimal parametric condition for getting maximum MRR. This research paper gives viability application of USM process for producing of through hole on metal matrix composites and various applications in industry.

1 Introduction

Physical or chemical properties of work piece does not affect by keeping the whole microstructure unchanged during Ultrasonic machining (USM). To machined very complex shapes of work piece, high accuracy and the precision ultrasonic machine are used. The material removal rate of USM depends on four parameters: such as slurry, work piece, tool, and machine-related factors. The material removal process is known as the secondary manufacturing process because this process provides the final shape and size with tighter control on dimension. This process is also divided into two groups; traditional and non-traditional processes. Hard and brittle materials are not machined in the traditional machining process that is why USM is used. The mechanism of USM is based on electric current at given amplitude that fits within the field of ultrasounds which is converted electrical into mechanical vibration that is transferred to a machining tool. Material is removed from the work piece such as; ceramics, quartz, precious stone, and graphite) is done by using axially vibrating frequency (15 kHz to 25 kHz) takes place. The ultrasonic machining process is widely used as a non-conventional machining process for machining hard, brittle, and electrically non-conductive material by abrasive grit particles [1]. Like other machining processes USM does not heated the work piece surface. During non-traditional machining process like EDM, ECM etc. electrically non-conductive materials cannot be machined, that is why USM is used because this process does not depend on electrically conductive material [2-5]. Whisker reinforced material composites have higher fracture

toughness. Values of material removal rate are yielded higher when fracture toughness is low. For better surface integrity in ultrasonic machining higher flexural strength is important [6]. Using a stationary ultrasonic machine brittle and hard materials scraping away. It is observed that machining rate is decreases with the increase of material hardness [7]. The work piece material properties during ultra sonic machining with different controlled process parameters like abrasive material, grain size, tool design has been chosen on basis of output parameters like, material removal rate, tool wear and penetration rate on six different work piece samples and three different cutting tools. While machining in USM it was found that work piece tool long time for machining with high value of toughness. Too wear is more when materials have high hardness and toughness where as tool wear is less for softer and brittle work materials [8]. Material removal mechanism, mainly for brittle structure form machined surface topology under various cutting parameters after applying RUFM on advanced ceramic has been studied [9]. Dynamic cutting force model with changing of cutting angle after survey on rotary ultrasonic milling of C/SiC in softer mode is analyzed [10]. Scratch grooves deformation characteristics of ductile and brittle materials are obtained. It disclosed that increase material removal proportion, reduced scratch loads, and effectively inhibit small crack generation when during ultrasonic vibration occurred [11]. Analyzing the machining of optical glass of brittle and ductile materials, specific cutting energies are consumed which defined cutting depth [12]. Ultrasonic assisted vibration test surface of work piece samples are damage and concluded that by the

* Corresponding author: author@e-mail.org

controlling the process parameters of RUFM surface quality could be improved achieve a ductile regime [13]. Some models measured the machining rate and also observed the effects of process parameters on tool wear rate, material removal rate and surface finish [14]. Simulation model using mesh free smooth hydrodynamics particles in ultrasonic machining process and stated the two abrasive particles and their interaction methods and effects on work piece surface crack formation [15]. A novel horn design is proposed and analysis for ultrasonic machining using ANSYS [16]. Machining of GFRP is become very important to researchers because of its wide range of applications in different sectors. High-speed machining (HSM) is a very useful process in manufacturing for its good behavior like higher productivity and lower production cost [17-18]. Various effect of high-speed drilling in GFRP is investigated. The result shows that in GFRP material drilling, high-value spindle speed is used to obtain a higher material removal rate [19]. Basic principle of the USM process and various process parameters affect material removal rate, tool wear rate, and surface finish is investigated [20]. Investigated USM on alumina bio-ceramic for stepped hole fabrication. The result shows that some process parameters like abrasive grit size, power rating, and slurry concentration are most important to achieve a better material removal rate and good accuracy [21]. Various effects on the drilling of GFRP material workpiece vibration during machining has been studied [22]. Designed and developed a tool for holding arrangement. Various investigations have been carried out about the USM process on Metal matrix composites. Experimental analysis has been performed to Producing the stepped hole in metal matrix composites, to achieving desired output characteristics like MRR [23]. In this research paper ultrasonic drilling operation has been performed by varying different USM process parameters like power rating, tool feed rate and slurry concentration. Main objective is to maximize the MRR to find out the most significant factor. RSM is used for optimization and modeling of quality characteristics. Experimental results are validated by USM process optimization.

2 Arrangement of Experimental setup according to Response surface methodology

Electrical energy which has high frequency is transformed into mechanical vibration during USM process. Transmitting motion is converted in tool and the horn. USM setup used in experiment purpose is shown in figure 1.



Fig.1. Ultrasonic Machining setup used for experimentation

Free abrasive slurry particles are supplied by pumping between tool and workpiece. This free abrasive grit particle provide effective material removal rate. In this experimental work the Aluminium (Al) powder and Silicon (SiC) carbide are used in where Al is used as matrix material and SiC is used as reinforcement material. Abrasive slurry (SiC 200 mesh) is used to optimize the process and parameter of Ultrasonic Machining (USM). Machining setup which is used during USM process is shown in Figure 1. There is no direct contact between tool and workpiece materials during experimentation by USM process; as a result work piece material is not heated up. In this research work SONIC-MILL Ultrasonic machine is used with vibration frequency 25 kHz and 25 μm amplitude. RSM methodology is used to perform USM process on metal matrix composites material for through hole generation. Second order polynomial equation model was developed. Model as follows:

$$Z_u = \alpha_0 + \sum_{j=1}^n \alpha_j x_{ju} + \sum_{j=1}^n \alpha_{jj} x_{ju}^2 + \sum_{j<i=2}^n x_j x_i + \epsilon_u \quad (1)$$

From above equation it is noted that Z_u is response, x_{ju} is the coded value of l_{th} number of machining controlled process parameters. The idioms α_0 , α_j , α_{jj} , and α_{ji} are the regression coefficients, ϵ_u is the error of the k_{th} number of experiment. Process parameters are selected based on literature review. A Pilot experiment has done at the beginning. In this experiment three constituents with three amounts have considered. Table 1 shows the process parameters for conduction experiment. Different controlled process parameters have been chosen for conduction of experiment such as, slurry concentration, power rating and tool feed rate is shown in table 1. Table 2 shows the design of experiment matrix (DOE) of process parameters and various obtained response.

Table 1. Process parameters for conduction experiment

Constrained process parameter	Unit	Level		
		1	2	3
Abrasive slurry Concentration	g/l	35	40	45
Power rating	v	35	55	75
Tool feed rate	mm/min	0.96	1.20	1.32

Table 2. Obtained results of MRR according to process parameters

Exp No.	Abrasive slurry Concentration (g/l)	Power rating (v)	Tool feed rate (mm/min)	MRR
1	35	35	0.96	0.54
2	35	35	1.2	0.89
3	35	35	1.32	1.77
4	35	55	0.96	0.79
5	35	55	1.2	1.21
6	35	55	1.32	0.97
7	35	75	0.96	1.11
8	35	75	1.2	0.68
9	35	75	1.32	0.91
10	40	35	0.96	1.01
11	40	35	1.2	0.86
12	40	35	1.32	0.52
13	40	55	0.96	0.41
14	40	55	1.2	0.88
15	40	55	1.32	1.2
16	40	75	0.96	1.11
17	40	75	1.2	1.29
18	40	75	1.32	0.68
19	45	35	0.96	0.59
20	45	35	1.2	0.87
21	45	35	1.32	0.66
22	45	55	0.96	0.43
23	45	55	1.2	1.19
24	45	55	1.32	0.96
25	45	75	0.96	1.21
26	45	75	1.2	0.78
27	45	75	1.32	0.89

Material removal rate has been calculated for every set of experiment by utilize this equation:

$$MRR = \frac{X_1 - X_2}{M} \quad (2)$$

Where, X_1 is weight before machining of the workpiece, X_2 is weight after machining of the workpiece and M is the total machining time.

3 Empirical model developments for procedure of benchmark

Minitab 18 software is used for analyzed the estimated response and developed a mathematical model with suitable parameters. Figure 2 shows the Schematic diagram of USM process.

Empirical model for material removal rate is:

$$Y_{MRR} = 0.9041 + 0.0815 \text{ Slurry Concentration}_{35} - 0.0196 \text{ Slurry Concentration}_{40} - 0.0619 \text{ Slurry Concentration}_{45} - 0.0474 \text{ Power rating}_{35} - 0.0107 \text{ Power rating}_{55} + 0.0581 \text{ Power rating}_{75} - 0.1041 \text{ Tool feed rate}_{0.96} + 0.0570 \text{ Tool feed rate}_{1.20} + 0.0470 \text{ Tool feed rate}_{1.32} \quad (3)$$

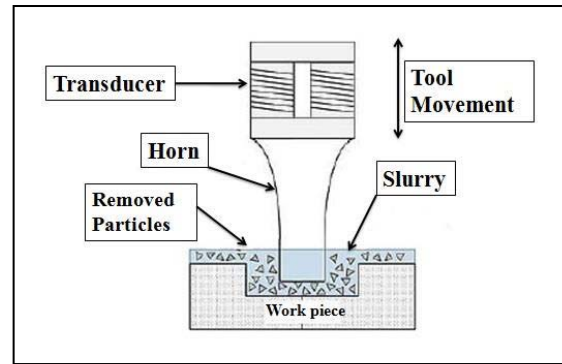


Fig. 2. Schematic diagram of USM process

4 ANOVA for testing the model

Table.2 shows the experimental result by using Taguchi's L27 orthogonal array. Taguchi statistical method has been used to improve the quality of products by optimizing the process parameters. Orthogonal array and 3-way analysis of variance are the two important methods in Taguchi. To determine, the output parameter like material removal rate, the input parameters like abrasive slurry concentration, power rating, and tool feed rate have been assigned in the machining process as discussed in an earlier section. To calculate the most significance machining parameters on MRR 3-way ANOVA has used. Some machining parameter has more significant than others. Using this ANOVA result, the percentage contribution of various sources has computed to justify the most important machining parameters. Minitab 18 Software has been used to perform 3-way ANOVA.

Table 3. 3-way ANOVA results for material removal rate

Sources	D F	Adj SS	Adj MS	F-Value	P-Value
Model	6	6.29602	0.04934	0.47	0.823
Linear	6	6.29602	0.04934	0.47	0.823
Slurry Concentration	2	0.09765	0.04883	0.46*	0.635
Power rating	2	0.05170	0.02585	0.25	0.784
Tool feed rate	2	0.14667	0.07334	0.708*	0.510
Error	20	2.10283	0.10514		
Total	26	2.39885			

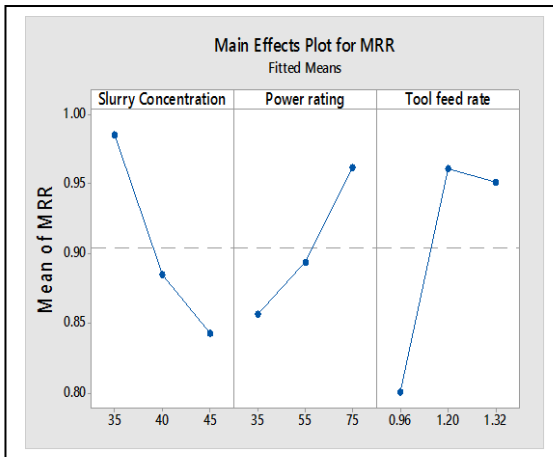


Fig. 3. Mean effect plot for MRR

From Figure 3 and 4, it is observed that by adjusting various process parameters like slurry concentration, power rating, and tool feed rate, the MRR may be controlled. It is observed that average MRR shows when slurry concentration is 40 g/l. The 3-way ANOVA result for MRR is shown in Table. 3.

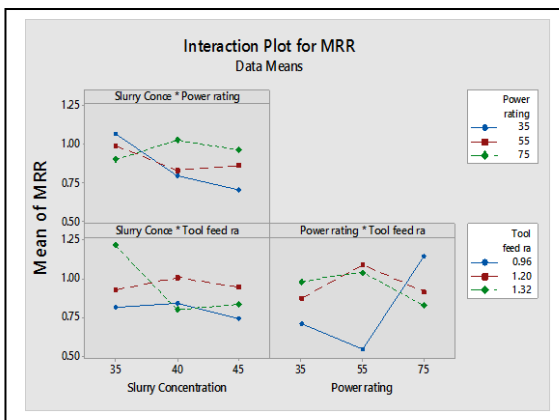


Fig. 4. Interaction plot for MRR

From table 3 it is observed that slurry concentration and tool feed rate are the most important process parameter in ultrasonic drilling during the material removal process of Al/SiC metal matrix material. It is also observed that power rating is a less significant parameter. From the ANOVA table it is observed that P-value and F-value show tool feed rate is more important compare to slurry concentration and power rating. It is also noticed from Figure 3 that, MRR is decreasing with the increase of material thickness, and MRR increases with the increase of slurry concentration. Another observation is that MRR increased linearly with the increase of thickness but MRR increases linearly with the increase of power rating and tool feed rate. Figure 4 stated that the interaction plot for MRR and it also shows that a lower tool feed rate has higher MRR. Friction between abrasive grit and the work piece is increasing with the increase of thickness. MRR is decreasing due to friction. MRR increases with the increase of voltage which has high momentum and impact on abrasive particles before distinct the work piece at high amplitude. Energy increases with high

momentum where abrasive grit hits the work piece surface that is why micro crack is occurred and affects the work piece surface. In this way MRR is increasing. The high-velocity force hit the work piece surface. Generated impact at work piece surface leads to an increase in the MRR concerning pressure. Figure 5 shows the actual versus predicted value for MRR. That means response of MRR in versus order between observation order (experimental results) and predicted value.

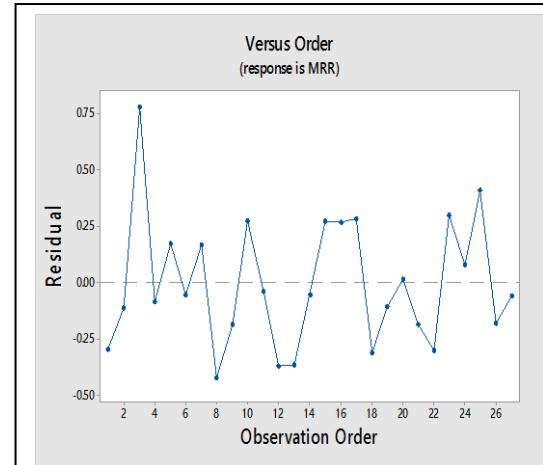


Fig. 5. Residual versus observation order for MRR

The normal probability graph whose response is MRR is shown in figure 6. From this figure it is expected that all experimental data are normally distributed. Plot for Residual versus fitted value is shown in figure 7. From this graph, it is stated that residuals are fitted in a straight line. It is also observed that all the errors are spread in a normal distribution. Therefore residual means difference between observed values (taken from experiment) and predicted value or fitted values have been observed.

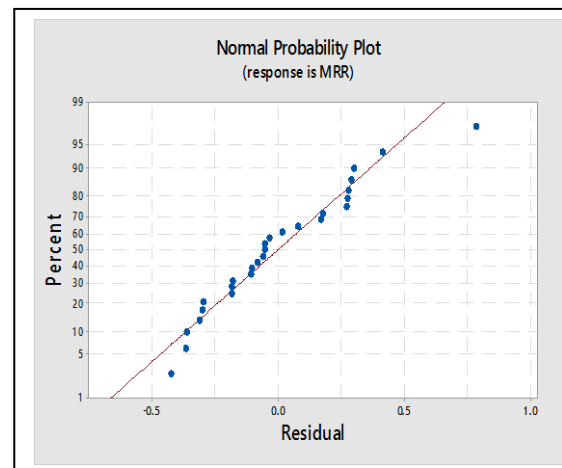


Fig. 6. Normal probability graph for MRR

From figure 5, 6 and 7 it is revealed that empirical developed model is acceptable for obtained response results.

5 Investigation of process parameters on material removal rate

Various optimization analysis has been done to determinate the impact of the unconstrained process parameters liketool feed rate, abrasive slurry concentration, power rating and on the machining response parameter i.e., is material removal rate (MRR).

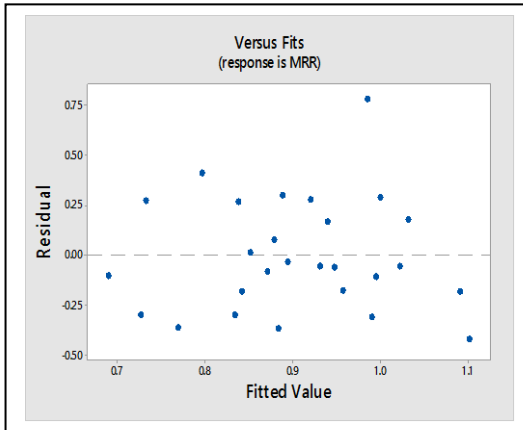


Fig. 7. Residual versus fitted value graph for MRR

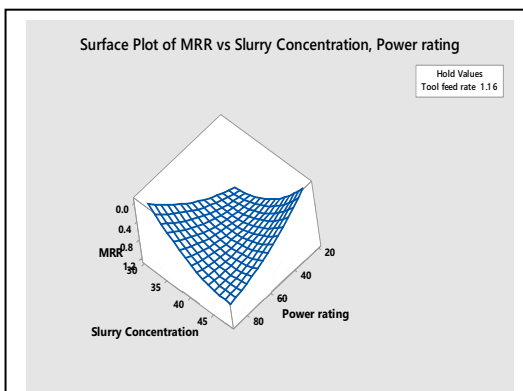


Fig. 8. Response surface for the influence of slurry concentration and power rating on MRR

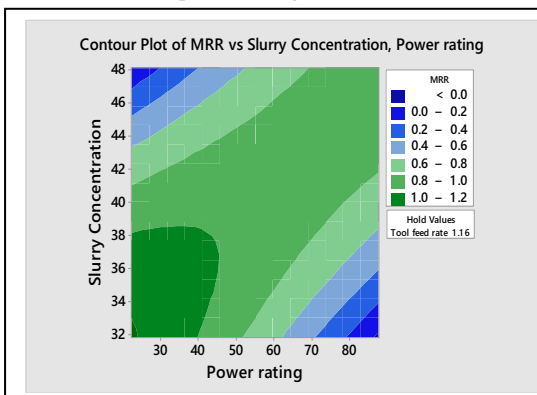


Fig. 9. Contour plot for the influence of slurry concentration and power rating on MRR

Through hole is done by USM process based on empirical model which was established through response surface plot and contour plot. Figure 8 shows the response surface graph for inspected the impact of slurry concentration and power rating on MRR during USM, while tool feed rate is taken as fixed value, i.e., 1.20 mm/min. From this plot it is stated that high MRR is

depends on abrasive slurry concentration. High value MRR is procured when abrasive slurry concentration is high. Total mass of abrasive particles is more for higher value of abrasive slurry concentration, so applied force on workpiece by abrasive particles also high. As a result MRR is high. It is also shown that power rating plays an important role during machining. Figure 9 shows the contour plot for exploration the impact of slurry concentration and power rating on MRR. Every contour plot represents the boundless number of contribution of two process variables. From figure 9 it is observed that power rating has less effect on MRR. MRR mostly depends on abrasive slurry concentration.

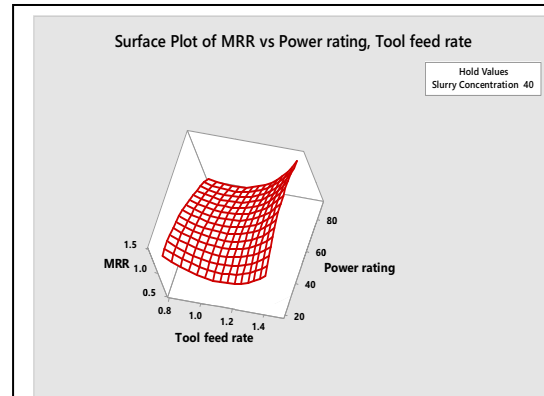


Fig. 10. Response surface for the influence of tool feed rate and power rating on MRR

Figure 10 shows the response surface plot for analyzing the impact of tool feed rate and power rating on MRR during USM, while slurry concentration taken as constant value, i.e., 40 g/l. From this figure it is observed that MRR is increases if tool feed rate increased. It is evident that high tool feed rate value gives more impact on workpiece surface. From this figure it is also stated that value of MRR is high according to higher value of power rating. High voltage provides high power to abrasive particles to hit the workpiece surface. Figure 11 shows the contour plot for exploration the impact of tool feed rate and power rating on MRR during USM. There is most important interlink age between two process parameters, i.e., power rating and tool feed rate.

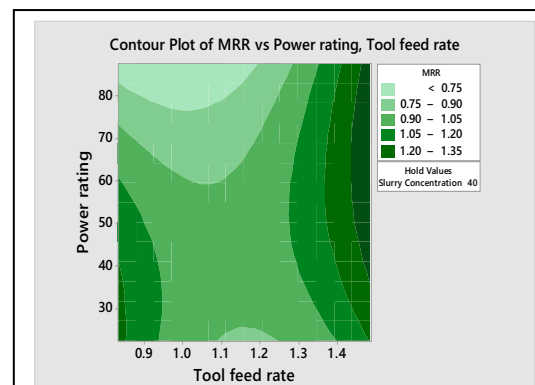


Fig. 11. Contour plot for the influence of tool feed rate and power rating on MRR

Both power rating and tool feed rate are most important process parameters. To achieve higher value

of MRR, the high value of tool feed rate and power rating are suggested.

Conclusion

In this research work the analysis and optimization of process parameters of USM for generating through hole on metal matrix composites have been discussed. Developed empirical models, response surface and contour plot from ANOVA have been done. Depends on experimental investigations and simulation model in ultrasonic machining of aluminium and silicon composites following conclusion can be made.

Maximum value of MRR is obtained when value of tool feed rate and slurry concentration are high. Low value of power rating gives minimum value of MRR. These results indicate that tool feed rate and slurry concentration are the most important parameters for removing metal from the metal matrix composites. It is also observed that power rating is less significant during this process.

The present research article on aluminium and silicon metal composite for through hole generation will give fruitful details about the best process parameter setting to bring of required performance.

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