Turkish Journal of Engineering

Turkish Journal of Engineering (TUJE)
Vol. 3, Issue 3, pp. 127-132, July 2019
ISSN 2587-1366, Turkey
DOI: 10.31127/tuje.479458
Research Article

AN INTEGRATED APPROACH BASED ON THE TAGUCHI METHOD AND RESPONSE SURFACE METHODOLOGY TO OPTIMIZE PARAMETER DESIGN OF ASBESTOS-FREE BRAKE PAD MATERIAL

Funda Kahraman [1] and Banu Sugözü *[2]

[1] Tarsus University, Technology Faculty, Mechatronics Engineering Department, Mersin, Turkey
ORCID ID 0000 – 0003 – 4333 – 4943
fundakahraman33@hotmail.com

[2] Mersin University, Engineering Faculty, Mechanical Engineering Department, Mersin, Turkey
ORCID ID 0000 – 0002 – 7798 – 2677
banusugozu@mersin.edu.tr

* Corresponding Author

Received: 06/11/2018 Accepted: 05/01/2019

ABSTRACT
Braking pressure and sliding velocity can affect wear behavior of brake pad material, so sliding velocity and braking pressure is often regarded as the key factor in defining quality performance of this material. For this reason, Taguchi Method has been used to screen the variables that have significant effects on the wear rate. Furthermore, an integrated approach of Taguchi Method and Response Surface Methodology has been employed to improve an empirical model for predicting wear rate and optimization of control factors. It has been observed that an integrated approach based on Taguchi Method and Response Surface Methodology gives 15.45% lower wear rate as compared to optimal results obtained from Taguchi method.

Keywords: *Taguchi method, Response Surface Methodology, Analysis of Variance, Wear*

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Vol. 3, Issue 3, pp. 127-132, July 2019

1. INTRODUCTION

The brake friction material composition (resin, fibers, fillers, friction modifiers, abrasives) plays a crucial role in getting the effective brake pad performance. Besides size, type and amount of added reinforcement, other important parameters influencing the tribological properties are the manufacturing conditions (pressure, temperature, time), and testing conditions (pressure, speed, temperature). The brakes require friction composites composed of eco-friendly components. The friction composites also have stable and high friction coefficient, low wear rate, low cost and no noise. This is because play important roles in brake performance such as disc wear, stopping distance, pedal fell and brake induced vibrations (Aleksendrić and Barton, 2009). It usually includes 10-15 different raw materials to carry out comfortable brake performance at wide range of sliding speeds, humidity and applied pressure (Aleksendric and Duboka, 2006). The researchers have been investigated friction and wear behaviors of brake system to observe the effect of components in the brake composites. A considerable number of articles related to brake pad materials have been published (Sugozu *et al.*, 2018, Gurunath and Bijwe, 2007, Sugozu *et al*., 2016, Bijwe *et al*., 2012, Sugozu *et al*., 2014a, Kumar *et al*., 2012, Sugozu *et al*., 2014b, Kukutschová *et al*., 2010, Djafri *et al*., 2014, Sugözü, 2015, Ertan and Yavuz, 2010). Recently, several researchers have been used statistical methods such as artificial neural networks, grey relational analysis, Taguchi design method, fuzzy logic method, response surface methodology, genetic, differential evolution and particle swarm algorithms to determine optimum brake performance of different brake pad materials (Aleksendrić and Barton, 2009, Aleksendric and Duboka, 2006, Zaharudin *et al*., 2011, Xiao and Zhu, 2010, Ficici *et al*., 2014, Mutlu, 2009, Anoop *et al*., 2009, Singh *et al*., 2014).

In this study, the effect of sliding velocity and braking pressure on the dry wear behavior of asbestos free brake pad material has been investigated by using integrated approach of Taguchi Method (TM) and Response Surface Methodology (RSM). The optimal results obtained from TM-RSM integrated approach and TM have been compared and discussed. Significant improvement in wear rate has been obtained by using TM-RSM integrated approach.

2. EXPERIMENTAL PROCEDURES

In this study, solid-state technique was used to prepare the brake pad materials (15% Phenolic resin, 10% Steel Fibers, 15% Copper particles, 10% Cashew dust, 4% Brass Particle, 10% Graphite, 29% Barite, 7% Alumina). Brake pad specimens were manufactured approximately 25.4 mm in diameter by a conventional procedure. All constituents were weighed and then mixed for 3–4 min for obtaining a homogeny dispersion. The mixture was hot pressed at 150 °C and 15 MPa load for 10 min. The experimental study was completed by following the procedure shown in Fig. 1. Wear tests were performed under unlubricated condition using a pin on disc tester with GG 20 gray cast iron as the counter face with a hardness of 200 HB and the average surface roughness of 1.50 μm. Contact temperatures between samples and disc were measured as 50-175 °C during wear test. Specific wear rate was calculated by using Eq. (1).

$$v = \frac{m_1 - m_2}{2 \cdot \pi \cdot R_d \cdot n \cdot f_m \cdot \rho} \qquad (1)$$

where, v is specific wear rate (cm^3/Nm), m_1 is mass of brake pad before testing (g), m_2 is mass of brake pad after testing (g), n is total revolution, R_d is radius of disc (m), f_m is average friction force (N), ρ is density of brake pad (g/cm^3) (TS 555, 1992).

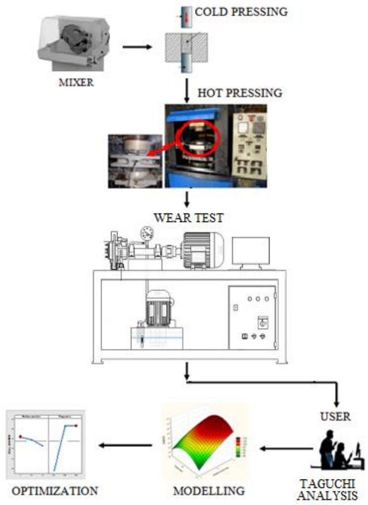

Fig. 1. A schematic diagram of the experimental study

Sliding velocity and braking pressure has been selected as input parameters, and wear rate has been selected as output parameter. Input parameters and their levels have been shown in Table 1. Taguchi analysis was performed by using Minitab 17 software.

Table 1. Factors and their levels for Taguchi design

Factors	Levels		
	Level 1	Level 2	Level 3
Braking pressure (*kPa*)	500	600	700
Sliding velocity (*m/s*)	6	7.5	9

RSM with CCD was used for designing and analyzing experiment by using The Design of Expert 7 software. CCD was used to obtain a mathematical model of wear rate (cm^3/Nm) as a function of the sliding velocity (m/s) and braking pressure (kPa). The optimal value of each parameter obtained from Taguchi analysis has been considered as a central value as "0" for the CCD matrix (Yadav, 2017). The range of each parameter was coded in five levels (−1.41, −1, 0, 1, 1.41). The levels of input factors are shown in Table 2. The relationship between the actual and coded values of factors was calculated by using Eq. (2).

$$x_1 = \frac{S - 500}{100} \qquad x_2 = \frac{V - 9}{3} \qquad (2)$$

where x_1 is braking pressure, x_2 is sliding velocity.

Table 2. Factors and their levels for CCD

Factors/Levels	-1.41	-1	0	+1	+1.41
Braking pressure (*kPa*)	360	400	500	600	641
Sliding velocity (*m/s*)	5	6	9	12	13

3. RESULTS AND DISCUSSION

3.1. Optimization of Wear Rate Using Taguchi Method

TM is a very effective statistical technique to deal with responses affected by number of variables. TM has been used to analyze and optimize single performance characteristic of manufacturing process. TM uses specially constructed tables named as "orthogonal array" to design of experiments and using of these orthogonal arrays reduces the number of experiments. Three categories for S/N ratios is suggested depending on the type of characteristic; smaller is better, nominal is the best, and higher is better.

Since lower wear rate, wear loss, surface roughness, tool wear and cutting force are desirable, smaller values are always preferred in this case (Asiltürk and Akkuş, 2011, Phadke, 1995).

In the present study, the S/N ratio was chosen according to the criterion the smaller the better, in order to minimize the response. The loss function of the smaller the better for response was calculated using Eq. (3).

$$\eta = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{3}$$

where η is the S/N ratio, n is the number of trials, y_i is the experimental value of the i th trial in experiments.

Table 3. Orthogonal array of Taguchi for wear rate and results

Trial no	A (*kPa*)	B (*mm/s*)	*v* (*cm³/Nm*)	S/N (*dB*)
1	500	6	0.116	18.71
2	500	7.5	0.113	18.94
3	500	9	0.110	19.17
4	600	6	0.190	14.42
5	600	7.5	0.180	14.89
6	600	9	0.172	15.28
7	700	6	0.255	11.87
8	700	7.5	0.250	12.04
9	700	9	0.248	12.11

The experiments were performed according to L_9 array based on Taguchi method. Each factor level combination was repeated three times and a total of 27 tests were concluded and the mean values were reported. Experimental conditions and results have been presented in Table 3. The average test results for the wear rate values were transformed into a signal-to-noise (S/N) ratio by using Eq. (2) (Table 3). The mean S/N ratio for each level of the control factors for wear rate was calculated and listed in Table 4. Mean of S/N ratios variation for each level has been shown in Fig. 2. It is seen from Fig. 2 and Table 4 that the first level of A factor, and the third level of B factor are higher and therefore the combination of parameters is A_1B_3. Consequently, the optimum wear condition of the brake pad material for wear rate was determined 500 kPa for the braking pressure and 9 mm/s for the sliding velocity.

Table 4. Mean S/N ratios (dB) for wear rate

Control factors/ Levels	1	2	3	Δ	Rank
A	18.94	14.86	12.01	6.93	1
B	15.00	15.29	15.52	0.43	2

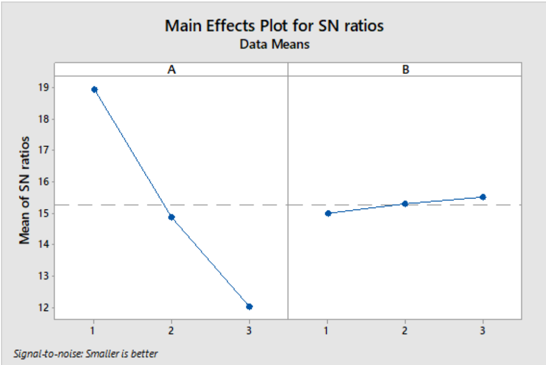

Fig. 2. Mean of S/N graph for wear rate

Further, relative effect of each design parameter is determined by the ANOVA test. Table 5 shows the ANOVA values for the experimental results. The most significant parameter affecting on wear rate was determined that braking pressure (99.28%) at 95% confidence level. Furthermore, F ratios and their percent contribution were taken into consideration to identify the significance level of the control variables.

Table 5. ANOVA results for wear rate

Source	A	B	Error	Total
Degrees of freedom	2	2	4	8
Sum of squares	0.02857	0.00016	0.00004	0.02877
Mean square	0.01428	0.00008	0.00001	
F-value	1266.63	7.16		
P	0.000	0.048		
Contribution (%)	99.28	0.562	0.156	100

3.2. Confirmation Test

Confirmation test was performed to verify experimental conclusions using optimal level of control variables. The predicted value of S/N ratio can be computed by Eq. (4). Table 6 shows that the comparison of the initial, actual and predicted values.

$$\hat{\eta} = \eta_m + \sum_{i=1}^{j} (\eta_i - \eta_m) \tag{4}$$

where $\hat{\eta}$ is the predicted value of S/N ratio, η_m is the total mean of S/N ratio, η_i is the mean of S/N ratio, j is the number of the main design parameters the affect the quality characteristic.

The predicted optimal wear rate (v_p) was calculated Eq. (5) by considering individual effects of the factors (A_1B_3), and their levels. Optimal wear rate was computed as 0.118 cm^3/Nm. Percentage error (%) was determined as 7.27 for the actual wear rate, 0.83 for the S/N ratio. The improvement in wear rate (38.88%), mean quality loss (28.74%) has been obtained as compared to the initial set value of control variables. Based on the confirmation experiment results, wear rate decreased 1.64 times.

$$v_p = T_v + (A_1-T_v) + (B_3- T_v) \quad (5)$$

where Tv is the wear rate total mean value.

Table 6. Results of the confirmation experiments

		Level	v (cm^3/Nm)	S/N (dB)
Initial combination		A_2B_2	0.180	14.89
Optimal combination	Experiment	A_1B_3	0.110	19.17
	Prediction	A_1B_3	0.118	19.33
Error (%)		-	7.27	0.83
Improvement (%)			38.88	28.74

In practice, the quality losses between initial and optimal combination are calculated by Eq. (6). It was calculated as 37% for wear rate. Thereby, quality losses for the wear rate was reduced 63% by using Taguchi method.

$$\frac{L_{opt}(y)}{L_{ini}(y)} = \left[\frac{1}{2}\right]^{\Delta\eta/3} \quad (6)$$

where $L_{opt}(y)$ and $L_{ini}(y)$ are optimal and initial combinations, respectively. Δ_η is the difference between S/N ratios of optimal and initial combinations.

3.3. Prediction of Wear Rate Using RSM Technique

RSM is a statistical technique for the modeling and analysis of problems in which a response of interest is influenced by several variables and objective is to optimize this response. CCD is an experimental design in RSM for developing a predictive model for the response variable. This design consists of a factorial portion and axial portion and a central point (Myer and Montgomery, 2002, Sagbas *et al*., 2009).

The first order and second order model polynomial model can be expressed by the general Eq. (7) and Eq. (8), respectively.

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \varepsilon \quad (7)$$

$$y = \beta_0 + \sum_{j=1}^{k} \beta_i x_j + \sum_{j=1}^{k} \beta_{ij} x_j^2 + \sum_{i}^{k-1} \sum_{j}^{j} \beta_{ij} x_i x_j + \varepsilon \quad (8)$$

where y: response, β_0: constant, β_1 ,…, β_k: regression coefficient, x_1, x_2 ,…, x_j: input factors, k: number of input factors, i=1,2, …, k-1 and j=1,2, …, k, Ɛ: random error

Sliding velocity and braking pressure were considered as model variables and wear rate as a response variable. The Design Expert 7 software was used for designing and analyzing experiment. CCD was used to obtain a mathematical model for wear rate (cm^3/Nm) as a function of the sliding velocity (m/s) and braking pressure (kPa). Experimental levels for input parameters were selected according to a CCD. The plan of experiments was made by randomizing the experiments to avoid accumulation of errors. The experiments were conducted based on randomized run number. Three replications of each factor level combinations were conducted and average values were reported.

The predicted and experimental (actual) wear rate values of based on the CCD rotatable design are presented in Table 7.

The relationship between wear rate and control factors is expressed as Eq. (9).

$$v = 0.11 + 0.032 x_1 + 0{,}013 x_1^2 \quad (9)$$

where; v is the estimated wear rate, x_1 is the coded factor that represents the braking pressure.

Table 7. Actual and predicted wear rate (cm^3/Nm) values

Std	Run	P (kPa)	V (m/s)	Actual v $*(10^{-6})$	Predicted $v*(10^{-6})$	% Error
13	1	500	9	0.120	0.110	8.33
10	2	500	9	0.112	0.110	1.78
5	3	360	9	0.085	0.093	9.41
6	4	640	9	0.175	0.180	2,85
12	5	500	9	0.110	0.110	0.00
4	6	600	12	0.162	0.150	7.40
1	7	400	6	0.110	0.100	9.09
11	8	500	9	0.111	0.110	0.90
7	9	500	5	0.118	0.130	10.16
3	10	400	12	0.100	0.093	0.16
2	11	600	6	0.180	0.170	5.55
9	12	500	9	0.115	0.110	4.34
8	13	500	13	0.105	0.110	4.76

ANOVA has been performed to test the applicability of improved model for the experimental data fitted in the model or not. Results of ANOVA for wear rate is presented in Table 8. Results indicate that x_1 and x_1^2 are significant model terms. Other model term is not significant. This insignificant model term is removed in developed model.

Table 8. ANOVA results for improved model

Source	SS	DF	MS	F value	Prob>F
Model	9.79E-003	5	1.96E-003	20.33	0.0005 significant
x_1	8.40E-003	1	8.40E-003	87.19	< 0.0001*
x_2	2.69E-004	1	2.69E-004	2.79	0.1388
x_1^2	1.09E-003	1	1.09E-003	11.30	0.0121*
x_2^2	7.40E-005	1	7.40E-005	0.77	0.4098
$x_1 x_2$	1.60E-005	1	1.60E-006	0.17	0.6959
Residual	6.75E-003	7	9.64E-005		
Lack of fit	6.09E-004	3	2.03E-004	12.46	0.1690 not significant

*significant factors at 5% significance level

As seen from the Table 8, braking pressure has the largest F-value which indicates the stronger influence on performance characteristics. Similar data is also provided by the contribution (%) in Table 5.

The F calculated value is greater than F table value ($F_{0.05,2,5}$=5.79) and hence the quadratic model can be said quiet adequate. Also, mean absolute percentage error (MAPE) and coefficient of correlation (R^2) were used to the developed model as the performance criterion. It was found to be as 4.98% for the wear rate. The value of Adj-R^2 between predictive values and experimental results is obtained 89% for the wear rate. This values showed that the developed quadratic model fit well with experimental results and it can be significantly used to predict wear rate.

3.4. Optimization Using TM-RSM Integrated Approach and Desirability Functions

After building the regression model, a numerical optimization technique using desirability functions analysis (DFA) described by Derringer and Suich can be used to optimize the response. Single response optimization determines how input parameters affect desirability of individual response. The objective of optimization is to find the best settings that minimize a particular response. Desirability ranges from zero to one for any given response. A value of one represents the ideal case, while zero indicates that one or more responses fall outside the desirable limits (Myer and Montgomery, 2002). DFA was also used control variables to find the best combination of control variables in the combined approach of TM-RSM. In this analysis, the goal used for the wear rate is "minimize" and the goal used for the control factors are "within range". Desirability value was obtained as 0.92. Consequently, the optimum wear rate 0.093 cm^3/Nm was obtained at 400 kPa for the braking pressure and 11 mm/s for the sliding velocity

Comparison of optimization techniques have been presented in Table 9. It has been observed that DFA based on TM-RSM integrated approach gives (15.45%) lower wear rate than result obtained from TM.

Table 9. Comparison of optimization techniques

Optimization technique	Wear rate (cm^3/Nm) Optimal	Wear rate (cm^3/Nm) Predicted	Absolute Error (%)
Taguchi approach	0.110	0.118	7.27
TM-RSM integrated approach	0.093	0.091	2.15
Improvement (%)	15.45	-	-

4. CONCLUSION

This study focuses on TM and TM-RSM integrated approach for investigating of the wear behavior of the asbestos-free brake pad materials. Following conclusions based on this study can be drawn from modeling and optimizing:

• The percentage contribution of braking pressure is as (99.28%), which follows by sliding velocity (0.562%).

• Braking pressure is obtained the most significant factor affecting wear rate by ANOVA.

• The percentage improvement in quality loss is (28.74%) at optimal parameters combination obtained by TM as compared to the initial set parameters.

• The developed quadratic model capable to predict the wear rate with MAPE (4.98%).

• The optimal combination obtained by TM is as braking pressure 500 kPa and sliding velocity 9 mm/s.

• The optimal combination obtained by TM-RSM integrated approach is as braking pressure 400 kPa and sliding velocity 11 mm/s.

• Optimum wear rate value obtained by DFA based on TM-RSM integrated approach is better (15.45%) than as compared to optimum value of TM approach.

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