Optimization of dry-sliding wear parameters on carbon fiber reinforced polyester composites using taguchi based greyrelation analysis

K Maneesh Geeth 1, M Chandra Sekhar Reddy 2 and MV Sai Kumar 3

1, 2 Department of Mechanical Engineering, University College of Engineering, Osmania University, Hyderabad, India
3 Department of Mechanical Engineering, R. V. R. & J.C. College of Engineering, Guntur, India

* Corresponding author e-mail: geethmaneesh22@gmail.com

Abstract. Fiber reinforced polymer composite materials gradually replace traditional metallic materials due to their high specific strength. The cost of composites, however, is still higher than the traditional materials. This paper examined the dry-sliding wear behaviour using a pin-on-disc type of wear arrangement on carbon fiber reinforced polyester (CFRP) composites, which were fabricated with the help of die-casting technique. The carbon fiber reinforced polyester specimens have been subjected to dry-sliding wear tests against a EN32 steel disc. The rate of wear and frictional force were selected as responses variables to the varying percentages of reinforcement, loads, sliding velocity and sliding distance were opted as control variables. The experimental design was carried out by using the Taguchi L 16 OA (Orthogonal Array). The approach used in the initial step of optimization is the dry-sliding performance of carbon fiber reinforced polyester composites was GRA (Grey Relational Analysis). Based on the GRA, the rate of wear and frictional force were found to be the parameters at optimum level for the whole GRG (Grey Relational Grade). According to the ANOVA (Analysis of Variance) result based on GRG, the most important process parameters influencing the wear performance of the composites were found to be load and percentage of reinforcement, which influenced the wear performance of the composites by 60% and 28% respectively, followed by sliding distance and sliding velocity.

Keywords. Carbon fiber reinforced composite (CFRP), Grey relational analysis (GRA), Orthogonal Array (OA), Taguchi method, Grey Relational Grade (GRG).

1. Introduction
Carbon fibre is an excellent choice for achieving a good balance of weight, mechanical properties, performance, and aesthetic. Its use enables innovative shapes to be combined with superior technical efficiency, allowing for greater design freedom. The key problems with carbon fibre processing are the manufacturing costs and the recyclability. As a result, its key uses remain in the racing industry and niche markets [1]. Enhance fibres and matrix structures (such as thermosets & thermoplastics) led to an increase use and practise, resulting in CFRP (Carbon Fibre Reinforced Plastics) composites with enhance mechanical properties, enabling them to displace more traditional materials for primary
structures such as titanium and aluminium alloys [2]. In jute fibre and CFRP composites, a glucose-based epoxy resin component was tested. The novel glucose-based epoxy monomers with complex mechanical properties, tensile strength, glass transition temperature and tensile modulus were calculated, indicating that it could be a feasible alternative to the widely used mineral oil-based diglycidyl-ether of bisphenol-A (DGEBA), also at high temperatures up to 160°C by using an amine-type curing agent certified for aircraft composites [3]. Practical use of PEEK (Poly-Ether-Ether-Ketone) and 30% carbon fibre reinforced PEEK (PEEK-CF30) for orthopaedic applications led to the decision to investigate the effect of carbon fibre reinforcement and the meaning of various parameter’s, such as contact stress, sliding velocity and counter-face roughness on frictional behaviour. Abrasion and adhesion wear processes are clearly caused by complex conditions applied to all components. Iron transferred films from the counter-face to the surface of pin, as well as PEEK content transferred from the surface of pin to the surface of disc, showed a significant adhesion wear [4].

Because of their major advantages in dielectric properties, cost, resistance to corrosion properties and processability, UPR (Unsaturated Polyester Resin) is commonly used in the fields of industry as a thermosetting component. TMSAP (phosphorus and nitrogen-containing silane coupling agent) and ammonium polyphosphate (APP) combined action had a multifunctional effect on mechanical properties of UPR composition, toxic pyrolysis risks and flame retardancy effectiveness [5]. The carbon composite filled with polyester resin has an electrical conductivity with low threshold value of 0.7-0.8 vol percent of a filler [6]. The effect of fibre glass wastes reinforced with polyester matrix composites boosted mechanical properties like impact and tensile strength significantly [7]. Under mechanical agitation, add the necessary amount of GNS (Graphene Nano Sheets) to unsaturated polyester resin. As a result, flexural and tensile performance have also been improved. Also, GNS increased the high voltage and resistance properties greatly [8].

Numerous decision-making methods, such as AHP (Analytic Hierarchy method), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), SMART (Simple Multi Attribute Rating Technique) and GRA (Grey Relational Analysis) have been proposed in the literature to investigate the various attributes correlated with wear resistance of composites. GRA is one of them, Deng discussed it in 1989 is one of the most commonly used strategy when the meaning of the knowledge is incomplete and unclear [9]. Basavarajappa et al. studied the impact of filler materials on the dry sliding wear behaviour of polymer matrix, and found that adding SiC & graphite to glass epoxy composite significantly improved wear resistance. Using Taguchi's orthogonal series, the dry-sliding wear behaviour of SiC & graphite particles reinforced with aluminium matrix was tested, and the findings demonstrated that graphite particles were efficacious for continuing to increase the wear resistance of Al/SiCp composites [10]. Rajmohan et al. used Taguchi based GRA on to refine the drilling parameters of fly ash packed with CFRP composites. According to GRA, the weight percent of fly ash & drill diameter are the most critical variables affecting drilling efficiency [11].

The current research is to improve the dry sliding wear factors in order to establish a desirable CFRP composite with potential applications in breaking and friction. Initially, a CFRP composite was fabricated using the die-casting technique. An experimental design using a Taguchi L16 OA with four varying parameters, namely the load applied (L), sliding speed (S), sliding distance (D) &% of reinforcement (R). For each of these four factors, four levels were defined. From the L16 OA, sixteen experimental runs were carried out in order to acquire data for the various responses of the wear and frictional force. Followed up by S/N ratios and GRA, the response to the optimum values was assessed. ANOVA was then used to identify the most important factors influencing CFRP. Finally, validation tests were performed using the optimum levels of the design criteria to validate the enhancement of the consistency attribute, namely the GRG (Grey Relational Grade). Figure 1 depicts the entire methodology used for the successful completion of current research.
2. Experimental details

2.1. Materials
Figure 1 shows the procedure for the current research work. In this study, the materials used for composite preparation were the carbon fibers of 85 µm, added as reinforcement material and matrix material as polyester resin added to it. A mild steel mould of Ø15mm×150mm in height was manufactured for preparation of samples used in current study.

2.2. Composite Fabrication
Polyester resin was blended with hardener [Methyl Ethyl Ketone Peroxide MEKP (MEKP), CO (Cobalt octoate)] and then carbon fiber of 85 µm was added to the matrix at a ratio of 0, 4, 8 and 12Wt%. The weighted quantity is mixed in a beaker by mechanical stirring at a suitable speed of 110 rpm. It is mixed up to when it comes to the semi solid state. For the easy removal of composites from the die a release agent (wax) coat was applied to the mould before pouring the mixture. The semi solid state mixture is now poured into the mild steel mould and left it for 24 hours at room temperature. After 24 hours, mild steel mould is removed and the specimens were taken out and then it is left for post cured. The samples in the mould had a diameter of 15 mm. They were machined to an 8 mm
diameter after curing in order to conduct wear tests. The composition of fabricated specimens is illustrated in Table 1.

**Table 1. Composition of fabricated specimens.**

| Sl. no | Composite Identification | Wt% of Carbon fiber | Wt% of Polyester resin | Wt% of Hardener (MEKP+CO) |
|--------|--------------------------|---------------------|------------------------|---------------------------|
| 1.     | Pure Polyester           | 0                   | 200                    | 4                         |
| 2.     | CF 4Wt% + Polyester      | 4                   | 200                    | 8                         |
| 3.     | CF 8Wt% + Polyester      | 8                   | 200                    | 10                        |
| 4.     | CF 12Wt% + Polyester     | 12                  | 200                    | 16                        |

2.3. *Dry-sliding Wear test*

Dry-sliding wear characteristics of prepared CFRP composites, according to ASTM G99-95 standards [12] were investigated using pin-on-disc wear measuring machine (Figure 2) with counter face of a hardened & polished disc made of EN32 steel disc (58-60 HRC). Figure 3 shows the wear specimens (pins) that were Ø8 mm×50 mm in height. The specimen's initial wt. was determined using an electronic balancing system with a precision of 0.0001 gm.

During the test, the load was applied to the pin, which was pressed against the counterpart on an EN32 disc made of steel. The specimens were removed after running through a sliding distance, cleanse with acetone, dried & weighted to assess the loss of weight due to wear. The wear loss of the composite was determined by the variation in weight measured before and after each examination. Normal loads (L), % of reinforcement (R), sliding velocity (S) and sliding distance (D) were examined as a function of the wear (W, µm) and frictional force (FF, N) of CFRP composites.

![Figure 2. Pin-on-disc wear test setup.](image)

![Figure 3. Wear pin samples (P- Pure Polyester, 4- CF 4Wt%+Polyester, 8- CF 8Wt%+Polyester, 12- CF 12Wt%+Polyester).](image)
2.4. Design of Experiments using Taguchi orthogonal array

Experimental design using Taguchi is a very powerful tool for determining the effect of various parameter degrees on output responses. The most crucial stage in the design of experiments is selecting the control factors influencing performance of output. Several factors are considered at first, and then the less important factors are eliminated, leaving only the more important factors. As shown in table 2, four major factors were considered in the current dry-sliding wear test: load (L), sliding velocity (S), sliding distance (D), and percent of fiber reinforcement (R), each at four levels according to L_{16} OA. At room temperature the experiments are conducted. Using Taguchi L_{16} OA, thereby saving much experimental time and money, reduced the number of Experiments from 4^4=256 traditional runs to just 16 runs (Table 3). Again, these experiments are transformed into signal-to-noise ratios (S/N) S/N ratio for minimal wear and frictional force is determined as a logarithmic transformation of the loss function [13-14] as in equation (1).

\[
S/N_{SB} = -10 \log_{10} \left[ \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right]
\]  

(1)

where \( n \) equals to number of observations and \( y \) equals to the response variables. For the present study \( n = 16 \) and \( y = 2 \)

| Control Factors       | Notation | Levels | Units |
|-----------------------|----------|--------|-------|
|                       |          | 1      | 2     | 3     | 4     | m/s   |
| Sliding velocity      | S        | 1      | 2     | 3     | 4     |       |
| Load                  | L        | 5      | 10    | 15    | 20    | N     |
| Sliding distance      | D        | 500    | 1000  | 1500  | 2000  | m     |
| % of Reinforcement    | R        | 0      | 4     | 8     | 12    | %     |

Table 2. Dry-sliding wear test levels and controlling factors.

| Runs | Independent Parameters |
|------|------------------------|
|      | S | L | D | R |
| 1    | 1 | 1 | 1 | 1 |
| 2    | 1 | 2 | 2 | 2 |
| 3    | 1 | 3 | 3 | 3 |
| 4    | 1 | 4 | 4 | 4 |
| 5    | 2 | 1 | 2 | 3 |
| 6    | 2 | 2 | 1 | 4 |
| 7    | 2 | 3 | 4 | 1 |
| 8    | 2 | 4 | 3 | 2 |
| 9    | 3 | 1 | 3 | 4 |
| 10   | 3 | 2 | 4 | 3 |

Table 3. Experimental design of L_{16} OA.
2.5. Grey Relational Analysis

Taguchi’s experimental approach is sufficient for evaluating the optimum process parameter setting for a particular response characteristic. Multi-response optimization with GRA is the optimal approach where there are two or more responses with dissimilar output characteristics. Grey relation analysis can also be used to evaluate the resemblance of unusual finite data [15-16]. As a result, multi-response optimization for wear parameters is done in this analysis using the following procedure in GRA, as seen in figure 4. The ANOVA approach describes the most critical factor impacting wear behaviour.

Taguchi’s Grey Relational Analysis is calculated using following steps are as follows [17-19]:

Step-I: Normalized data for wear and frictional force equivalent to the "Lower-the-Better" criteria, represented in grey relational generation by equation (2).

\[ y_i(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)} \]  \hspace{1cm} (2)

Where \( i = 1, 2, 3 \ldots 16 \) (no. of runs) & \( k = 1, 2 \) (no. of responses), \( x_i(k) \) is obtained value, \( \max x_i(k) \) equals to maximum value of \( x_i(k) \) and \( \min x_i(k) \) equals to minimum value of \( x_i(k) \).

Step-II: Equation (3) determines the deviation sequence for all corresponding process variables.

\[ \Delta_{oi}(k) = |x_o(k) - x_i(k)| \]  \hspace{1cm} (3)

Where \( \Delta_{oi}(k) \) is the deviation sequence for the reference sequence \( x_o(k) \) & the comparability sequence \( x_i(k) \).

Step-III: Following formulae [Equation(4)] are used to calculate the GRC (Grey Relational Coefficients) from normalized values in GRA method.

\[ \xi_i(k) \]  \hspace{1cm} (4)

GRC,

Where \( \zeta \) is distinguishing coefficient (i.e., \( \sim 0.5 \)).

Step-IV: The GRG (Grey Relational Grade), which is predicted by averaging the number of GRC, is the key step using equation (5).

\[ \gamma_i \]  \hspace{1cm} (5)

Where \( \gamma_i \) ranges in between 0 - 1 and ‘n’ equals to the number of output responses.
3. Results and Discussion

3.1. Taguchi Approach and Optimization

3.1.1. Analysis of S/N Ratio. Minitab 18 was used as software for statistical analysis of the experimental findings made. Table 4 predicts the experimental results of wear and frictional force along with the associated S/N ratios, while tables 5 & 6 shows S/N ratio responses for wear (W) and frictional force (FF).

Figures 5 & 6 illustrate how control factors influence the S/N ratio for wear and frictional force, respectively. By considering the lowest S/N ratios values, an optimal control factor setting for a better performance can be achieved. The bold values in tables 5 and 6 denote the lowest S/N ratios. From figure 5 & table 5, % of reinforcement (R) is an influencing parameter on the wear (W) and from figure 6 & table 6, load (L) is an influencing parameter on the frictional force (FF). It can be perceive from figure 5 & table 5, that the combination of factors; Sliding velocity: S (Level 3 i.e., 3 m/s), Load: L (Level 4 i.e., 20 N), Sliding distance: D (Level 4 i.e., 2000 m) and % of Reinforcement: R (Level 4 i.e., 12%) gives minimum wear. Furthermore, as illustrated in figure 6 and table 6, the combination of factors; Sliding velocity: S (Level 1 i.e., 1 m/s), Load: L (Level 4 i.e., 20 N), Sliding distance: D (Level 3 i.e., 1500 m) and % of Reinforcement: R (Level 1 i.e., 0%) gives minimum frictional force.
Table 4. Taguchi L\(_{16}\) OA & multi-response findings with S/N ratio.

| Runs | Control Factors | Response variables | S/N Ratios |
|------|-----------------|--------------------|------------|
|      | S (m/s) | L (N) | D (m) | R (%) | W (μm) | FF (N) | W (dB) | FF (dB) |
| 1    | 1 | 5 | 500 | 0 | 254 | 10.50 | -48.0967 | -20.4238 |
| 2    | 1 | 10 | 1000 | 4 | 124 | 9.00 | -41.8684 | -19.0849 |
| 3    | 1 | 15 | 1500 | 8 | 88 | 6.30 | -38.8897 | -15.9868 |
| 4    | 1 | 20 | 2000 | 12 | 24 | 4.40 | -27.6042 | -12.8691 |
| 5    | 2 | 5 | 1000 | 8 | 52 | 19.30 | -34.3201 | -25.7111 |
| 6    | 2 | 10 | 500 | 12 | 45 | 15.10 | -33.0643 | -23.5795 |
| 7    | 2 | 15 | 2000 | 0 | 213 | 8.00 | -46.5676 | -18.0618 |
| 8    | 2 | 20 | 1500 | 4 | 96 | 4.40 | -39.6454 | -12.8691 |
| 9    | 3 | 5 | 1500 | 12 | 37 | 13.80 | -31.3640 | -22.7976 |
| 10   | 3 | 10 | 2000 | 8 | 40 | 11.30 | -32.0412 | -21.0616 |
| 11   | 3 | 15 | 500 | 4 | 83 | 9.90 | -38.3816 | -19.9127 |
| 12   | 3 | 20 | 1000 | 0 | 122 | 5.30 | -41.7272 | -14.4855 |
| 13   | 4 | 5 | 2000 | 4 | 79 | 13.30 | -37.9525 | -22.4770 |
| 14   | 4 | 10 | 1500 | 0 | 94 | 9.55 | -39.4626 | -19.6001 |
| 15   | 4 | 15 | 1000 | 12 | 41 | 8.80 | -32.2557 | -18.8897 |
| 16   | 4 | 20 | 500 | 8 | 73 | 4.90 | -37.2665 | -13.8039 |

Figure 5. Main effect of wear for the S/N ratio plots.
Table 5. $S/N$ ratio for Wear response table.

| Level | S   | L   | D   | R   |
|-------|-----|-----|-----|-----|
| 1     | -39.11 | -37.93 | -39.20 | -43.96 |
| 2     | -38.40 | -36.61 | -37.54 | -39.46 |
| 3     | **-35.88** | -39.02 | -37.34 | -35.63 |
| 4     | -36.73 | **-36.56** | **-36.04** | **-31.07** |
| Delta | 3.24 | 2.46 | 3.16 | 12.89 |
| Rank  | 2   | 4   | 3   | 1   |

Table 6. $S/N$ ratio for Frictional force response table.

| Level | S   | L   | D   | R   |
|-------|-----|-----|-----|-----|
| 1     | **-17.09** | -22.85 | -19.43 | **-18.14** |
| 2     | -20.06 | -20.83 | -19.54 | -18.59 |
| 3     | -19.56 | -18.21 | **-17.81** | -19.14 |
| 4     | -18.69 | **-13.51** | -18.62 | -19.53 |
| Delta | 2.96 | 9.35 | 1.73 | 1.39 |
| Rank  | 2   | 1   | 3   | 4   |

Figure 6. Main effect of frictional force for the $S/N$ ratio plots.
3.1.2. Analysis of Variance. ANOVA (Analysis of Variance) was used to identify the relevant control factors that influence wear and frictional force response values. The overall sum of squared value is used to calculate the relevant importance of factors. The greater the sum of squared value, is the most influencing factor is to control the response values. The percentage contribution factors are calculated using these values [20]. At a confidence level of 95% & a significance level of 5%, the study is carried out. Tables 7 and 8 illustrates the ANOVA results for wear and frictional force, respectively.

As per table 7, the most significant factor influencing wear is % of reinforcement (R), with a contribution percentage of 77.71%, followed by sliding velocity (S) with 5.69%, sliding distance (D) with 4.33%, and load (L) with 3.59%. As per table 8, the most significant factor influencing frictional force is load (L), with a contribution percentage of 84.25 %, followed by sliding velocity (S), with 8.75 %, sliding distance (D), with 3.35 %, and % of reinforcement (R), with 1.93 %.

| Table 7. ANOVA table for the S/N ratio of Wear. |
|-----------------------------------------------|
| **Source** | **SS**<sup>a</sup> | **DF**<sup>b</sup> | **MS**<sup>c</sup> | **F-value** | **P-value** | **Contribution %** |
| S         | 26.51         | 3          | 8.837        | 0.66        | 0.631        | 5.69               |
| L         | 16.72         | 3          | 5.575        | 0.41        | 0.756        | 3.59               |
| D         | 20.19         | 3          | 6.731        | 0.50        | 0.708        | 4.33               |
| R         | 361.76        | 3          | 120.587      | 8.97        | 0.052        | 77.71              |
| Error     | 40.35         | 3          | 13.449       |             |              | 8.66               |
| Total     | 465.53        | 15         |              |             |              |                    |

S = 3.66, R<sup>2</sup> = 91.33%, R<sup>2</sup><sub>adj</sub> = 56.67%

| Table 8. ANOVA table for the S/N ratio of Frictional force. |
|-----------------------------------------------|
| **Source** | **SS**<sup>a</sup> | **DF**<sup>b</sup> | **MS**<sup>c</sup> | **F-value** | **P-value** | **Contribution %** |
| S         | 20.327         | 3          | 6.776        | 5.11        | 0.107        | 8.75               |
| L         | 195.602        | 3          | 65.201       | 49.20       | 0.005        | 84.25              |
| D         | 7.780          | 3          | 2.593        | 1.96        | 0.298        | 3.35               |
| R         | 4.489          | 3          | 1.496        | 1.13        | 0.461        | 1.93               |
| Error     | 3.976          | 3          | 1.325        |             |              | 1.71               |
| Total     | 232.173        | 15         |              |             |              |                    |

S = 1.15, R<sup>2</sup> = 98.29%, R<sup>2</sup><sub>adj</sub> =91.44%

<sup>a</sup> Sum of Squares.<br><sup>b</sup> Degrees of Freedom.<br><sup>c</sup> Mean squares.

The value of ‘Prob > F’, also known as the ‘P-value’< 0.05 at a 95% confidence level, the interactions and factors are considered relevant. Furthermore, a high F-value indicates that a process parameter has a characteristic impact on the significant performance [21-22]. Table 7 shows that the P-value of % of reinforcement is <0.05, indicating that it is a contributing factor to the change in wear. Similarly, the P-value of load in table 8 is <0.05, indicating that it is a contributing factor to the change in frictional force.Tables 7 and 8 also show that R<sup>2</sup> (coefficient of correlation) and R<sup>2</sup><sub>adj</sub> (adjusted coefficient of correlation) values are high & comparable. This predicts the model's goodness of fit [23-24].
3.2. Multi-Response Optimization Using GRA

Wear and frictional force are process parameters that happen at the same time. As a result, they must be optimised in combination. GRA was selected for this role because it can transform a multi-objective to a single-objective problem, which it then optimises [25].

3.2.1. Calculation of GRG Table 4 displays the responses for various parameter combinations depending on the L16 OA. Since minimum wear and frictional force was acceptable, equation (2) was used to normalize wear and frictional force. The deviation sequences were calculated using equation (3) based on the normalized value. Once the deviation sequences were ascertained, GRC (Grey Relational Coefficients) are determined for all responses using equation (4). Finally, using equation (5) the GRG (Grey Relational Grade) was calculated by taking the mean of all GRC.

Table 9 displays the GRA results for all run’s, beginning with the normalisation process and ending with the calculation of GRG. The bold values in table 9 indicates that experiment number (4) has the maximum GRG value of 1.00, suggesting that the outcomes of the subsequent experiments are similar to the optimal value. The greater the GRG rating, the best the efficient characteristics, and the particular experimental run has better multiple response characteristics.

Table 9. Normalized, Deviation sequence, GRC and GRG for Wear and Frictional force.

| Runs | Normalized data $[y_i(k)]$ | Deviation sequence $[\Delta_{ol}(k)]$ | GRC $[\xi_i(k)]$ | GRG $(\gamma_i)$ | Rank |
|------|-----------------------------|--------------------------------------|-----------------|-----------------|------|
| 1    | 0.000 0.591                | 0.909 0.409                          | 0.333 0.550     | 0.442           | 16   |
| 2    | 0.514 0.691                | 0.395 0.309                          | 0.535 0.618     | 0.577           | 12   |
| 3    | 0.656 0.872                | 0.253 0.128                          | 0.642 0.797     | 0.720           | 5    |
| 4    | **0.909 1.000**            | **0.000 0.000**                      | **1.000 1.000** | **1.000**       | 1    |
| 5    | 0.798 0.000                | 0.111 1.000                          | 0.804 0.333     | 0.569           | 13   |
| 6    | 0.826 0.282                | 0.083 0.718                          | 0.846 0.410     | 0.628           | 9    |
| 7    | 0.162 0.758                | 0.747 0.242                          | 0.378 0.674     | 0.526           | 15   |
| 8    | 0.624 1.000                | 0.284 0.000                          | 0.615 1.000     | 0.807           | 3    |
| 9    | 0.857 0.369                | 0.051 0.631                          | 0.898 0.442     | 0.670           | 8    |
| 10   | 0.845 0.537                | 0.063 0.463                          | 0.878 0.519     | 0.699           | 7    |
| 11   | 0.676 0.631                | 0.233 0.369                          | 0.661 0.575     | 0.618           | 10   |
| 12   | 0.521 0.940                | 0.387 0.060                          | 0.540 0.892     | 0.716           | 6    |
| 13   | 0.691 0.403                | 0.217 0.597                          | 0.676 0.456     | 0.566           | 14   |
| 14   | 0.632 0.654                | 0.277 0.346                          | 0.622 0.591     | 0.606           | 11   |
| 15   | 0.841 0.705                | 0.067 0.295                          | 0.871 0.629     | 0.750           | 4    |
| 16   | 0.715 0.966                | 0.194 0.034                          | 0.701 0.937     | 0.819           | 2    |

Table 10 shows the GRG responses calculated at their respective levels for each parameter and figure 7 shows the GRG's main effect plot on control factor derived from Minitab 18 application. Based on the GRG, S4 L4 D3 R4 (i.e., sliding velocity = 4 m/s, load = 20 N, sliding distance = 1500m and 12Wt% carbon fiber) is used for the optimum wear and friction force obtained from CFRP composite. Higher is the GRG, closer the quality of the product to ideal value. As a result, for optimal performance, a higher GRG is desired.
### Table 10. GRG Response table.

| Level | S       | L       | D       | R       |
|-------|---------|---------|---------|---------|
| 1     | 0.6844  | 0.5617  | 0.6267  | 0.5726  |
| 2     | 0.6326  | 0.6274  | 0.6528  | 0.6421  |
| 3     | 0.6757  | 0.6535  | **0.7010** | 0.7015  |
| 4     | **0.6854** | **0.8357** | 0.6977  | **0.7621** |
| Delta | 0.0528  | 0.2740  | 0.0742  | 0.1895  |
| Rank  | 4       | 1       | 3       | 2       |

Average value of the GRG = 0.670

![Main Effect Plots for Means](image)

**Figure 7** Main effect plots of GRG

3.2.2. *ANOVA for GRG.* Essence of ANOVA (Analysis of Variance) is to look into factors that have a significant impact on characteristic performance. This is accomplished by splitting overall variability of the GRG, as determined by the sum of squared deviations from the averages value of the GRG, in contributions from each wear parameter and listing them in table 11. According to ANOVA, a factor's relative ability to minimise variance is indicated by the percent of contributions. The factor with a high contribution % has a significant impact on performance. The percent of contribution of load, L (60.48 %) was known to be the most important factor influencing performance to wear. The % reinforcement, R (28.93%) was found to be the 2nd most influencing factor, followed by sliding distance, D (5.71%) and sliding velocity, S (2.74%).
Table 11. ANOVA table for GRG.

| Source | SS a | DF b | MS c | F-value | P-value | Contribution % |
|--------|------|------|------|---------|---------|----------------|
| S      | 0.007498 | 3 | 0.002499 | 1.28 | 1.28 | 2.74 |
| L      | 0.165087 | 3 | 0.055029 | 28.28 | 28.28 | 60.48 |
| D      | 0.015574 | 3 | 0.005191 | 2.67 | 2.67 | 5.71 |
| R      | 0.078959 | 3 | 0.026320 | 13.52 | 13.52 | 28.93 |
| Error  | 0.005838 | 3 | 0.001946 | | | 2.14 |
| Total  | 0.272956 | 15 | | | | |

S = 0.044, R^2 = 97.86%, R^2 adj = 89.31%

a Sum of Squares.
b Degrees of Freedom
c Mean squares.

3.2.3. Confirmation test. Based on identification of the optimal parameter’s impacting the multiple responses, a confirmation test was conducted to validate experimental results. Equation (6) is used to calculate the predicted GRG. As per Table 12, the predicted & experimental findings are in close agreement, indicating that the study was implemented successfully. For the optimal combination level, experimental GRG is 0.9532, while the predicted GRG is 0.9742. The experimental and predicted results agreed well. This means that the grey relation method is useful in order to optimize the wear parameter, where several characteristics must be examined simultaneously [26].

\[ \hat{y} = y_m + \sum_{i=1}^{q} (y_i - y_m) \]  

(6)

Where \( \hat{y} \) equals to the predicted grey relation grade, \( y_m \) equals to the mean value of GRG, \( y_i \) GRG at optimum levels and \( q \) equals to number of factors.

Table 12. Confirmation test findings.

| Optimal process parameters | Predicted | Experimental |
|---------------------------|-----------|--------------|
| Combination level         | S_4 L_4 D_3 R_4 | S_4 L_4 D_3 R_4 |
| GRG                       | 0.9742    | 0.9532       |

% of improvement in GRG = 2.20%

4. Conclusion

The fabrication of carbon fiber reinforced polyester (CFRP) composites using die-casting technique with varying concentrations of 0, 4, 8, and 12Wt percent and the predicted results show that sliding wear decreases significantly with increase in the content of carbon fiber.

- The Grey Relational Analysis technique can be used to integrate multi-objective optimization into single-objective optimization, & the Taguchi orthogonal array can be used to lower the number of experiments required to obtain an optimised result.
- Using Taguchi method and GRA, the dry-sliding wear parameters with multi-response characteristics was effectively optimized. The S_4 L_4 D_3 R_4 combination (i.e., sliding velocity (S = 4 m/s), load (L = 20 N), sliding distance (D = 1500 m), & 12Wt percent carbon
fiber) was found to have the optimal value dry sliding wear behaviour accountable for low wear and frictional force. The confirmation test demonstrated that the optimal parameters formulti responses were found to be effective.

- The significant and influencing factors from ANOVA (Analysis of Variance) revealed that load (L) and percent of reinforcement (R) were significantly contributed to performance of wear, but other parameters were non-significant.
- The carbon fiber reinforced polyester composites with 12Wt% reported excellent wear performance for the optimized wear variables combination.
- Finally, due to their superior mechanical & wear properties despite their low density, fabricated CFRP composites may be contemplate as a propitious material in the field of aerospace, automotive & marine applications.
- The Taguchi optimization approach may be used in the future to determine the effect of parameters in certain forms of wear testing methods.

Acknowledgement
The authors would like to thank Y.N.V. Sai Ram, Assistant Professor, Department of Mechanical Engineering for their assistance in the preparation of composites, planning of experiments as well as the Research Centre of R.V.R & J.C College of Engineering, Guntur for the wear and friction measurement facilities.

References
[1] Messana, A., Sisca, L., Ferraris, A., Airale, A.G., de Carvalho Pinheiro, H., Sanfilippo, P. and Carello, M., 2019. From design to manufacture of a carbon fiber monocoque for a three-wheeler vehicle prototype. Materials, 12(3), p.332.
[2] Soutsis, C., 2005. Fibre reinforced composites in aircraft construction. Progress in aerospace sciences, 41(2), pp.143-151.
[3] Niedermann, P., Szebényi, G. and Toldy, A., 2015. Characterization of high glass transition temperature sugar-based epoxy resin composites with jute and carbon fibre reinforcement. Composites Science and Technology, 117, pp.62-68.
[4] Davim, J.P., Marques, N. and Baptista, A.M., 2001. Effect of carbon fibre reinforcement in the frictional behaviour of Peek in a water lubricated environment. Wear, 251(1-12), pp.1100-1104.
[5] Chu, F., Yu, X., Hou, Y., Mu, X., Song, L. and Hu, W., 2018. A facile strategy to simultaneously improve the mechanical and fire safety properties of ramie fabric-reinforced unsaturated polyester resin composites. Composites Part A: Applied Science and Manufacturing, 115, pp.264-273.
[6] Vilčáková, J., Sáha, P. and Quadrat, O., 2002. Electrical conductivity of carbon fibres/polyester resin composites in the percolation threshold region. European Polymer Journal, 38(12), pp.2343-2347.
[7] Araújo, E.M., Araújo, K.D., Pereira, O.D., Ribeiro, P.C. and de Melo, T.J., 2006. Fiberglass wastes/polyester resin composites: mechanical properties and water sorption. Polímeros, 16, pp.332-335.
[8] Swain, S., 2013. Synthesis and characterization of graphene based unsaturated polyester resin composites. Transactions on Electrical and Electronic Materials, 14(2), pp.53-58.
[9] Pervez, M., Shafiq, F., Sarwar, Z., Jilani, M.M. and Cai, Y., 2018. Multi-response optimization of resin finishing by using a taguchi-based grey relational analysis. Materials, 11(3), p.426.
[10] Basavarajappa, S., Chandramohan, G. and Davim, J.P., 2007. Application of Taguchi techniques to study dry sliding wear behaviour of metal matrix composites. Materials & design, 28(4), pp.1393-1398.
[11] Rajmohan, T., 2019. Experimental investigation and optimization of machining parameters in drilling of fly ash-filled carbon fiber reinforced composites. Particulate Science and Technology, 37(1), pp.21-30.
[12] Gee, M.G. and Owen-Jones, S., 1998. Wear testing methods and their relevance to industrial wear problems.
[13] Tarasasanka, C. and Ravindra, K., 2017. Application of Taguchi techniques to study dry sliding wear behaviour of magnesium matrix composites reinforced with alumina nano particles. Journal of Engineering Science and Technology, 12(11), pp.2855-2865.
[14] TR, H.K., Swamy, R.P. and Chandrashekar, T.K., 2011. Taguchi technique for the simultaneous optimization of tribological parameters in metal matrix composite. Journal of Minerals & Materials Characterization & Engineering, 10(12), pp.1179-1188.
[15] Achuthamenon Sylajakumari, P., Ramakrishnasamy, R. and Palaniappan, G., 2018. Taguchi grey relational analysis for multi-response optimization of wear in co-continuous composite. Materials, 11(1), p.1743.
[16] Antil, P., Singh, S. and Manna, A., 2018. Electrochemical discharge drilling of SiC reinforced polymer matrix composite using Taguchi’s grey relational analysis. Arabian journal for Science and Engineering, 43(3), pp.1257-1266.
[17] Tarasasanka, C., Snehita, K., Ravindra, K. and Sameerkumar, D., 2019. Optimization of dry sliding wear properties ofAZ91E/nano Al 2 O 3 reinforced metal matrix composite with grey relational analysis. International Journal of Engineering, Science and Technology, 11(4), pp.41-48.
[18] Raju, S.S., Senapathi, A.K. and Rao, G.S., 2017. Estimation of tribological performance of Al-MMC reinforced with a novel in-situ ternary mixture using grey relational analysis. Indian J. Sci. Techno, 10(15), pp.1-9.
[19] Parihar, R. and Jathar, S., 2015. GREY RELATIONAL ANALYSIS TO OPTIMIZE WELDING PARAMETERS FOR DISSIMILAR SHEETS OF MATERIAL IN RESISTANCE SPOT WELDING. Technology, 6(11), pp.23-32.
[20] Ozsoy, N., Ozsoy, M. and Mimaroglu, A., 2017. Taguchi approach to tribological behaviour of chopped carbon fiber-reinforced epoxy composite materials. Delta, 2, p.3.
[21] Çiçek, A., Kivrak, T. and Ekici, E., 2015. Optimization of drilling parameters using Taguchi technique and response surface methodology (RSM) in drilling of AISI 304 steel with cryogenically treated HSS drills. Journal of Intelligent Manufacturing, 26(2), pp.295-305.
[22] Sudheer, M., Prabhu, R., Raju, K. and Bhat, T., 2013. Modeling and analysis for wear performance in dry sliding of Epoxy/Glass/PTW composites using full factorial techniques. International Scholarly Research Notices, 2013.
[23] Kilickap, E., Yardimedan, A. and Çelik, Y.H., 2017. Mathematical modelling and optimization of cutting force, tool wear and surface roughness by using artificial neural network and response surface methodology in milling of Ti-6242S. Applied Sciences, 7(10), p.1064.
[24] Rakić, T., Kasagić-Vujanović, I., Jovanović, M., Jančić-Stojanović, B. and Ivanović, D., 2014. Comparison of full factorial design, central composite design, and box-behnken design in chromatographic method development for the determination of fluconazole and its impurities. Analytical Letters, 47(8), pp.1334-1347.
[25] Wojciechowski, S., Maruda, R.W., Kroczek, G.M. and Niesłony, P., 2018. Application of signal to noise ratio and grey relational analysis to minimize forces and vibrations during precise ball end milling. Precision Engineering, 51, pp.582-596.
[26] Siriyala, R., Alluru, G.K., Pennetsa, R.M.R. and Duraiselvam, M., 2012. Application of grey-taguchi method for optimization of dry sliding wear properties of aluminum MMCs. Frontiers of Mechanical Engineering, 7(3), pp.279-287.
[27] Lacminarayana, P., 2018. Optimization of electrode tool wear in micro holes machining by die sinker EDM using Taguchi approach. Materials today: proceedings, 5(1), pp.1824-1831.
[28] Kumar, U.A., Saidulu, G. and Lacminarayana, P., 2020. Experimental investigation of process parameters for machining of Nimonic alloy 75 using wire-cut EDM. Materials Today: Proceedings, 27, pp.1362-1368.