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Experimental Investigation and Optimization of Machining Parameters using Grey-Relational Analysis Approach and Fuzzy Based Taguchi Loss Function Method

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Abstract

Objectives: The objective of present study is to investigate the machinability effect on turning of hybrid metal matrix composites (Al/SiC/B4C) by coated carbide inserts. Then the application of Grey-Relational Analysis approach (GRAA) and Fuzzy-Taguchi Loss Function (FTLF)are used for the optimization ofmulti quality criteria response is reported. **Methods/Statistical Analysis:** The bar type hybrid composite are fabricated using stir casting technique. The composite has356Alalloy as 'matrix' and 'SiC'with different wt%(volume fraction) of 5%, 10%, 15%and B4C (5%) particles as reinforcement material. Force (Fz) and roughness (Ra and Rt) are considered as two quality characteristics. L9orthogonal array, the ratio of signal to noise (S/N), multi-response performance characteristics (MPC), and variance test (ANOVA) are applied to investigate the quality characteristics for developed new composites. **Findings:** The optimal cutting parameters are determined using Grey-relational analysis Approach (GRAA) and fuzzy-Taguchi Loss Function (FTLF). Based on both approaches, the optimal levels of machining parameters are determined as A1B1C1D1.As a result, the grey relational analysis and the fuzzy-Taguchi method confirm the effectiveness for optimization of machining parameters with multiple quality criteria responses. Among these methods, fuzzy-Taguchi Loss Function (FTLF) is the most superior. **Application/Improvements:** In addition, the variance test (ANOVA)is identifies, the factor D (cutting depth) and C (feed rate),two influential parameters which account 55.77% and 69.8 % of the variance for grey-relational grade (GRA) and fuzzy- reasoning grade (FRG).

Keywords: Fuzzy, Grey Relational Apporach, Investigation, Optimization, Taguchi's Loss Function Method.

1. Introduction

Metal Matrix Composites (MMCs) are considered as a new class of engineering material due to its superior physical and mechanical properties compared to unreinforced alloys. Among the various MMCs particle reinforced Al-MMCs are found increasing application in structural and wear resistance components in automotive and aerospace industries[1-3]. The various reinforcements are used such as Al_2O_3[4-6,] and SiC[7-9].In this,particulateB_4C offers a good mechanical property and possesse slow density of about 2.52 g/cm^3 as close by that of aluminium series. Moreover, B_4C is the 3rd hardest material so that its maximum produced and used as hard ceramic material[10]. Due to high magnitude of hardness it offers an excellent choice for the preparation of compositeto have more wear resistance. As it also offers good chemical resistance and absorbs neutrons it finds away to use in nuclear reactors. Possible applications take in are transmission and brake disc components, automotive engines, air-frame components and bicycle frames[11-12]. Despite the benefits mentioned above, particulate embedded matrix (MMCs) found in commercial applications is limited due to the hard particles cause challenges in machining[13-14].

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Considerable researches on machinability or by mechanical testing is performed in the last two decades on developing a new composites with either single or multiple reinforcement MMCs. Hybrid particulate metal matrix composites (HPMMCs) are obtained by strengthening the base matrix aluminium alloy with more than one type of particulate reinforcements by captivating different properties. Premnath[15] studied the influence of feed rate, speed and volume fraction of alumina on the face milling of graphite reinforced hybrid composite using RSM and reported the speed is high influencing factor followed by feed rate and % reinforcement of ceramics. In[16] reported the optimization of machining parameters of fabricated Al/10%SiC/5%B_4C hybrid PMMC using taguchi's based desirability function analysis and found that the used technique gives a reasonable result. Many researchers attempted to study cutting tool wear for various cutting inserts found that the main wear is due to abrasion of hard reinforced particles in the MMCs irrespective the cutting tool selection. Most of the recent research work presents their experimental results with single reinforcement material. However, the information available is limited on the machinability of hybrid particulate metal matrix composites with the reinforcement of more than one materials[17-20]. The objective is to fabricate and study the machinability parameters along with volume fraction of SiC on two responses of force and roughness while machining thenew composite (Al/SiC/5%B4C) fabricated by stir casting method with different volume fraction of SiC with 5wt%B_4C. From the author's knowledge, no work has been found related to the grey-relational analysis approach and fuzzy-taguchi's loss function method (FTLM) for multi performance characteristics of hybrid composites.

2. Experimental Work

2.1 Fabrication of Mmcs

The hybrid particulate metal matrix composites (HPMMC) comprises Al356 aluminium alloy as a 'matrix'base alloy and B_4C with SiCas particle 'reinforcements'. Samples are prepared by stir casting route thereby embedding the B_4C (5%)with different ratio of volume fraction of SiC (5, 10, 15 wt.%). The fabrication procedure is as follows: 356Alingots is scrubbed using acetone and then the ingotis melted in an electric arc furnace around 700˚C. The B_4C and SiC are preheated to a temperature around 650˚Cwhose particle sizes arerange from 30 to 70 µm. Then preheated reinforcement is addedcontinuously to the melted ingot. The melt is stirred for about 15 min at 350 rpmwith help of a mechanical actuated stirrer. The cylindrical bar of dimension 35mmX200mm are obtained using stir casting method.

3. Methodology

The machining experiments are carried out according to Taguchi's L_9 orthogonal array. The machinability parameters of speed, feed and cutting depth and reinforcement parameter of volume fraction of SiC are considered as controllable factors for machinability investigation. Theeach of these factors with their varied levels is listed in Table 1. The selected cutting tool is designated with an ISO coding CNMG 120408 and mounted on PCLNR 2020M12 tool holder. Cutting force Fz was measured using 9257B type Kistler dynamometer. The Ra surface roughness is measured using Mhar surf test (Model GD120) instrument. According to Taguchi, optimal the process parameters are estimated by calculating the signal to noise ratio[21]. The present objective is to minimize the surface roughness and cutting force. Hence, lower-the-better case (LB) is used for calculating signal to noise ratio (S/N) ratio for quality characteristics[22]. The average surface roughness values (Ra and Rt) and cutting force measured and their S/N ratio are listed in Table 2.

Table 1. Parameters and their levels

Parameter, Symbol	Units	Levels		
		1	2	3
% reinforcement of SiC (A)	%	5	10	15
Cutting speed (B)	m/min	80	120	160
Feed rate (C)	mm/rev	0.118	0.174	0.235
Depth of cut (D)	Mm	0.4	0.8	1.2

4. Results and Discussion

4.1 Taguchi's Single Process Characteristics Optimization (Tspc)-Signal to Noise (S/N) Ratio Approach

From Table 3, feed and depth are two variables that shows highest 'max-min' values of 2.30 and 3.70 for Ra,

Table 2. Experimental results of surface roughness and cutting force

Exp. Run	Control factors				Average Response values			Mean S/N ratio		
	% reinforcement	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	R_a µm	R_t µm	F (N)	R_a (dB)	R_t (dB)	F (dB)
1	5	80	0.118	0.4	1.877	14.931	11.63	-5.469	-23.48	-21.31
2	5	120	0.174	0.8	2.963	22.603	65.93	-9.434	-27.08	-36.38
3	5	160	0.235	1.2	2.905	24.202	135.65	-9.264	-27.67	-42.64
4	10	80	0.174	1.2	3.440	25.916	75.84	-10.73	-28.27	-37.59
5	10	120	0.235	0.4	2.347	18.895	23.35	-7.409	-25.52	-27.36
6	10	160	0.118	0.8	2.728	22.625	96.13	-8.716	-27.09	-39.65
7	15	80	0.235	0.8	3.998	31.982	98.71	-12.03	-30.09	-39.88
8	15	120	0.118	1.2	2.403	20.219	53.12	-7.615	-26.11	-34.50
9	15	160	0.174	0.4	2.538	18.718	33.36	-8.091	-25.44	-30.46

Table 3. Analysis of S/N ratio

Cutting Parameters	Mean S/N ratio (dB)			Max – Min
	Level 1	Level 2	Level 3	
Surface Roughness (R_a)				
% reinforcement (A)	-8.056*	-8.952	-9.248	1.192
Cutting Speed (B)	-9.413	-8.153*	-8.690	1.260
Feed rate (C)	-7.267*	-9.419	-9.570	2.303
Depth of cut (D)	-6.990*	-10.06	-9.203	3.072
Total Mean to S/N ratio (η) = -8.7518 *Optimum Level= A1B2C1D1				
Surface Roughness (R_t)				
% reinforcement (A)	-26.08*	-26.96	-27.22	1.14
Cutting Speed (B)	-27.28	-26.24*	-26.74	1.04
Feed rate (C)	-25.56*	-26.93	-27.77	2.20
Depth of cut (D)	-24.82*	-28.09	-27.35	3.27
Total Mean to S/N ratio (η) = -26.752; Optimum Level= A1B2C1D1				
Cutting Force (F_z)				
% reinforcement (A)	-33.45*	-34.87	-34.95	1.51
Cutting Speed (B)	-32.75*	-32.93	-37.59	4.84
Feed rate (C)	-31.83*	-34.81	-36.63	4.81
Depth of cut (D)	-26.83*	-38.64*	-38.25	12.26
Total Mean to S/N ratio (η) = -34.424; *Optimum Level= A1B1C1D1				

respectively and the depth of cut, speed have highest 'max-min'values of 12.46 and 4.84, respectively for Fz. The increment in cutting depth resulted in higher value of cutting force and promotes the built-up-edge (BUE) growth. Therefore, the roughness increased with increment in cutting depth. The increment in feed upto 0.174 mm/revresulted in linearly increment in roughness. Further progress in feed (0.174 to 0.235 mm/rev), the formation of built-up-edge readily and is accomplished by feed marks resulted in increment of roughness. The results show that the roughness of the fabricated composite is influenced by the wt% of silicon carbide (SiC) particles in the workpiece, feed, andcutting depth. The speed also has a significant role on composite machining process in deciding the value of surface roughness. From the above study it is thus concluded that higher speed provide for better surface finish, but will lead to higher cutting force. From the above S/N ratio results for surface roughness, the arrived optimum points are:(i) speed:120 m/min,(ii) wt% of SiC:5%, (iii) cutting depth:0.4 mm and (iv) feed:0.118 mm/rev. From the above S/N ratio results for cutting force, the arrived optimum points are:(i) speed: 80 m/min,(ii) wt% of SiC:5%,(iii) cutting depth:0.4 mm and (iv) feed:0.118 mm/rev. Results of analysis of mean, the cutting depth are the most significant machinability parameter followed by speed and feed. To address this problem, Taguchi based grey theory and Taguchi based fuzzy logic method is applied for the optimizing of the multi quality response process.

4.2 Taguchi's Multi Process Characteristics (Tmpc)-Grey Relational Approach

The grey theory is an efficient tool to manage vagueness, multi process characteristics criteria and discrete data problem. The step by step procedure as follow:

(1) By applying equation 1, calculated S/N (η) for Ra roughness and Fz force.

$$\frac{S}{N} = -10Log\left(\frac{1}{n}\sum_{i=n}^{n} y_i^2\right) \quad (1)$$

(2) By applying the equation 2, normalize the S/N ratio(η) for Ra roughness and Fz force.

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (2)$$

Table 3 shows the outcomes of normalized value of S/N (η).

(3) By applying equation 3, calculate the corresponding grey-relational coefficients. The grey relational coefficient (ξ) can be calculated as follows

$$\xi(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{oi}(\mathbf{k}) + \zeta\Delta_{max}} \quad (3)$$

ξ is the distinguishing coefficient. If the value of the ξ is smaller, then the distinguished ability is larger. In general, ξ = 0.5 is used,

$$\Delta_{oi} = \left\|x_0^*(k) - x_i^0(k)\right\| \quad (4)$$

$$\Delta_{max} = \min_{\forall j \in i} \min_{\forall k} \left\|x_0^*(k) - x_j^*(k)\right\| \quad (5)$$

$$\Delta_{min} = \max_{\forall j \in i} \max_{\forall k} \left\|x_0^*(k) - x_j^*(k)\right\| \quad (6)$$

(4) By applying equation 7 and 8, calculate the grey relational grade. The grey relational grade is defined as follows

$$\propto i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \quad (7)$$

$$\propto i = \frac{1}{n}\sum_{k=1}^{n} W_k \xi_i(k) \quad (8)$$

where W_k, denotes the normalised weight of factor k. If W_k is same for all factors then, Eqs. (7) and (8) are equal.

From the layout of L_9experimental design, it confirms from Table 4 that the machinability parameters points of trial 1 have the highest grey-relational grade.

4.3 Taguchi's Multi Process Characteristics (Tmpc)- Fuzzy Based Taguchi Loss Function Method (Ftlm)

The calculated S/N (η) values of the processed machined component are observed between -5.459 and -12.073 db for Ra, -23.482 and -30.098 db for Rt and -21.32 and -42.648 db for Fz. It is observed form the Table 3, trial 7 have highest S/N ratio(η) for Ra, Rt and trial 3 for Fz. Therefore,

Table 4. Normalized data, Grey relation coefficient and Grey relational grade

Trial	Normalized data			Grey relation coefficient			Grey relational grade	Rank
	Ra	Rt	Fz	Ra	Rt	Fz		
1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1
2	0.4880	0.5501	0.5622	0.4941	0.5263	0.5331	0.5179	6
3	0.5153	0.4563	0.0000	0.5078	0.4791	0.3333	0.4401	7
4	0.2631	0.3558	0.4823	0.4042	0.4370	0.4913	0.4442	8
5	0.7784	0.7675	0.9055	0.6929	0.6826	0.8410	0.7389	2
6	0.5988	0.5488	0.3187	0.5548	0.5256	0.4232	0.5012	5
7	0.0000	0.0000	0.2979	0.3333	0.3333	0.4159	0.3609	9
8	0.7520	0.6899	0.6655	0.6685	0.6172	0.5991	0.6283	4
9	0.6884	0.7779	0.8248	0.6160	0.6924	0.7405	0.6830	3

one process response is necessary for the optimization of a multi response process. In the direction of address this problem, fuzzy-logic method is acquaint with Taguchi 'Loss function' method (TLM) for multi-performance optimization characteristics. Figure 1 shows the graphic diagram of fuzzy model. The input quality parameters and the output variable is the multi performance Characteristics (MPC), whose membership function is assigned by fuzzy-logic model is shown in Figure 2.As presented in Figure 2, the computed S/N (η) values of surface roughness and cutting force are considered as three input variables or three linguistic variables as S, small;M, medium and L, large and for output variable for MPC as S, small:SM, small-medium:M, medium;ML, medium-large;L, large of the fuzzy-logic modeling are used. The linguistic variables and their fuzzy intervals for the fuzzy logic modeling are presented in Table 5. In this fuzzy modeling, membership function used is triangular shape for both input and output variables because it has less computational times. Thus, for three input variables and their corresponding membership values number of fuzzy rules formed are 27 rules. Using Mamdani interference, these input variables are 'fuzzified' and their output for Multi performance characteristics (MPC) can be achieved. Next, the 'defuzzification' method by the centre of gravity is cast off to compute the final MPC outputs. Table 6 shows the fuzzy values for MPC value obtained from the fuzzy logic modeling corresponding to each of the 9 experimental run. The maximum value of MPC has the highest ranking and the minimum value of MPC has lowest ranking as shown in Table 6. From the analysis, the determined optimum points are:(i) speed:80 m/min,(ii) % weight fraction of SiC:5%,(iii) cutting depth:0.4 mm and (iv) feed:0.118 mm/rev.

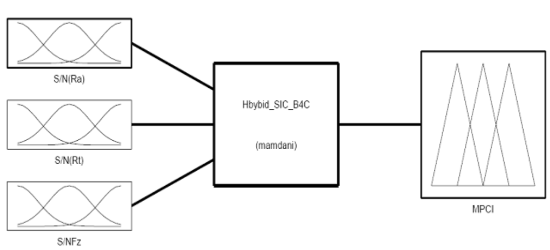
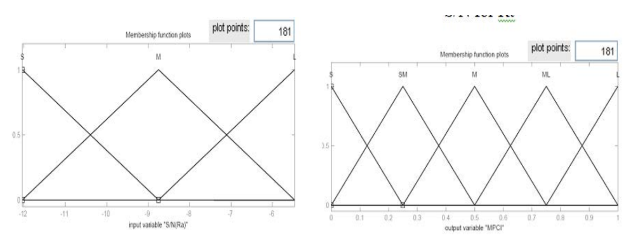


Figure 1. Schematic diagram of Fuzzy model for MPC.

Table 5. Input and output variable for Fuzzy values

Input variables	Linguistic variables	Linguistic values	Fuzzy intervals
Input variables	Input variable S/N (η) –Ra	Small (s)	-12.04 to -8.752
		Medium (M)	-8.752 to -5.469
		Large (L)	-5.469 to -2.828
	Input variable S/N (η) –Rt	Small (S)	-30.01 to -26.69
		Medium (M)	-26.69 to -23.48
		Large (L)	-23.48 to -20.84
	Input variable S/N (η) –Fz	Small (S)	-42.65 to -31.98
		Medium (M)	-31.98 to -21.31
		Large (L)	-21.31 to -12.78
Output variables	Multi performance Index (MPI)	Small (S)	0.00 to 0.25
		Small (SM)	0.25 to 0.50
		Medium (M)	0.50 to 0.75
		Medium ML)	0.75 to 1.00
		Large (L)	1.00 to 1.25



a) S/N of Input variableb) S/N for MPC

Figure 2. Membership for input and MPC variable.

Table 6. Fuzzy values: Multi performance Characteristics (MPC)

Exp. Run	Mean S/N ratio			MPC	Rank
	R_a (dB)	R_t (dB)	F (dB)		
1	-5.46	-23.48	-21.31	0.920	1
2	-9.43	-27.08	-36.38	0.467	6
3	-9.26	-27.67	-42.64	0.456	7
4	-10.73	-28.27	-37.59	0.430	8
5	-7.40	-25.52	-27.36	0.589	2
6	-8.71	-27.09	-39.65	0.483	5
7	-12.03	-30.09	-39.88	0.396	9
8	-7.61	-26.11	-34.50	0.538	4
9	-8.09	-25.44	-30.46	0.575	3

4.4 Variance Test (Anova) for Grey-Relational Grade and Fuzzy-Reasoning Grade

The factors decomposition and their effects on roughness Ra, Rt and cutting force (Fz) of SiC/B_4C/Al MMC'sduring machinability process has been carried out by response table and variance test (ANOVA).The complete response table for Multi performance characteristics in orthogonal array is shown in Table 7. From the 'max-min' range method, the decomposition effect of each controllable factor on the MPC can be determined. It is clear that control factor D has the most significant effect on the MPC, followed by the factors C, A and B for the both the approach. Therefore, the optimal point of machinability parameters are % reinforcement at level A1, speed at level B1, feed at level C1 and cutting depth at level D1. From the result of the variance test shown in Table 8, the controlled facto to the MPCs in descending order as D (69.38%), C(21.3%), A(5.62%) and B (3.85%) for fuzzy reasoning approach and D (55.77%), C(26.66%), A(12.80%) and B (4.71%) for grey relational approach. It seems form the above two method, grey-relational method is straighter than fuzzy-reasoning grade. The result of the validation experiment using the optimal levels is shown in Table 9.

Table 7. S/N ratio for multi performance characteristics

Cutting Parameters	Mean S/N ratio (dB)			Max – Min
	Level 1	Level 2	Level 3	
Grey Relational grade				
% reinforcement (A)	0.6527*	0.6284	0.5574	0.0953
Cutting Speed (B)	0.6017*	0.5614	0.5414	0.0869
Feed rate (C)	0.7098*	0.5484	0.5133	0.1965
Depth of cut (D)	0.8073*	0.4600	0.5042	0.3473
Fuzzy Reasoning grade				
% reinforcement (A)	-0.6143*	-0.5007	-0.5030	0.1137
Cutting Speed (B)	-0.5820*	-0.5313	0.5047	0.0773
Feed rate (C)	0.6470*	0.4907	0.4803	0.1697
Depth of cut (D)	0.6947*	0.4487	0.4747	0.2460

*Optimum Level

Table 8. Results of analysis of variance for MPI

Feed rate (C)	**0.7098***	**0.5484**	**0.5133**	**0.1965**
Depth of cut (D)	**0.8073***	**0.4600**	**0.5042**	**0.3473**
Fuzzy Reasoning grade				
% reinforcement (A)	-0.6143*	-0.5007	-0.5030	0.1137
Cutting Speed (B)	-0.5820*	-0.5313	0.5047	0.0773
Feed rate (C)	0.6470*	0.4907	0.4803	0.1697
Depth of cut (D)	0.6947*	0.4487	0.4747	0.2460

*Optimum Level

Table 9. Results of the confirmation experiments

Optimal setting	Optimal results			
	Prediction		Experiment	
$A_1B_1C_1D_1$	Mean	S/N ratio	Mean	S/N ratio
Ra	1.343	-4.211	1.452	-4.465
Rt	11.223	-22.437	13.563	-24..345
Fz	12.043	-21.127	10.524	-19.453

5. Conclusion

This study has discussed the effects of machinability parameters on the performance measures of surface roughness and cutting force in turning of Al/SiC/B4C MMCS. Statistical results show that the cutting depth (D), feed (C), speed (B), and % reinforcement (A) are the order of significance to affect roughness and force. It has been also found that the optimal points of machinability parameters lies at two set for roughness (A1B2C1D1) and force (A1B1C1D1). However, the study through novel application of grey and fuzzy-logic on the Taguchi method the optimal levels are 5% reinforcement, 80 m/min for speed, 0.118 mm/rev for feed and 0.4 mm for cutting depth. From the comparison, grey relational method is straighter than fuzzy reasoning grade. From the confirmation result, the minimum surface finish Ra, Rt and minimum cutting force value is calculated as 1.452 µm, 13.563 µm and 10.524 N by Taguchi's optimization method, respectively.

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