Study of friction and wear properties of ABS/Kaolin polymer composites using grey relational technique

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Abstract

The tribological properties of friction coefficient and specific wear rate of acrylonitrile-butadiene-styrene (ABS) polymer filled with micron-sized kaolin powder are studied in this paper. The tribological tests are carried out for a constant time of 300 seconds in dry condition on multi-tribotester (block-on-roller configuration) based on Taguchi L27 orthogonal array (OA). Filler content, normal load and sliding speed are considered as the design parameter. Using grey relational analysis, multi response optimization problem is converted into single response optimization problem and the optimum combination of design parameters is found as 5 wt % of filler content, 35 N of normal load and 120 rpm of sliding speed. A confirmation test is carried out to validate the optimized result and the result shows that the grey relational grade is increased about 59.39% from initial to optimum parameter conditions. From ANOVA, it is seen filler content is the most significant factor followed by normal load and sliding speed. Finally, SEM images are investigated to identify the wear mechanism.

Keywords: ABS; Kaolin; Grey relational technique; Friction; Wear; Polymer composite

1. Introduction

Polymer composites are considered as one of the interest areas because of its advantages of lower weight alternatives to metallic properties, easiness of processing with different size and shape and low cost by replacing the...
volume of costly resins by incorporating cheap fillers to enhance the properties like modulus, strength, heat deflection temperature etc. Various kinds of fillers are incorporated into polymers to enhance the properties [1, 2]. The polymer composite has a special property of self-lubrication and that makes the composite to use in tribological applications in the field of cams, seals, brakes, bearings etc. In contrary, neat polymers limits its application in tribology due to high friction coefficient and wear rate. Therefore, incorporation of inorganic particulate fillers such as calcium carbonate, talc, mica, zinc oxide, kaolin, copper-oxide, titanium di-oxide etc. of micrometer-sized particles are used to improve modulus, hardness and wear resistance but at the cost of reduced impact strength and tensile strength in the polymer composites [3, 4].

Acrylonitrile–butadiene–styrene (ABS) is one of the engineering thermoplastic terpolymer widely used over the past decades and found applications in many fields like automotive, aerospace, business machines, computers, telephone handsets etc. It has been used as a homopolymer or matrix of the composite materials and found applications in many engineering components like business machines, computers, telephone handsets, automotive interior etc. whereas high coefficient of friction and wear rate for neat ABS polymer limit its applications in tribology [5]. Kaolin is one among the most important fillers used in polymer composites to modify the matrix properties. Kaolin is white, soft, plastic clay mainly composed of fine-grained plate-like particles. Because of its whiteness, fine particle size and plate-like structure, kaolin is suitable for adding as functional filler, extender, ceramic raw material and pigment. Kaolin is a unique industrial mineral that remains chemically inert over a wide pH range. It is soft and non-abrasive and has a low conductivity of heat and electricity. In general, the addition of kaolin to thermosetting and thermoplastic mixes gives smoother surfaces, a more attractive finish, good dimensional stability, and high resistance to chemical attack. Kaolin filled polymers are studied in many research articles related to the rheological and mechanical properties [6, 7].

Many researchers have investigated the effect of polymer with the incorporation of fillers [8-10]. Polymer composites can be effective if the right combination of filler and matrix and the suitable operating process are used in order to achieve the tribological properties [11]. To overcome these problems, some investigators have incorporated the design of experiments to determine the optimum parameters. Cho et al. [12] have used design of experiments approach to study the tribological performance of copper concentrate mineral as a filler in PPS polymer. They have found the lowest steady state wear rate in polyphyelene sulphide (PPS) +20%CC+15% polytetra-fluoro ethylene (PTFE) composition. It has been found from the literature that the optimum quality characteristic can affect the other quality characteristics. It is always desired to optimize the multiple quality characteristics of the process at the same time. Xiang and Gu [13] have investigated the friction and wear behaviour of PTFE with ultrafine kaolin particles. The incorporation of kaolin particles reduces the wear rate by two orders of magnitude as compared to the unfilled PTFE, but friction coefficient increases over unfilled PTFE at filler concentrations of 10 wt %. Guofang et al. [14] have studied the tribological properties of ultra-high molecular weight polyethylene (UHMWPE) polymer composites with the addition of kaolin filler. It is found that the appropriate amount of kaolin filler can greatly improve the tribological property of UHMWPE.

The present study is focused on the tribological behaviour of ABS / kaolin composites using grey relational analysis method with orthogonal array design of experiments. The filler content (A), normal load (B) and sliding speed (C) are selected as design factors with three levels for each design parameter [2-4, 15-17]. The responses selected are coefficient of friction and specific wear rate. The optimum combination of design parameters are found out using grey relational analysis coupled with Taguchi method. A confirmation test is carried out to validate the study. Analysis of variance (ANOVA) is also used to find out the most significant factor which affects the responses. An effort is also made to study the morphology of wear tracks of composites after the friction tests using scanning electron microscopy (SEM) images.

2. Experimental details

2.1. Materials and samples preparation

Acrylonitrile-butadiene-styrene (ABS) polymer is selected as a matrix material supplied by Styrolution ABS Limited, India for the study. It is Absolac–920 grade with a density of 1.04 g / cm$^3$ and melt flow index of 21 g / 10 min. The filler selected for the study is calcined kaolin supplied by Shree ram minerals Ltd, India in the form of
powder with a mean particle size of 1.3–1.7 μm and bulk density of 2.60 g / cm$^3$.  

A Haake single screw extruder (Rheocord–9000) with a screw diameter of 18mm and L/D ratio of 24:1 is employed for the mixing of kaolin powders into ABS pellets homogeneously. The temperature profile of the extruder is shown in Table 1 and the mixing for different compositions is carried out in a continuous manner. In order to improve the mixing, kaolin powder and neat ABS pellets are dried at 60°C in a vacuum oven for 6 hours to remove moisture. The extruded composite are pelletized into granules form in uniform size by using a pelletizer machine. The pelletized composites are dried at 60°C in a vacuum oven for 6 hours to remove moisture before compression molding process. The pelletized granules are placed in a rectangular mold of size 150 X 100 X 8 mm$^3$ and subjected to hot compression mold (Carver Press, Germany) with a temperature of 260°C and load of 8 metric tonnes kept for 1 min and then lowered the load to 6 metric tonnes to allow the entrapped air out from the mold and kept for 15 min with the same load. The specimens for tribological tests are cut from the rectangular bar with a specimen size of 20 X 20 X 8 mm$^3$.

Table 1 Temperature profile along the extruder barrel

| Feed Zone        | Compression Zone | Metering Zone | Die     |
|------------------|------------------|---------------|---------|
| 210°C            | 220°C            | 230°C         | 240°C   |

2.2. Design of experiments

The design parameters with their levels are shown in Table 2. For the present study, three design parameters viz., filler content (A), normal load (B) and sliding speed (C) with three levels of each factor are selected based on the literature survey [2-4, 15-17]. In order to study the effect of parameters and their interactions, a pre-designed orthogonal array (OA), L$_{27}$ is used in this study considering both the main factor effects and its interactions. It is selected on the basis of total degrees of freedom of the experiments. The main factors has 2 (no of levels minus 1, i.e., 3-1) degrees of freedom (DOF) and for two way interaction of the factors, the degrees of freedom is 4. Therefore, total degrees of freedom will be (3 X 2) + (3 X 4) = 18. The total DOF of the OA should be greater than the experimental DOF of the factors. So, L$_{27}$ (26 DOF) OA is chosen for the study. Here, each row represents the test conditions and the column represents the test parameter. The tests are conducted as per the experimental design given in Table 3 at room temperature.

Table 2 Design factors with different levels.

| Design factors | Unit       | Levels       |
|----------------|------------|--------------|
| % of filler (A)| %          | 1 2 3        |
| Load (B)      | N          | 15 25* 35   |
| Speed (C)     | rpm        | 80 100* 120 |

'*' initial testing conditions

2.3. Friction and wear tests

Friction and wear tests of ABS / kaolin polymer composites with different compositions are performed on a block on roller multi-tribotester, TR25 (Ducom, India) under dry condition. The composite samples are pressed against a rotating steel roller (diameter 50 mm, thickness 50 mm and material EN8 steel) of hardness 55 HRc. The rotating steel roller serves as a counter face and the stationery block serves as the test specimen. The tribological tests are carried out based on L$_{27}$ orthogonal array (OA) design of experiments. Each experiment is carried out for a constant time of 300 sec. The experimental data of coefficient of friction are recorded on a computer attached to the testing apparatus. The samples are weighed before and after the experiments to an accuracy of 0.0001 g in mettler toddler electronic balance. The specific wear rate (W$_s$) defined as the volume losses of the specimen per unit sliding distance per unit applied normal load is calculated by the equation (3) [8].

$$W_s = \frac{W_1 - W_2}{\rho \times P \times v \times t}$$  \hspace{1cm} (1)
where $W_s$ is the specific wear rate in mm$^3$/N.m, $W_1$ is the weight before the test in g, $W_2$ is the weight after the test in g, $p$ is the computed density of composites in g/cm$^3$, $P$ is the applied normal load in N, $v$ is the relative sliding velocity in m/s and $t$ is the experimental time in sec.

2.4. Grey relation analysis

Taguchi method [18] is useful for the optimization of the single performance characteristics. However, multiple performance characteristics optimization is different from the single performance characteristic. The main disadvantage for this analysis is the higher S/N ratio for one performance may correspond to a lower S/N ratio for other characteristics. The overall evaluation of the S/N ratio is required for the optimization of multiple performance characteristics. To overcome this problem, Deng [19] has proposed grey relational analysis, which is used in this study because it is an efficient tool for solving inter-relationships among multiple-performances.

The first step in solving the grey relational analysis is the grey relational generation based on equation (2), which is lower-the-better criterion [19] as for the present study COF and specific wear rate need to be minimized.

$$X_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$$  \hspace{1cm} (2)

where $x_i(k)$ is the normalized grey relational value for the $k^{th}$ response, $\max y_i(k)$ is the largest value of $y_i(k)$ for the $k^{th}$ response, $\min y_i(k)$ is the smallest value of $y_i(k)$ for the $k^{th}$ response, $y_i(k)$ is the experimental value for the $k^{th}$ response and $i = 1$ to 27, which is experiment number, $k = 1$ to 3 depends on the number of factors.

The second step is to calculate the grey relational coefficient of the responses from the normalized results, which represent the correlation between the desired and actual experimental data based on equation (3).

$$\xi_i(k) = \frac{\Lambda_{\min} + \zeta \Lambda_{\max}}{\Delta_{o_i}(k) + \zeta \Lambda_{\max}}$$  \hspace{1cm} (3)

where $\xi_i(k)$ is the grey relational coefficient, $\Delta_{\min}$ and $\Delta_{\max}$ is the minimum and maximum values of absolute differences ($\Delta_{o_i}$) of all comparing sequences, $\Delta_{o_i} = \|x_o(k) - x_i(k)\|$ is the difference of the absolute value between $x_o(k)$ and $x_i(k)$, $x_o(k)$ is the reference sequence and $\zeta$ is the distinguishing coefficient $0 \leq \zeta \leq 1$. The distinguishing coefficient $\zeta$ depends upon the weightage of responses. For this study, equal weightage are given to the responses ($\zeta = 0.5$).

After calculating grey relational coefficients, the grey relational grade $\gamma_i$ can be calculated by using equation (4). The overall evaluation of multiple performances is based on the grey relational grade. The higher values of grey relational grade are considered to be the best relation among the sequences.

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k)$$  \hspace{1cm} (4)

where $n$ is the number of responses.

Thus multiple response problems can be converted into a single response problem. Now, Taguchi method [18] may be applied to find out the optimum combination of design parameters taking grey relational grade as the performance index. The S/N ratio is calculated as the logarithmic transformation of the loss function by using larger-the-better criterion as per equation (1) as larger values of grey relational grade are required [20].

$$\frac{S}{N} \text{ ratio} = -10 \times \log_{10} \left( \frac{1}{n} \times \frac{1}{y^2} \right)$$  \hspace{1cm} (5)

where $y$ represents experimental data for grey relational grade and $n$ denotes the number of experiments.
2.5. Analysis of variance

ANOVA is a statistical technique used to predict the process parameters and their interactions significantly affect the quality characteristics [21]. This is done by separating the total variability of grey relational grades, which is measured by the sum of squared deviations from the total mean of grey relational grade, into contributions for each process parameters and the error. F-ratio [22] can be used to determine the parameter which has a significant effect on the quality characteristics based on 95% confidence level. Usually, when F value is large the parameter has a significant effect on the performance. Using Minitab 16 software [23], ANOVA is performed to determine which parameter and interaction significantly affect the performance characteristics.

3. Results and discussions

3.1. Grey relational analysis of friction coefficient and specific wear rate

The tribological testing experiments are conducted based on L27 OA and the experimental data for coefficient of friction and specific wear rate are shown in Table 3. Since there are two responses i.e. COF and specific wear rate, this is a multi-response optimization problem. Using grey relation analysis, multi-response problem is converted into single response problem. The first step in grey relation analysis is to normalize the experimental data in the range between 0 and 1. It is done to avoid the problems of difference in units, scales and targets of the responses. The normalization of results is calculated according to lower-the-better criterion as per equation (2), where the minimum values of responses are the targets. The normalized values of both the responses are shown in Table 3. Ideally, the larger normalized values in both the responses are the best normalized value and are equal to unity. Next step in grey relation analysis is to calculate the grey relational coefficient from the normalized value based on equation (3).

![Table 3 Normalized and grey relational coefficient for responses](image-url)
The grey relation coefficients are used to show the relationship between the ideal (best) and the actual experimental data. In this study, equal weightage are given to the responses so the distinguishing coefficient $\xi$ is taken as 0.5. The grey relation coefficients for the responses are shown in Table 3.

Then grey relational grade is calculated by averaging the grey relational coefficients corresponding to each performance characteristics based on equation (4). It is used to show the relationship among the responses. By using the grey relational grade, the multi-response characteristics can be converted into single response. The grey relational grade and their orders are shown in Table 3. The optimum level of the factors will be the level with the highest grey relational grade. The best optimal parameters obtained from the grey relational grade table for different levels are independent because design of experiments is orthogonal. Taguchi method is used to find the mean of each factor level. Using Minitab 16 software, the grey relational grades are converted into S/N ratio according to larger-the-better criterion, and shown in Table 4 and Table 5. The influences of each factor with their levels are shown in Fig. 1. The highest average grey relational grade for each factor will be the optimum parameters for this study. It is seen from the table that the optimal design parameter combination for minimum COF and wear rate is found as A1B3C3 (5 wt% filler content, 35 N applied load, 120 rpm speed). From the main effects plot (Fig. 1), also same combination of design parameters is found as the optimal one.

### Table 4 Response table for each factor levels of S/N ratio
| Level | A       | B       | C       |
|-------|---------|---------|---------|
| 1     | 0.8358* | 0.5433  | 0.6293  |
| 2     | 0.5015  | 0.6300  | 0.5878  |
| 3     | 0.5293  | 0.6933* | 0.6495* |
| Delta | 0.3343  | 0.1501  | 0.0618  |
| Rank  | 1       | 2       | 3       |
* * indicates optimal process level

### Table 5 Response table for each factor levels of mean
| Level | A       | B       | C       |
|-------|---------|---------|---------|
| 1     | -1.5780*| -5.673  | -4.375  |
| 2     | -6.0970 | -4.340  | -4.971  |
| 3     | -5.6740 | -3.337* | -4.005* |
| Delta | 4.5190  | 2.336   | 0.966   |
| Rank  | 1       | 2       | 3       |
* * indicates optimal process level

![Fig. 1 Influence of factors with their levels](image)

3.2. ANOVA and the effect of factors

ANOVA is performed based on 95% level of confidence and shown in Table 6. The ANOVA table shows the F-ratio and percentage contribution of each factor affecting the response. F – ratio shows that factor A (filler content) has the most significant effect on the response followed by factor B (applied load) and C (sliding speed). According to percentage contribution, filler content has the highest contribution of 78.10% followed by applied load and sliding speed. In case of interactions, the percentage contribution is lower than the error percentage and has no significant effect on the responses. The results of ANOVA analysis are supported by previous studies [12].

3.3. Confirmation test

Using the optimal level of testing parameters, the estimated grey relational grade, $\hat{\gamma}$ is calculated using equation (6) [20], and the factors which are insignificant are neglected while calculating the grade.
where $\gamma_m$ is the total mean grey relational grade, $\bar{\gamma}_i$ is the mean grey relational grade at the optimal testing parameter level and 0 is the number of main design process parameters that significantly affect the performance of polymer composites. The experimental values of grade are compared with an initial condition of A2B2C2 and it is found that the optimal parameter combination enhances the grey relational grade from 0.5558 to 0.8344 by 59.39%. The comparisons of the estimated and the actual grey relational grade are shown in Table 7.

Table 6 ANOVA table for each factor

| Source of variation | Degrees of freedom | Sum of squares | Mean squares | F - ratio | % contribution |
|---------------------|--------------------|----------------|--------------|-----------|----------------|
| A                   | 2                  | 0.6195         | 0.61949      | 116.05*   | 78.1001        |
| B                   | 2                  | 0.1021         | 0.1021       | 19.13*    | 12.8767        |
| C                   | 2                  | 0.0178         | 0.0178       | 3.34      | 2.2492         |
| AxB                 | 4                  | 0.0185         | 0.0185       | 1.74      | 1.2937         |
| AxC                 | 4                  | 0.0103         | 0.0103       | 0.96      | 0.6661         |
| BxC                 | 4                  | 0.0036         | 0.0036       | 0.33      | 0.2486         |
| Error               | 8                  | 0.0214         | 0.0214       |           | 2.6920         |
| Total               | 26                 | 0.7932         |              |           | 100            |

Significant at 95% confidence level ($F_{0.05,2,8} = 4.46$ & $F_{0.05,4,8} = 3.84$)

"*" indicates most significant factor.

Table 7 Confirmation test for estimated and actual grey relational grade

| Level               | Initial parameter | Predicated Optimal | Experimental |
|---------------------|-------------------|--------------------|--------------|
| COF                 | A2B2C2            | A1B3C3             | A1B3C3       |
| Specific wear rate  | 0.002178          | 0.000597           |              |
| Grey relational grade | 0.523500         | 0.9069             | 0.834400     |

(a) (b)

Fig. 2 SEM images after tribological tests (a) initial condition (A2B2C2) (b) optimal condition (A1B3C3)

3.4. Scanning electron microscopy

SEM examinations are carried out for the composite surfaces coated with platinum on a JEOL, Japan (model JSM 6390LV) manufactured microscope to observe the morphology of wear tracks. Fig. 2 (a) shows the SEM image at initial condition (10 wt% filler content, 25N load and 100rpm speed). Fig. 2 (b) shows the SEM image at optimal combination (5 wt% filler content, 35N load and 120rpm speed) obtained from the grey relational analysis. From the micrographs, it is seen that the composite surface are mainly composed of longitudinal grooves due to the effect of micro-cutting and micro-ploughing action. Due to these actions, the materials are removed and displaced resulting in the formation of side edges and microchips in the composite surfaces. If the load and speed increase, the friction
coefficient and wear rate decrease because the surface temperature of the composites increases at high load and speed, hence the composite surfaces become soft due to frictional heat at the interface, thus the reduction in response occurs [12]. From the micrographs of Fig. 2 (b), it is clear that the composite surface is smooth due to frictional heat generated and small amount of debris are formed with increased load and speed, hence COF and wear rate decreases, which supports the optimal condition from the analysis.

4. Conclusions

The tribological behaviour of ABS filled with kaolin composites prepared by compression molding process through melt compounding is investigated in this study. It has found from the study that 5% of filler content, 35 N of load and 120 rpm of speed gives the optimum values of grey relational grade. The confirmation test shows the improvement of grade from initial to optimal condition by 59.39%. It is also found from ANOVA that filler content (A) will affect the grey relational grade significantly followed by load (B) and speed (C). It can be concluded from the study that with addition of kaolin at right combination of factors, the tribological properties are improved.

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