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Friction and Wear Performance of Brake Pad and Optimization of Manufacturing Parameters using Grey Relational Analysis

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ABSTRACT

Brake pads play very important role in the safety of automobiles as they control the speed of the vehicle. Therefore manufacturing aspects of the brake pads and improvement in their performance were studied in this paper. Experiments are designed based on Taguchi's L9 orthogonal array. Manufacturing pressure, temperature and time are taken into consideration as process variables. Nine sets of experiments were conducted. Each experiment consisted of distinct combination process variables. Thus Brake pads with Kevlar and Lapinus fibers as a reinforcement and Epoxy resin as a binder, Barium sulfate as a filler and Aluminium oxide as a friction modifier were manufactured using the hot compression method during each experiment. Friction and Wear performance was accessed by the measurement of the coefficient of friction and weight loss during the trial on the pin on disc apparatus. Specific wear rate was obtained by measuring the differences in density and weight values before and after the trial run.The required values of process parameters i.e. pressure (500 psi), time (8 min.) and temperature (180 °C) which give optimum values of coefficient of friction and Wears were determined using Grey relational analysis.

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NOMENCLATURE

COF	Coefficient of friction	CBP	Commercial brake pad sample
SWR	Wear rate	GRA	Grey relational analysis

1. INTRODUCTION

The performance assessment of brake pads is required on regularly because the brake pad is mainly responsible for maintaining the vehicle's safety and control. The performance of the brake pad is assessed by the comparison method. In this comparison, friction and wear characteristics of newly developed brake pads were compared with the same characteristics of commercial brake pads available in the market. The friction and wear characteristics for both the brake pads are obtained by conduction of trial using pin on disc apparatus or dynamometers. The dry sliding behavior of friction composite predicts the accurate friction performance for the automobile brake pads [1]. The comparison of dry sliding behavior and wear mechanism of low metallic and copper-free brake pads was performed to select the optimum friction composite [2]. Two commercial pads 1) high metallic fiber material, includes 7% copper fibers, 2) low metallic friction material contains thermal graphite (TG), and cellulose fibers as copper substitutes were investigated. The thermal behavior of the two friction materials was nearly identical. Cu-based friction material, on the other hand, was more thermally stable. This work is related to the work discussed in this paper as both compares newly developed brake pads with commercial brake pad used in practice. Pin-on-disc testing was performed to investigate the sliding behavior

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and wear products of a low-steel friction material against a cast iron disc at varied applied loads to study the influence of the temperature rise produced by frictional heating [3]. Dry sliding test runs were performed on the composite specimens prepared during the current work in an exactly similar way which was presented by Wahlström et al.[4] The pin on disc test is performed on the brake pad. The wear and coefficient of friction are the two characteristics that vary depending on the load and speed conditions. The wear formation mechanism is affected by the load and speed of the rotor disc and pin. i.e. at low speed less iron oxide is formed in between the disc and pin; as a result collected wear debris shows equiaxed morphology during low load and lower temperature wherein plate-like wear particles can be seen during high load and higher temperature test conditions [5]. The pin on disc test parameters is selected to study their effect on the morphology of wear debris [6].

The quality of the brake pad mainly depends on material selection, mold design and process parameters. Because mould design and material selection are done at the product development stage, process parameter selection becomes critical for decreasing the faults and enhancing the quality. Process parameters are selected using optimization techniques such as Taguchi approach and the grey relational analysis approach. The study of process parameters that contributes to the mechanical stability of epoxy-based composites is effectively carried out using Taguchi optimization-based grey relational approach [7]. The use of Taguchi L9 orthogonal array was made to design the number of experiments. It was found that a set of nine experiments results in an adequate combination of process parameters that determines the performance of the brake pad [8, 9]. However, the use of grey relational analysis on the experiments obtained by Taguchi L9 orthogonal array was rarely attempted in the previous literature for optimizing the performance of synthetic fibers reinforced polymer composite.

An attempt was made in this paper to manufacture the Kevlar / Aramid fiber reinforced epoxy composite for use as a brake pad in the automobile. Nine combinations of three process parameters namely pressure, temperature and time were selected to manufacture nine sets of brake pads using Taguchi L9 orthogonal array. Friction and wear performance of brake pads were evaluated using the trials conducted on the pin on disc test apparatus. The required combination of process parameters that gives optimum tribological performance was obtained using grey relational grades. Finally, the comparison of newly developed brake pad with commercial brake pad is carried out considering the COF, wear and wear rate.

2. EXPERIMENTAL

The brake pads utilized in this investigation were mostly non-asbestos organic friction materials with five major components (see Table 1). Brake pad prototypes were made utilizing the traditional compression molding method. i.e. Dry mixing, compaction, hot molding and heat treatment (post-curing) [10]. To achieve homogenous mixing of ingredients, a dry mix was made using ball milling for 30 minutes. A hot press with a capacity of 150 tonnes was used to compress the material. The punch was hydraulically powered, and the die was a 14-cavity steel plate. The mold was heated by 1500 W heaters, and the machine's electrical controls and safety switches were situated on a separate panel. Two heaters were placed above the die plate and two heaters were placed below it, for a total of four heaters (Figure 1). Brake samples were produced in the set of nine experiments under consideration of distinct values of time, pressure and temperature. Time, pressure, and temperature, which are all manufacturing characteristics, are used as control variables at three distinct levels (see Table 2).

2. 1. Design of Experiments

L9 orthogonal array was used to investigate the influence of factors [8]. and nine distinct combinations of process parameters were obtained designing the nine experiments (see Table 3).

TABLE 1. Formulation of friction composite

Sr. No	Ingredients	Weight %
1	Phenolic resin	15.00
2	Barium Sulfate	50.00
3	Kevlar fiber	3.00
4	Lapinus fiber	27.00
5	Aluminium oxide	5.00

Figure 1. Hot press machine

Each experiment yields a separate set of samples, thus nine experiments give nine samples.

2. 2. Pin on Disc Test Tribological testing on kevlar and lapinus fiber reinforced friction composite materials was conducted in dry conditions using a pin-on-disc test setup (DUCOM product) in line with ASTM: G 99V [11]. The machine comprises a stationary loaded test specimen that slides against a spinning disc with its axis in the normal direction to the disc (see Figure 2) [12]. The test was conducted on a grey cast iron disc (0.61 Ra surface roughness, hardness 72 HRC) with a 60 mm diameter track to simulate the speed-load limits of genuine brake systems. Before starting a new test, the disc surface was cleaned with acetone-soaked paper and dried with a hot air blower for two minutes. During the test, COF was calculated automatically by taking into account the normal load and frictional force. The frictional force was measured using a transducer mounted on the loading arm. DUCOM's WINDCOM software was used to continuously monitor the COF and record the individual readings. The difference in weight before and after the intended test was determined using a precision electronic scale with an accuracy of 60.01 mg to estimate the weight loss of the specimen.

TABLE 2. Levels of process parameters

Factors		Levels		
Moulding parameters	Process parameters	1	2	3
	Time (minutes) (A)	4	6	8
	Pressure (psi) (B)	500	600	700
	Temperature (°C) (C)	140	160	180

TABLE 3. Design of experiments using L9 orthogonal matrix

Exp. No.	Time (A) (minutes)	Pressure (B) (psi)	Temperature (C) (°C)
1	4	500	140
2	4	600	160
3	4	700	180
4	6	500	160
5	6	600	180
6	6	700	140
7	8	500	180
8	8	600	140
9	8	700	160

The specific wear rate (WR, cm^3/N-m) was then computed as follows [13].

$$SWR = \frac{\Delta M}{(\rho \times F \times L)} \quad (1)$$

where, ΔM (g) is the weight loss after the ending of the whole test, ρ (g/cm^3) is the friction samples density, F (N) is the average friction force and L (m) is the sliding distance.

The experimental trials were performed thrice for each test, average values of the results were reported.

3. RESULTS AND DISCUSSION

To select the superior specimen, higher is the better criteria were adopted for COF and lower is the better criteria were adopted for the values of wear and wear rate of the samples [14]. The maximum value of COF (0.486) was obtained for experiment 7 which is carried out at extreme conditions of temperature and time i.e. at 180 °C, 8 minutes and moderate pressure 500 psi. The minimum value of the coefficient of friction was obtained at 180 °C, 700 psi and 4 minutes. Specific wear rate was a maximum of 7.312 at experiment 8 which is performed at 140 °C, 600 psi and 8 min. The minimum value of specific wear rate (1.283) is observed for experiment 7 which is performed at 180 °C, 500 psi and 8 minutes. The value of wear in terms of weight loss is maximum for experiment 6 which is performed at 140 °C, 700 psi and 6 minutes. Minimum wear in terms of weight loss is observed in experiment 7. Also the wear rate is found lower (1.283×10^{-6} cm^3 / Nm) for experiment 7 which yields sample 7. However there was no exact trend found for values of COF, specific wear rate and wear in terms of weight loss corresponding to individual process

Figure 2. (a) Pin on Disc test set up (b) Pins

TABLE 4. Experimental values for manufactured samples

Properties	Exp. 1 (Sample 1)	Exp.2 (Sample 2)	Exp.3 (Sample 3)	Exp. 4 (Sample 4)	Exp. 5 (Sample 5)	Exp.7 (Sample 7)	Exp. 6 (Sample 6)	Exp. 8 (Sample 8)	Exp. 9 (Sample 9)
COF	0.389	0.316	0.252	0.400	0.29	0.486	0.391	0.283	0.329
SWR (10^{-6} cc / Nm)	1.301	2.999	4.31	2.158	2.807	1.283	5.441	7.312	3.951
Wear (gm)	0.009	0.011	0.01	0.011	0.009	0.005	0.024	0.022	0.011

parameters. But when the combination of process parameters is considered then corresponding values of COF, SWR and wear (gm) follows a particular trend (see Table 4).

The performance characteristics such as wear, COF are assessed under the same load, speed, time and sliding distance conditions for all nine samples. Careful examination of graphs of COF and wear of best three samples from all nine samples revealed the drastic variation because all samples were manufactured by varying the process parameters as per Table 3 [15] (see Figures 3-5). The maximum value of COF was obtained by sample 7. Also, Minimumun wear in terms of weight loss was observed for Expiment 7 i.e. sample 7. Wear rate (1.283 10^{-6}cm^3 / N.m) was also observed for sample 7.

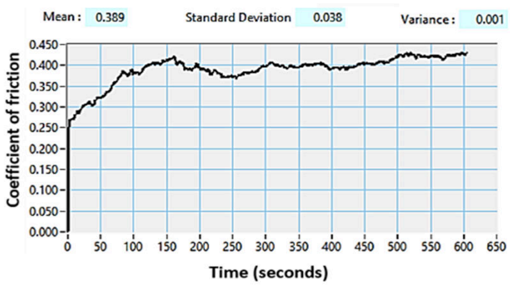

Figure 3. Friction graph (Sample 1)

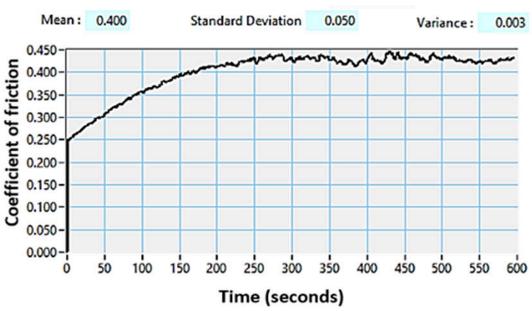

Figure 4. Friction graph (Sample 4)

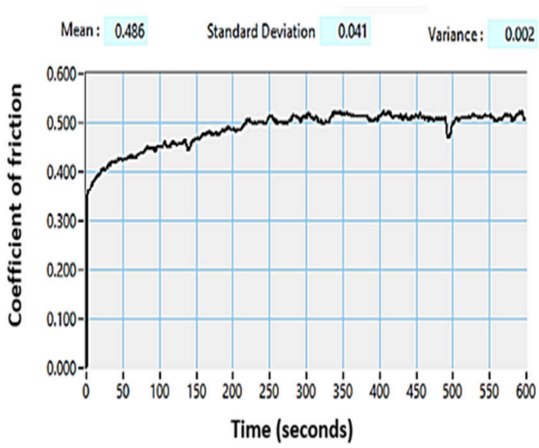

Figure 5. Friction graph (Sample 7)

However minimum wear in micrometer was observed by comparing the wear trend through the DUCOM software interface (Figures 6-9). All nine samples were compared in groups of three at a time, with the superior sample resulting in the least amount of wear. As a result, sample 3 has shown smaller wear compared to samples 1 and 2 (see Figure 6). Sample 4 showed minimum wear when compared to samples 5 and 6 (see Figure 7). Also sample 9 showed minimum wear as compared to samples 7 and 8 (see Figure 8).Thus, sample 7 had a larger COF (0.486) and the same sample exhibited the smaller wear (0.005 gm). However, when the Wear value was retrieved in a micrometers using a software interface, sample 4 was found to be superior, as it showed the least amount of wear among samples 3, 9 and 4 during the 10-minute test (see Figure 9) [16]. This situation has resulted in the Multi response optimization problem.

3. 1. Grey Relational Analysis

GRA was performed to arrive at an optimum combination of process parameters which results in optimum COF, wear and wear rate. A response such as COF should be maximized while wear rate, wear must be minimized

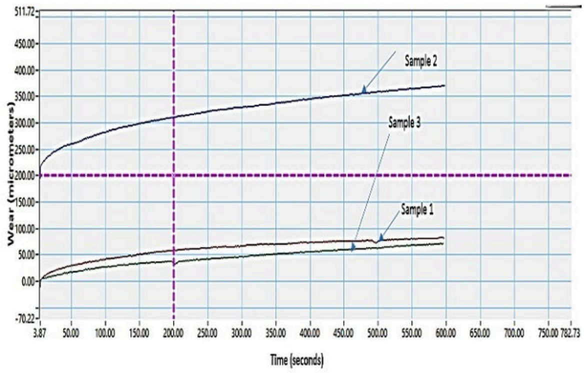

Figure 6. Wear Graph (Sample 1, 2, 3)

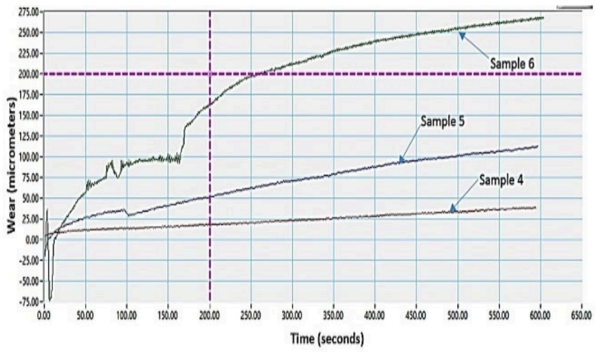

Figure 7. Wear graph (Sample 4, 5 and 6)

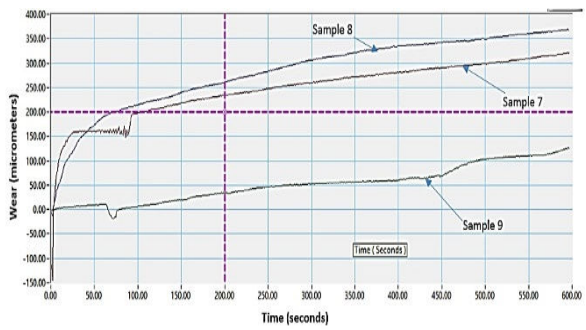

Figure 8. Wear Graph (Sample 7, 8 and 9)

[17]. Therefore the COF response was assigned with higher-the-better and wear and wear rate were assigned lower-the-better respectively to process the data in GRA. All of the sequences were analyzed using Equations (2), (3) and the outcomes were represented in Tables 5 and 6. means reference and comparability sequence. the distinguishing coefficient ϵ can be put into Equation (5) to obtain the Grey relational coefficient (Table 7). Using Equations (5-8) thus Grey relational grade and rank of each experiment are evaluated (Table 8) [18].

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

$$a^*(k) = \frac{a^i(k) - \min a^i(k)}{\max a^i(k) - \min a^i(k)} \quad (3)$$

$$\varepsilon(k) = \frac{\Delta_{min} + \gamma\, \Delta_{max}}{\Delta_o(k) + \gamma\, \Delta_{max}} \quad (4)$$

$$\Delta_i(k) = [x_o(l) - x_i(l)] \quad (5)$$

$$\Delta_{max} = \max\max [x_o(l) - x_i(l)] \quad (6)$$

$$\Delta_{min} = \min\min [x_o(l) - x_i(l)] \quad (7)$$

$$y_i = \frac{1}{n}\sum_{k=1}^{n} \epsilon_i(k) \quad (8)$$

where $x_o(l)$ is the reference sequence and $x_i(l)$ is the comparability sequence. $\epsilon_i = 0.5$ is well-known, and the lower value of ϵ_i pointed at higher distinguished ability.

TABLE 5. Normalized Value

Exp. No	COF	Wear	SWR
1	0	0.211	0.003
2	0.556	0.316	0.285
3	1	0.263	0.502
4	0.366	0.316	0.145
5	0.838	0.211	0.253
6	0.369	1	0.69
7	0.866	0.895	1
8	0.084	0	0
9	0.812	0.316	0.443

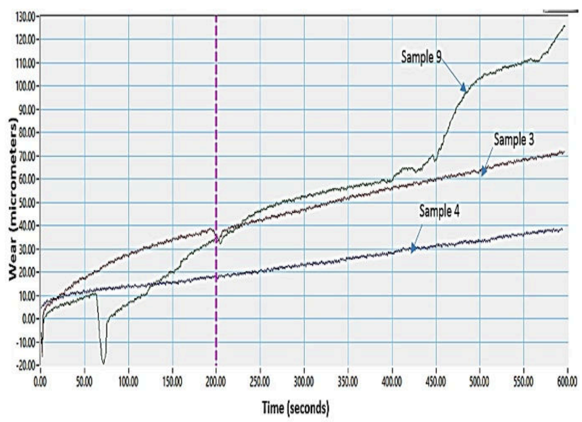

Figure 9. Wear Graph (Sample 3, 4, 9)

Experiment 7 which yields sample 7 showed rank 1 since it has higher grade value (Table 9). Thus experiment 7 can be chosen as an experiment that gives optimum performance among all nine experiments according to Grey relational analysis. Thus the optimum combination of process parameters are 8 minutes, Pressure at 500 Psi and Temperature of 180 ºC .

TABLE 6. Deviation sequence responses

Exp No.	COF	Wear	SWR
1	1	0.789	0.997
2	0.444	0.684	0.715
3	0	0.737	0.498
4	0.634	0.684	0.855
5	0.162	0.789	0.747
6	0.631	0	0.31
7	0.134	0.105	0
8	0.916	1	1
9	0.188	0.684	0.557

TABLE 7. Grey relational coefficients

Exp No.	COF	Wear	SwR
1	0.333	0.388	0.334
2	0.53	0.422	0.411
3	1	0.404	0.501
4	0.441	0.422	0.369
5	0.755	0.388	0.401
6	0.442	1	0.617
7	0.789	0.826	1
8	0.353	0.333	0.333
9	0.727	0.422	0.473

TABLE 8. Rank using GRA

Exp. No.	Grade	Rank
1	0.35	8
2	0.45	6
3	0.64	3
4	0.41	7
5	0.51	5
6	0.69	2
7	0.87	1
8	0.34	9
9	0.54	4

TABLE 9. comparison of developed brake pad with commercial brake pad

Properties	CBP	Sample 7
COF	0.403	0.5666
Wear rate	0.163	1.283
Wear (gm)	0.006	0.005

Figure 10. Brake pads (a) Commercial (b) Newly developed

4. CONCLUSIONS

In this study, friction composites consisting of Kevlar and Lapinus fibers are manufactured and tested for tribological properties utilizing a hot compression process. Taguchi design of experiments was used to create the experimental design, which was then followed by Grey relational analysis to find the optimal combination of process parameters to increase the COF and decrease the wear and wear rate.

The following are some of the study's key findings:

1. The number of experiments obtained by using the Taguchi L9 orthogonal array technique has resulted in nine sets of results which proved to be adequate to reveal the improvement in tribological properties of brake pads
2. The COF, Wear and Wear rate values did not follow the specific trend in response to the change in individual process parameters.
3. The COF, wear and wear rate values follow a particular declining or increasing trend in response to change in values of a combination of process parameters.
4. The highest COF value (0.566), lowest wear (0.005 gm) and wear rate (1.283) value was determined for experiment 7, which was conducted at extreme

temperatures and times, namely 180°C for 8 minutes and moderate pressure 500 psi.

5. The wear values in micrometers during the pin on disc test were obtained as the lowest value for experiment 9 which yield sample 9.
6. GRA gives an optimum combination of process parameters in conditions where multiple superior values (samples 7 and 9) for multiple responses (COF, wear) are available. Experiment 7 which yields sample 7 showed the highest grade (0.87) and rank one.
7. When the newly developed brake pad was compared with the commercial brake pad, COF showed a 14.46 % rise where wear had decreased by 16.67 % and wear rate showed a 87.29 % rise in its value.
8. The optimum combination which gives optimum tribological performance for brake pad is obtained at 8 minutes, Pressure at 500 Psi and Temperature 180 °C.

Thus Kevlar / Lapinus fibers reinforced epoxy composite proved to be effective against the commercial brake pad samples and could be a possible replacement.

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Persian Abstract

چکیده

لنت های ترمز نقش بسیار مهمی در ایمنی خودرو دارند زیرا سرعت خودرو را کنترل می کنند. بنابراین جنبه های تولید لنت ترمز و بهبود عملکرد آنها در این مقاله مورد مطالعه قرار گرفته است. آزمایشات بر اساس آرایه متعامد Taguchy L9 طراحی شده است. فشار تولید ، دما و زمان به عنوان متغیرهای فرآیند در نظر گرفته می شوند. نه مجموعه آزمایش انجام شد. هر آزمایش متغیرهای فرآیند ترکیبی متمایزی را شامل می شد. بنابراین لنت های ترمز با الیاف کولار و لاپینوس به عنوان تقویت کننده و رزین اپوکسی به عنوان چسب ، سولفات باریم به عنوان پرکننده و اکسید آلومینیوم به عنوان اصلاح کننده اصطکاک با استفاده از روش فشرده سازی گرم در طول هر آزمایش تولید شدند. عملکرد اصطکاک و سایش با اندازه گیری ضریب اصطکاک و کاهش وزن در طول آزمایش روی پین بر روی دستگاه دیسک قابل دسترسی بود. میزان سایش خاص با اندازه گیری تفاوت در چگالی و مقادیر وزن قبل و بعد از اجرای آزمایشی به دست آمد. مقادیر مورد نیاز پارامترهای فرآیند یعنی فشار، زمان و دما که مقادیر بهینه ضریب اصطکاک و سایش را ارائه می دهد با استفاده از تجزیه و تحلیل رابطه خاکستری تعیین گردید.