# INVESTIGATION OF SURFACE GRINDING CHARACTERISTICS OF AL/SIC/$AL_2O_3$ COMPOSITE USING GREY RELATIONAL ANALYSIS

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**Abstract**

Grinding is a vital finishing process employed in the final stages of fabrication on hard materials. Surface grinding is applied to produce fine finish and accurate dimensions in components. Advanced materials like hybrid metal matrix composites (MMCs) require grinding to produce components with desired tolerances. The proper selection of grinding parameters like wheel speed, feed rate and depth of cut is essential to obtain the required finish. The paper discloses the application of grey relational analysis (GRA) to optimize the surface grinding characteristics of Al/SiC/Al2O3 composite. Grinding trials are designed using Taguchi's L9 orthogonal array and surface roughness is observed along with the tangential force as the quality characteristics. The approach of GRA is validated through confirmation experiments. Depth of cut is found to contribute more towards the observed responses than the other two factors.

***Key words:*** Al/SiC/Al2O3 composite; Grey relational analysis; Optimization; grinding; Taguchi; Surface finish.

## I. INTRODUCTION

The metal matrix composites (MMCs) have noteworthy applications in aerospace and automotive components. The hybrid MMCs reinforced with ceramic particulates exhibit good strength-to-weight ratio and superior mechanical properties compared to the parent matrix material [1]. Grinding is a finishing operation carried out on a majority of parts to produce a better finish. Though the process of grinding is associated with a lower metal removal rate, it is highly desired for a better dimensional accuracy of parts. The ceramic particles used as reinforcements increase the tool wear in machining [2]. Higher feed rate and cutting speeds increase the flank wear of tools while handling SiC reinforced aluminium [3]. The applications of these hybrid MMCs can be enhanced with practical solutions to problems associated with machining and mainly grinding. Hence a proper set of guidelines with optimal grinding parameters becomes essential to obtain better quality characteristics.

The quality of the prepared surfaces is important as good machined surfaces avoid or minimize further processing, hence reducing the processing time and cost as well [4-7]. The effect of grinding parameters can be clearly seen from the machined surface quality. Generally Taguchi based approaches use the signal-to-noise ratio as an index; however the grey relational analysis (GRA) uses the grey relational grade as the performance index. GRA can optimize multiple responses and can overcome the difficulties in basic Taguchi method which is effective only in single response optimization [8-10]. Grinding is viewed as a multi input process with multiple quality characteristics. The methods suggested for solving the multi response optimization problems include the principal component analysis (PCA), grey relational analysis (GRA), simulated annealing algorithm, technique for order performance by similarity to ideal solution (TOPSIS), response surface methodology (RSM) and data envelopment analysis [11-14]. The method of RSM employed in a pure form or in a combined form along with other methodology is capable of predicting the optimal operating conditions for various manufacturing processes. However the method was observed to lose its strength in irregular regions [15, 16, 17]. Similar effectiveness is observed with combined approaches involving Taguchi, grey theory and desirability analysis [18, 19].

It is understood from the review of literature that optimal surface grinding condition while handling hybrid MMCs is limited. This urged the focus and required motivation towards obtaining the optimal condition for surface grinding for Al/SiC/Al2O3 composite. Taguchi based grey relational analysis is disclosed for optimization of multiple responses.

## II. EXPERIMENTAL DESIGN AND OBSERVATION

The aluminium alloy (Al6061) which has wide engineering applications is chosen as the matrix material. It is dispersion strengthened with 5% silicon carbide (SiC) and 5% alumina (Al2O3). Stir casting is used for in-situ fabrication of Al/SiC/$Al_2O_3$ composite plates. The work specimen used for grinding experimentations are square samples, each of side 25 mm and thickness 12 mm. The surface grinder (Model: BJ-1020-Bhurji make) with a maximum spindle speed of 2800 rpm is employed for the grinding trials (Figure 1).

Fig. 1 Surface grinder used for experimentation

The grinding parameters taken for trials include the wheel speed, input parameters taken for the study includes the spindle speed, feed rate and depth of cut. The inputs are varied at three levels and Taguchi's L9 orthogonal array is used for grinding trials. The levels are sorted out using the available literature. The grinding parameter range is listed in Table 1. The specimen subjected to grinding is shown in Figure 2.

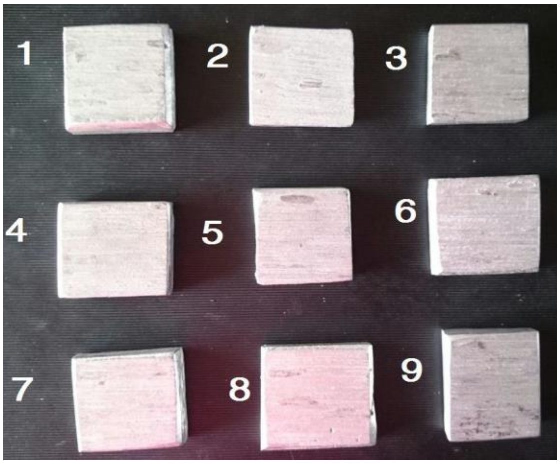


Fig. 2 Specimen subjected to surface grinding

**Table 1. Grinding parameters and their range chosen for trials**

| Sym-bols | Parameter Parameters | unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| A | Wheel speed | rpm | 300 | 500 | 800 |
| B | Feed rate | mm/s | 0.9 | 1.31 | 1.5 |
| C | Depth of cut | mm | 0.1 | 0.2 | 0.3 |

The responses observed include the surface roughness (SR) and tangential force (Ft). Two replications are obtained for each response and the trials are conducted at random to avoid extraneous effects [5]. A strain gauge (model: FT 100) is used for measuring the tangential force using a transducer in half bridge configuration digitally. The surface finish is measured by using a Talysurf SR tester for a cut-off length of 0.8 mm and a probe speed of 0.1 mm/s. The observed SR and Ft values are listed in Table 2.

**Table 2 Responses obtained during grinding trials**

| Trial | Levels of grinding parameters | | | Responses | |
|---|---|---|---|---|---|
| | A | B | C | SR (μm) | Ft (N) |
| 1 | 1 | 1 | 1 | 1.734 | 91 |
| 2 | 1 | 2 | 2 | 1.321 | 95 |
| 3 | 1 | 3 | 3 | 1.863 | 98 |
| 4 | 2 | 1 | 2 | 1.004 | 93 |
| 5 | 2 | 2 | 3 | 1.223 | 104 |
| 6 | 2 | 3 | 1 | 1.024 | 89 |
| 7 | 3 | 1 | 3 | 0.935 | 109 |
| 8 | 3 | 2 | 1 | 0.846 | 103 |
| 9 | 3 | 3 | 2 | 1.248 | 117 |

## III. GREY RELATIONAL ANALYSIS

In grey relational analysis, black represents an *off state* with no information and white represents an *on state* having all information [6]. GRA is used to represent the grade of correlation between the two so that the distance of two factors can be measured discretely. In cases where the experimental method cannot be carried out exactly, GRA helps in compensating the shortcoming of statistical regression. In GRA, the 'signal-to-noise' ratio (S/N ratio) is considered as a measure of performance and accordingly, each performance characteristic would have a target or nominal value [7].

*Step 1*:Calculate the S/N ratio ($y_{ij}$) for the responses using the appropriate formula based on its quality characteristic [8]. A quality characteristic is one which determines the outcome of a process. Usually a quality characteristic will have a target which may be *Nominal-the-best, Smaller-the-better or Larger-the-better.*

### A. Nominal-the-best

A *nominal-the-best* characteristic is one with a specific user-defined target value. The S/N ratio ($y_{ij}$) for such a characteristic is indicated in the formula (1), the mean (μ) and the standard deviation (σ) are calculated from the formula (2) and formula (3) respectively.

$$\frac{S}{N}\text{Ratio}(\eta) = 10\, log_{10} ( \quad (1)$$

$$\mu = \frac{y_1+y_2+\cdot}{r} \quad (2)$$

$$\sigma = \sum_{i=1}^{r} \frac{(y_i}{r} \quad (3)$$

Where *r* is the number of replications and *m* is the number of observations.

### B. Smaller-the-better

The target of the *smaller-the-better* characteristic is 0 (zero). Minimization of such a characteristic is intended in the *smaller-the-better type* problems. The S/N ratio ($y_{ij}$) for such a characteristic is calculated by using the formula (4):

$$\frac{S}{N}\text{Ratio}(\eta) = -10\, log_{10} \left(\frac{1}{r}.\sum_{i=1}^{r} \right. \quad (4)$$

### C. Larger-the-better

A larger-the-better characteristic has a target of infinity and the maximization of such a quality characteristic is achieved by calculating the S/N ratio by using the formula (5):

$$\frac{S}{N}\text{Ratio}(\eta) = -10\, log_{10} \left(\frac{1}{r}.\sum_{i=1}^{r} \right. \quad (5)$$

*Step 2*:Calculate the normalized S/N ratio ($Z_{ij}$) using the formula (6) to avoid the effect of variability among the S/N ratio [9]. The Normalized S/N ratio varies as $0 \leq Z_{ij} \leq 1$.

$$Z_{ij} = \frac{y_{ij} - \min(y_{ij}, \ i=1,2,3,...,r}{\max(y_{ij}) - \min(y_{ij}) \ \ i=1,2,3} \quad (6)$$

Where *n* is the number of trials.

*Step 3*: Compute the Grey Relational Coefficient (γ) using the formula (7):

$$\gamma_i^j = \frac{\Delta min + \xi\Delta}{\Delta_{oj}(i) + \xi\Delta} \quad (7)$$

ξ is the distinguishing coefficient whose value is taken to be 0.5 to ensure the equal importance for all the responses.

*Step 4:* Calculate the grey relational grade (GRG) by taking the average of the grey relational co-efficient values by using the formula (8). The grey relational grade values lies between 0 and 1.

$$GRG_j = \frac{1}{n}\sum_{i=}^{n} \quad (8)$$

*Step 5:*Determine the optimal level of the grinding parameters using GRG. The main effect ($\varepsilon_i$) is calculated using formula (9) to determine the optimal level.

$$\varepsilon_i = \max(\overline{GRG_{ij}}) - \min(\overline{GR} \quad (9)$$

Where $\overline{G_i}$ is the average grey relational grade value of $i^{th}$factor at $j^{th}$level. The best level $j^*$ of a factor '*i*' is selected by $j^*$ = max ( $\overline{G_i}$).

*Step 6:* Calculate the predicted S/N ratio at the selected optimal levels of the parameter using formula (10).

$$\bar{\eta} = \eta_m + \sum_{i=1}^{f}(\bar{\eta} - \quad (10)$$

Where $\eta_m$ is the average S/N ratio, *f* is the number of control factors and is the average S/N ratio.

*Step 7:*Perform ANOVA to predict the significant parameters and their contribution.

## IV. RESULTS AND DISCUSSION

### *A. Grey relational generation*

Taguchi's techniques use S/N ratio for data pre-processing, as it takes into account both the mean and variability. Linear normalization of both 'SR' and 'Ft' is done to bring the responses on a normal scale. The calculated values of both GRC and GRG are listed in Table 3. The observed responses are minimized (*smaller-the-better* characteristics) taking the target for them to be zero. A larger value of S/N ratio was desired, irrespective of the nature of quality characteristic. The plots of GRG values signify the chosen levels of parameters (Figure 3).

**Table 3. S/N ratio, normalized S/N ratio and GRC of responses**

| Trial | S/N ratio | | Normalized S/N ratio | | GRC | | GRG |
|---|---|---|---|---|---|---|---|
| | SR | Ft | SR | Ft | SR | Ft | |
| 1 | -4.7810 | -39.1808 | 0.0909 | 0.9188 | 0.3548 | 0.8602 | 0.6075 |
| 2 | -2.4181 | -39.5545 | 0.4355 | 0.7615 | 0.4697 | 0.6770 | 0.5734 |
| 3 | -5.4043 | -39.8245 | 0.0000 | 0.6478 | 0.3333 | 0.5867 | 0.4600 |
| 4 | -0.0347 | -39.3697 | 0.7831 | 0.8393 | 0.6974 | 0.7567 | 0.7271 |
| 5 | -1.7485 | -40.3407 | 0.5331 | 0.4306 | 0.5171 | 0.4675 | 0.4923 |
| 6 | -0.2060 | -38.9878 | 0.7581 | 1.0000 | 0.6740 | 1.0000 | 0.8370 |
| 7 | 0.5838 | -40.7485 | 0.8733 | 0.2589 | 0.7978 | 0.4029 | 0.6003 |
| 8 | 1.4526 | -40.2567 | 1.0000 | 0.4659 | 1.0000 | 0.4835 | 0.7418 |
| 9 | -1.9243 | -41.3637 | 0.5075 | 0.0000 | 0.5038 | 0.3333 | 0.4186 |

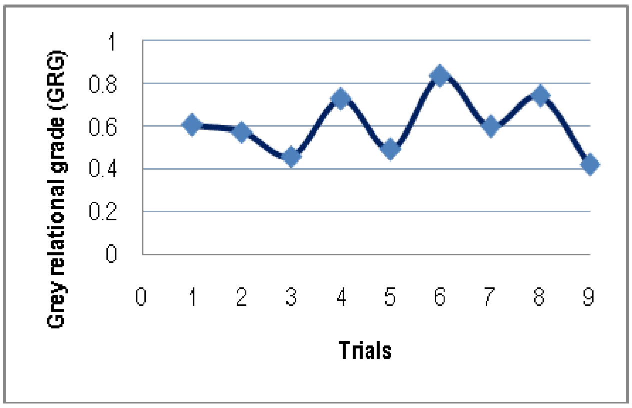


Fig. 3 Distribution of grey relational grade for various trials

### *B. Parameter effects in terms of GRG*

After calculating the GRG values for various trials, it can be used to study the effects of various parameters on the responses converted into a single representative. The GRG values are taken as the performance measure and higher values of GRG is desired irrespective of the nature of the quality characteristics. The parameter effect at a particular level can be studied by observing the mean of all GRG values at the same level. The plots showing the effect of various grinding parameters at different levels on the GRG values is shown in Figure (4-6). The grinding parameter level matching with the largest GRG value can produce good output characteristics. A moderate level of wheel speed is desired for better characteristics (Figure 4), as the tangential forces are observed to increase at higher wheel speeds though there is an improvement in finish of the machined surface. The improvement in finish along with a lower value of tangential force is noticed at lower feed rate and depth of cut (Figure 5 and Figure 6). An increase in feed rate brings a better finish but increases the tangential force as well. Hence a lower value of feed rate is desired. A higher value of depth of cut spoils both the observed quality characteristics.

### *B. Calculation of main effects*

The main effect of grinding parameters on GRG for each level is estimated and shown in Table 4. The best level of each grinding parameter is identified as the one having the maximum value of average GRG among the different levels. The optimal parameter level was identified as $A_2B_1C_1$.

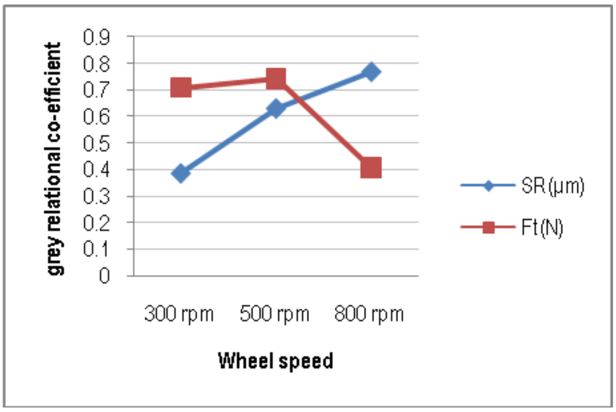


Fig. 4 Effect of wheel speed on responses

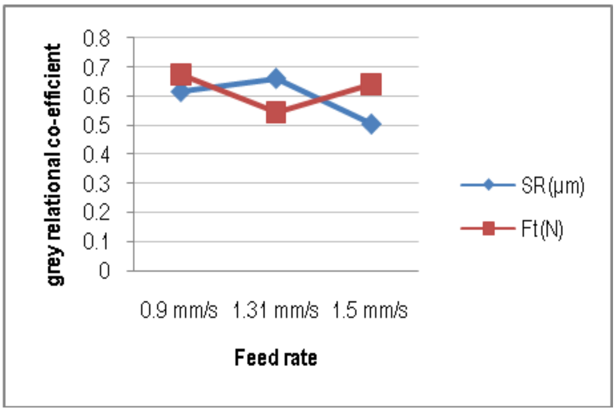


Fig. 5 Effect of feed rate on responses

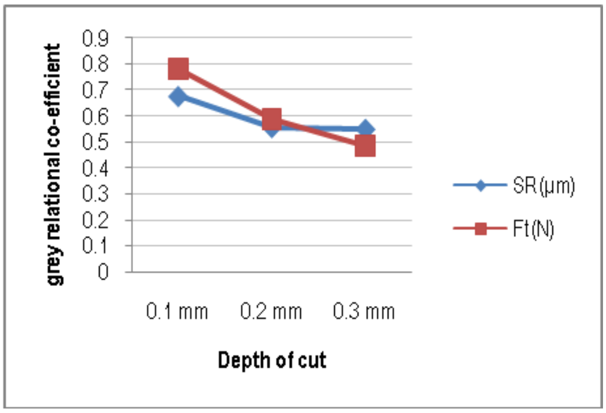


Fig. 6 Effect of depth of cut on responses

*C. Analysis of variance (ANOVA)*

The analysis of variance (ANOVA) can be used to identify the percentage contribution of various parameters in influencing the observed process outputs. ANOVA was performed on the GRG values (Table 5). A pictorial representation of the contribution of grinding parameters various factors is shown in Figure 7.

**Table 4. Grinding parameter effect on GRG**

| Parameters | Level 1 | Level 2 | Level 3 | Max-Min |
|---|---|---|---|---|
| A | 0.5470 | 0.6855 | 0.5869 | 0.1385 |
| B | 0.6450 | 0.6025 | 0.5719 | 0.0731 |
| C | 0.7288 | 0.5730 | 0.5176 | 0.2112 |

*Best level of grinding parameter.

**Table 5. ANOVA Table**

| Source of variation | Sum of square | Degrees of freedom | Mean sum of square | F-ratio | % Contribution |
|---|---|---|---|---|---|
| A | 0.0305 | 2 | 0.0152 | 0.6573 | 19.4341 |
| B | 0.0464 | 2 | 0.0232 | 0.1745 | 29.5654 |
| C | 0.0719 | 2 | 0.0360 | 1.5505 | 45.8423 |
| Error | 0.0081 | 2 | 0.0040 | | 5.1582 |
| Total | 0.156899 | 8 | | | 100 |

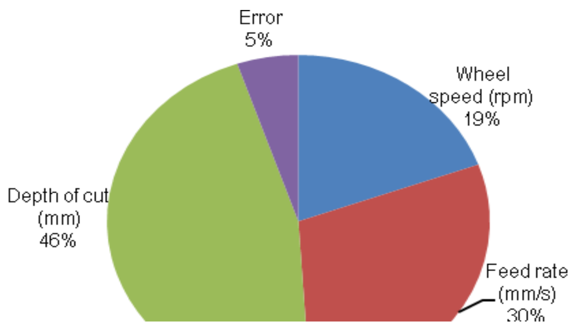


Fig.7 Contribution chart (based on GRG)

*D. Confirmation experiment*

The predicted values of S/N ratio are calculated using the appropriate equation. The confirmation test is performed to verify the magnitude of improvement in the responses. The results of the confirmation experiment conducted with the optimal parameter setting and the consequent comparison with the outputs from initial setting is presented in Table 7. A significant improvement in the response values is observed.

**Table 6 Results of confirmation experiment**

| Responses | Initial parameter Setting | | Optimal parameter (GRA) setting | | Improvement | |
|---|---|---|---|---|---|---|
| | Observed S/N ratio | Response value | Predicted S/N ratio | Response value | S/N ratio | Response value |
| SR (μm) | -0.2060 | 1.024 | 0.6665 | 0.693 | 0.8725 | 0.331 |
| Ft (N) | -38.9878 | 89 | -36.1140 | 83 | 2.8738 | 6 |
| Setting | $A_2\,B_3\,C_1$ | | $A_2\,B_1\,C_1$ | | | |

## V. CONCLUSION

The article presents an informative report on the application of GRA for optimizing the surface grinding parameters for $Al/SiC/Al_2O_3$ composite. The following conclusions are drawn.

- The technique of GRA is employed to identify the optimal surface grinding parameters for $Al/SiC/Al_2O_3$ composite as: wheel speed- 500 rpm, feed rate- 0.9 mm/s and depth of cut- 0.1 mm.
- The optimal combination of grinding parameters has improved by finish and decreased the tangential force significantly.
- ANOVA performed on the GRG value has revealed the contribution of depth of cut and feed rate as 46% and 30% respectively.

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