Journal of Basic and Applied Engineering Research
Print ISSN: 2350-0077; Online ISSN: 2350-0255; Volume 1, Number 2; October, 2014 pp. 79-83

http://www.krishisanskriti.org/jbaer.html

Optimization in Drilling of MMC Composites: A Case Research

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Abstract: **The metal matrix composite (MMC) Aluminum silicon carbide has widespread application in aerospace, automotive and electronics engineering due to its excellent properties like high toughness, low weight to volume ratio, high strength, etc. Drilling is one of most common conventional machining processes being applied on MMCs. For obtaining high product quality and satisfactory process performance yield it is indeed necessary to control and optimize several drilling parameters. Taguchi's philosophy has been manly concerned with optimization of single objective function, whereas drilling involves multi-response characteristics viz. thrust force, torque and circularity at entry and exit; hence exploration of an appropriate multi-objective optimization technique is certainly essential. This paper reports the application of PCA-Grey integrated with Taguchi method to obtain an optimal parametric combination in drilling of Al-20%SiCp composites. First, Principal Component Analysis (PCA) has been implemented for evaluation of correlation between various performance characteristics (process output). Then grey analysis which has been efficiently applied to convert principal components into a single objective function (overall grey relation grade). The overall grey relation grade (OPI) which has been finally optimized by Taguchi method.**

1. INTRODUCTION

Metal matrix composite has widespread applications because of its excellent properties like high strength, fracture toughness and stiffness which draw a quite more attention now-a-days. More emphasis has been given for development of lighter MMCs using aluminum matrix and SiC reinforcement due to the significant potential of improvement in the thrust-to-weight ratio; suitable for aerospace and automobile applications. Hence, it is important to know the machinability behavior of these composites. Out of several conventional method of machining, drilling is mainly considered to study machinability aspects of these composites. Researchers highlighted the effect of drilling parameters such as drill speed, feed rate, drill diameter, type of drill etc. and examined to get an optimal parametric combination to improve the properties of these composites as well as to reduce experimental cost. Ahamed et al. [1] focused on drilling of Al-5% SiCp-5% B4Cp hybrid composite with high-speed steel (HSS) to minimize tool wear and improve surface finish. It was noticed that drilling of Al-5%SiC-5%B4C composites with HSS drills was possible with lower speed and feed combination. Basavarajappa et al. [2] concentrated on the influence of cutting parameters on thrust force, surface finish, and burr formation in drilling Al2219/15SiCp and Al2219/15SiCp-3Gr composites fabricated by the liquid metallurgy method. The tools used were commercially available carbide and coated carbide drills. The results revealed that feed rate had a major influence on thrust force, surface roughness, and exit burr formation. Graphitic composites exhibited lesser thrust force, burr height, and higher surface roughness when compared to the other material and it was due to the solid lubricating property of the graphite particles. The higher surface roughness value for Al2219/15SiCp-3Gr composite was due to the pullout of graphite from the surface. Davim [3] investigated the influence of cutting parameters (cutting velocity and feed rate) and cutting time on drilling of metal matrix composites. Taguchi based experiments were performed on controlled machining with cutting conditions prefixed in work pieces. Correlation between cutting velocity, feed rate and the cutting time with the evaluator the tool wear, the specific cutting pressure and the holes surface roughness was established by using multiple linear regressions analysis.

Dhavamani et al. [4] emphasized to determine the optimum machining condition for maximizing metal removal rate and minimizing the surface roughness in drilling of Aluminum Silicon Carbide (AlSiC) by using Desirability function approach. An attempt was made to establish a comprehensive mathematical model for correlating the interactive and higher-order influences of various machining parameters using Taguchi method. A multiple regression model was used to represent relationship between input and output variables and a multi-objective optimization method based on a Genetic Algorithm (GA) was used to optimize the process. Haq et al. [5] implemented a new approach for the optimization of drilling parameters on drilling Al/SiC metal matrix composite with multiple responses based on orthogonal array with grey relational analysis. Experiments are conducted on LM25-based aluminum alloy reinforced with green bonded silicon carbide of size 25 μm. Drilling tests were carried out using TiN coated HSS twist drills of 10 mm diameter under dry condition. Drilling parameters viz. cutting speed, feed and point angle were optimized with the considerations of multi-responses such as surface roughness, cutting force and torque. Mayyas et al. [6] used multiple regression analysis (MRA) and artificial neural networks (ANN) to investigate the influence of some parameters on the thrust force and torque in the drilling processes of self-lubricated hybrid composite materials. In this model cutting speed, feed, and volume fraction of the reinforcement particles were used as input data and the thrust force and torque as the output data. ANNs showed better predictability results compared to MRA due to the nonlinearity nature of ANNs. The statistical analysis accompanied with artificial neural network results showed that Al2O3, Gr and cutting feed (f) were the most significant parameters on the drilling process, while spindle speed seemed insignificant. Rajmohan et al. [7] used Taguchi method with grey relational analysis to optimize the machining parameters with multiple performance characteristics in drilling hybrid metal matrix Al356/SiC-mica composites. Experiments were conducted on a CNC vertical machining center and L18 orthogonal array was chosen for the experiments. The drilling parameters namely spindle speed, feed rate, drill type and mass fraction of mica were optimized based on the multiple performance characteristics including thrust force, surface roughness, tool wear and burr height (exit) and found that the feed rate and the type of drill were the most significant factors which affect the drilling process.

Ramulu et al. [8] studied the behavior of process parameter on machining Al2O3 aluminum-based metal matrix composites using different drills (high-speed steel, carbide-tipped, and polycrystalline diamond (PCD) drills). The drilling characteristics were evaluated in terms of drilling forces, tool wear, chip formation, and drilled-hole quality. It was found that PCD drills outperformed all other drills in terms of drilled-hole quality and minimum drilling forces induced. Somasundaram et al. [9] carried out comprehensive analysis on friction drilling of Al/SiCp metal matrix composites. The parameters considered for the experiment were: the composition of work piece, work piece thickness, spindle speed, and feed rate. The effect of parameters on roundness errors was analyzed using experimental design matrix and empirical relation between the process parameters and roundness error is established using response surface methodology. Shivapragash et al. [10] focused on multiple response optimization of drilling process for composite Al-TiBr2 to minimize the damage events occurring during drilling process. Taguchi method with grey relational analysis was used to optimize the machining parameters with multiple performance characteristics in drilling of MMC Al-TiBr2 and found that the maximum feed rate, low spindle speed are the most significant factors which affect the drilling process and the performance in the drilling process can be effectively improved by using this approach.

Literature highlights that immense effort were put by pioneer researchers to optimize various process parameters during machining operation of MMC composites. Motivated by this, present work aims to add value to the previous research and proposes application of PCA-grey approach integrated with Taguchi philosophy for simultaneous optimization of quality of holes in drilling of Al-20%SiCp composites.

2. EXPERIMENTAL DESIGN

Drilling of Al-20%SiCp composites of diameter 25 mm has been carried on CNC drilling machine [MAXMILL 3 axis CNC machine with FANUC Oi Mate MC Controller, Model No. CNC 2000EG]. In this study, effects of drilling parameters (such as drill speed, feed rate and drill diameter each varied in three different levels; as shown in Table 1) has been highlighted on different machining performance features namely thrust force, torque, circularity (at entry and exit) of the drilled hole. Taguchi has been mainly concerned for designing of experiments as it requires the less number of experiments which reduces the operating cost. Here, L9 orthogonal array has been used as shown in Table 2. Thrust force and torque has been evaluated by using Digital Drilling Tool Dynamometer [Make: Medilab Enterprises, Chandigarh, INDIA], whereas circularity has been measure by using Image processing technique in MATLAB.

Table 1: Domain of Experiments

Factors	Unit	Level 1	Level 2	Level 3
DrillSpeed	RPM	500	750	1000
Feed rate	mm/min	50	100	150
Drilldiameter	mm	5	6	8

Table 2: Design of Experiments

Sl.No.	Drill Speed (RPM)	Feed Rate (mm/min)	Drill Diameter (mm)
1	500	50	5
2	500	100	6
3	500	150	8
4	750	50	6
5	750	100	8
6	750	150	5
7	1000	50	8
8	1000	100	5
9	1000	150	6

3. METHODOLOGY

Step 1: Collection of Experimental data: Aforesaid machining performance evaluation characteristics viz. thrust force, torque, circularity at entry and exit has been obtained for each experimental run.

Table 2: Experimental Data

Sl.No.	Thrust force (KN)	Torque (KN-m)	Circularity (in)	Circularity out
1	1.509	2.45	0.899563	0.921397
2	3.136	2.4206	0.925190	0.914893
3	3.616	6.664	0.926926	0.910740
4	4.116	1.8718	0.893270	0.923538
5	2.499	6.272	0.969112	0.969411
6	3.684	6.86	0.894751	0.941456
7	2.254	7.938	0.9328	0.895282
8	2.136	6.958	0.956107	0.989500
9	2.048	2.254	0.882489	0.941998

Step 2: Data pre-processing: As optimal value of a quality characteristic is too enormous; experimental data should be normalized to eliminate these types of effects. Normalization can be done according to the following equation:

Higher-is-Better (HB) $$X_i^* = \frac{\hat{y} - y_{min}}{y_{max} - y_{min}} \quad (1)$$

Lower-is-Better (LB) $$X_i^* = \frac{\hat{y} - y_{max}}{y_{min} - y_{max}} \quad (2)$$

Here y_{min} denotes the lower experimental value of $\hat{y}$, the y_{max} represents the upper experimental value of $\hat{y}$

Step 3: Application of PCA for assessing the quality loss estimates [11-12]: Assess the Eigen value λ_k and the corresponding Eigen vector β_k $(k = 1,2,3,..........n)$ from the correlation matrix formed by all the quality characteristics and also compute principal component scores of the normalized reference sequence and comparative sequences using the equation shown below:

$$Y_i(k) = \sum_{j=1}^{n} X_i^*(j)\beta_{kj}, i = 0,1,2....,m, k = 1,2,3...,n \quad (3)$$

Here, $Y_i(k)$ is the principal component score of the k^{th} element in the i^{th} series. Let, $X_i(j)$ be the normalized value of the j^{th} element in the i^{th} sequence, and β_{kj} is the j^{th} element of the Eigen vector β_k.

Step 4: Application of Grey Analysis for evaluating overall Grey relation grade:

Individual grey coefficient has been assessed by using as:

$$\gamma_{ij} = \frac{\Delta_{min} + \tau\Delta_{max}}{\Delta_{0i}(j) + \tau\Delta_{max}} \quad (4)$$

Here, $\Delta_{0i}(j) = \left| y_0(j \quad y_i(j)) \right|$, $\Delta_{min} = \min_i \min_j \Delta_{0i}(j)$,

$\Delta_{max} = \max_i \max_j \Delta_{0i}(j)$, $i = 1,2,........,m \quad j = 1,2,.......n$

$\tau \in [0,1]$ the distinguishing coefficient, usually, $\tau = 0.5$

The overall grey relational grade computed as: $R_i = \frac{1}{n}\sum_{j=1}^{n} \gamma_{ij}$ (5)

Step 5: Implementation of Taguchi for determining optimal parametric combination:

Finally, Taguchi has been adopted on overall grey relation grade to obtain the optimal machining condition. Higher-is-better criterion of Taguchi has been taken in consideration to maximize the overall grey relation grade.

$$S/N = 10\log \frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2} \quad (HB) \quad (6)$$

Here, n is the number of measurements, and y_i the measured i_{th} characteristic value i.e. i_{th} quality indicator.

4. DATA ANALYSIS

Experimental data presented in Table 3 have been analyzed by following aforesaid procedures. Experimental data has been normalized firstly to convert all response dimensions into a common scale within the range 0 to 1. For the thrust force and torque; Lower-is-Better (LB) has been considered whereas for circularity Higher-is-Better (HB) has been taken in consideration. The normalized data has been shown in Table 4. Then, principal component analysis has been implemented for checking the correlation among the responses. Eigen value and Eigen vector has been computed and it has been noticed from Table 5 that first three principal component has major contribution and fourth principal component has negligible effect. The principal components for each experimental run has been calculated and shown in Table 6. The quality loss has been determined and shown in Table 7. After that, grey relation has been implemented to obtain individual grey relation coefficient (Table 8). Table 9 represents the overall grey relation grade; Finally, Taguchi has been adopted for evaluating the optimal machining condition as (shown in Fig. 1). It has been observed that predicated S/N ratio for $N_{1000}f_{100}d_5$ has highest value among all computed S/N ratios.

Table 4: Normalized Data

Sl. No.	Thrust force	Torque	Circularity (in)	Circularity out
Ideal	**1**	**1**	**1**	**1**
1	1	0.9046	0.1971	0.2771
2	0.3759	0.9095	0.4929	0.2081
3	0.1917	0.2100	0.5129	0.1640
4	0	1	0.1244	0.2999
5	0.6203	0.2746	1.0000	0.7867
6	0.1654	0.1777	0.1415	0.4900
7	0.7142	0	0.5807	0
8	0.7593	0.1615	0.8498	1
9	0.7932	0.9369	0	0.4958

Table 5: Eigen value, Eigen vector, AP and CAP

	PC1	PC2	PC3	PC4
Eigen value	**1.8911**	**1.0644**	**0.7134**	**0.0657**
Eigen vector	$\begin{vmatrix} -0.262 \\ 0.531 \\ 0.645 \\ 0.482 \end{vmatrix}$	$\begin{vmatrix} 0.777 \\ 0.508 \\ 0.152 \\ -0.340 \end{vmatrix}$	$\begin{vmatrix} 0.559 \\ -0.322 \\ -0.076 \\ 0.760 \end{vmatrix}$	$\begin{vmatrix} -0.126 \\ .0.597 \\ -0.745 \\ 0.271 \end{vmatrix}$
AP	0.473	0.266	0.178	0.083
CAP	0.473	0.739	0.917	1.000

Table 6: Major Principal Components

Sl. No.	PC1	PC2	PC3
Ideal	1.396	1.097	0.921
	0.479126	1.172293	0.46338
	0.802755	0.758298	0.038025
	0.471257	0.277846	0.125274
	0.75583	0.424945	-0.10352
	1.007548	0.505981	0.780275
	0.37855	0.073687	0.396955
	0.187473	0.643281	0.355145
	0.916989	0.461301	1.067894
	0.528712	0.923748	0.518546

Table 7: Quality loss (Δ_{ok})

Sl. No.	Δ_{01}	Δ_{02}	Δ_{03}
	0.916874	0.075293	0.45762
	0.593245	0.338702	0.882975
	0.924743	0.819154	0.795726
	0.64017	0.672055	1.024522
	0.388452	0.591019	0.140725
	1.01745	1.023313	0.524045
	1.208527	0.453719	0.565855
	0.479011	0.635699	0.146894
	0.867288	0.173252	0.402454

Table 8: Individual grey coefficients (γ_{ij})

Sl. No.	γ_1	γ_2	γ_3
	0.916874	0.075293	0.45762
	0.593245	0.338702	0.882975
	0.924743	0.819154	0.795726
	0.64017	0.672055	1.024522
	0.388452	0.591019	0.140725
	1.01745	1.023313	0.524045
	1.208527	0.453719	0.565855
	0.479011	0.635699	0.146894
	0.867288	0.173252	0.402454

Table 9: Overall grey coefficients (γ_{ij})

Sl. No.	R_i	SNRA1	PSNRA1
	0.775293	-2.21068	-1.34604
	0.662411	-3.57745	
	0.529844	-5.51704	
	0.572828	-4.83951	
	0.844098	-1.47214	
	0.541545	-5.32731	
	0.587097	-4.62580	
	0.806204	-1.87111	
	0.748483	-2.51636	

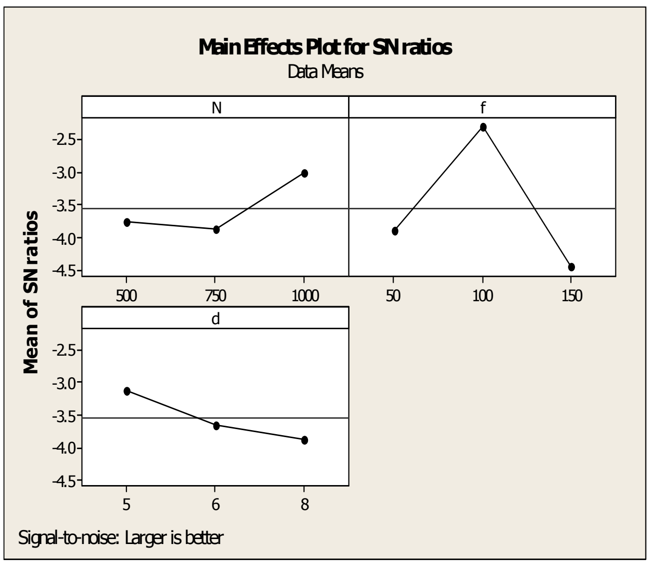

Fig. 1 Evaluation of optimal parametric combination

5. CONCLUSIONS

The present paper aims to determine the optimal parametric combination in drilling of Al-20%SiCp composites to produce good quality of holes. The effect of process parameter such as drill speed, feed rate and drill diameter has been investigated on thrust force, torque and circularity at entry and exit. In this study, grey based Taguchi method coupled has been found suitable method to handle a multi-objective optimization problem with PCA to eliminate response correlation and to convert a multi-objective optimization problem to a single response optimization by accumulating the principal components into the overall grey relational grade. The integrated approach presented in this paper can be effectively applied for continuous quality improvement and off-line quality control in any manufacturing process which involves multiple response characteristics correlated with each other.

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