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TAGUCHI METHOD FOR OPTIMISING THE MANUFACTURING PARAMETERS OF FRICTION MATERIALS

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ABSTRACT

Semi-metallic friction materials were produced by powder metallurgy method. This study investigated the optimization of manufacturing parameters (molding pressure, molding temperature and molding time) for friction materials using Taguchi Method. Physical properties (hardness and specific gravity) and tribological properties (wear and fade) were selected as the quality target. It was determined that molding pressure has the strongest effect on physical and tribological properties. It was observed that friction materials with optimal level of parameters proved to be the best performance in tribological behavior. Physical properties however, did not show any correlation with tribological properties.

***Keywords**:* Taguchi method, Tribological behavior, Friction material

1. INTRODUCTION

Brake friction material is a heterogeneous material that diverse in physical, mechanical and chemical properties of the developed formulation. They are classified as binders, reinforcements, fillers, friction modifiers. Friction and wear characteristics of the developed formulation cannot be predicted based on physical and mechanical properties. Selection of ingredient materials is the difficult task as it requires a great number of experiments to obtain reliable brake performance. A variety of techniques have been employed to investigate the development of ingredients for friction materials in order to provide stable friction, durability, adequate wear resistance, thermal conductivity and vibration for all braking, and acceptable environmental conditions (Cho et al., 2005; Jang et al., 2001; Tang and Lu, 2003).

Limited reports are available in the literature on the investigation on the manufacturing processes of brake friction materials even though they are critical for the tribological as well as physical properties of the brake friction materials. Ibhadode and Dagwa, 2008 in their study have demonstrated the relationship between the manufacturing parameters and tribological properties. In the automotive brake friction industry, friction material is manufactured using powder metallurgy according to two critical methods; first, hot molding of a mixture under high pressure and second, subsequent heat treatment (post-curing). The molding processes involves rearrangement of powder particles, the elastic deformation of the particles and finally, plastic deformation accompanied by reduction in porosity (Al-Qureshi et al., 2008). Heat treatment is performed to enhance curing uniformity and to relieve the residual stresses in the brake friction materials. Phenolic resin used as a binder in brake friction materials plays a crucial role in determining the tribological properties since the manufacturing conditions are affected by thermal properties of the binder (Bijwe et al., 2005; Kim et al., 2008). Hence in this work, the economical and viable experimental strategy based on Taguchi's parameter design has been used to analyze the effect of various manufacturing parameters of friction materials for molding in order to improve tribological properties.

Table 1: Ingredient of friction materials

Ingredients	wt.%	Ingredients	wt.%
Steel fiber	20	Iron oxide	8
Ceramic Fiber	10	Magnesium oxide	3
Friction dust	8	Copper chip	10
Iron powder	5	Barium sulphate	5
Phenolic resin	12	Calcium carbonate	4
Rubber	3	Graphite	12

2. METHODOLOGY

2.1 Sample Preparation

Friction material used in this work containing 12 ingredients is listed in Table 1. The friction material was prepared by mixing, pre-forming hot molding and post curing. Mixing was carried out in a turbula mixer for 30 min. The mixer could move in three dimensions during mixing process. The mixture was pre-formed under 20 tonnes of pressure for 3 min at room temperature. The mixture was molded by a hot press according to 8 different combinations of manufacturing parameters to form L8 (2^3) orthogonal array (OA) of the Taguchi. Post curing was then carried out in an oven at 120^{o}C for 60 min, 150^{o}C for 60 min and 180^{o}C for 120 min to relieve the residual stress in the friction material specimens. The surfaces of the friction material specimens were then grinded to attain the desired thickness and smooth surface.

Thermogravimeric analysis was carried out to obtain the transition temperature of phenolic resin. Figure 1 shows the DTG curve of phenolic resin indicating an exothermic reaction in temperature range between 140^{o}C to 170^{o}C.

Table 2: The experimental layout of Taguchi L8 orthogonal array

Set	A	B	C
1	1	1	1
2	1	1	2
3	1	2	1
4	1	2	2
5	2	1	1
6	2	1	2
7	2	2	1
8	2	2	2

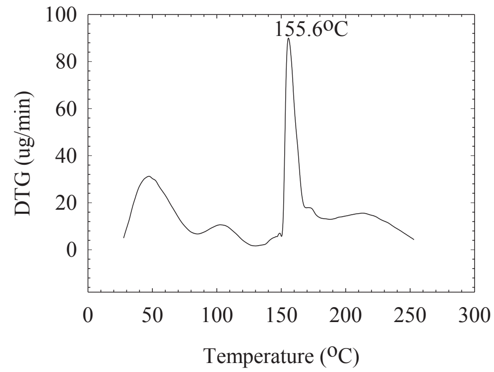


Figure 1 DTG analysis of phenolic resin as a function of temperature

A total of 8 experiments were designed according to standard Taguchi's L8 OA, which has 8 rows corresponding to the number of tests with three factors at two levels, as shown in Table 2. Molding pressure, molding temperature and molding time were selected as the manufacturing parameters to analyze their effect on the physical and tribological properties of the friction materials. The first column in Table 2 was assigned to molding pressure (A), the second to molding temperature (B) and the third to molding time (C). The settings of molding pressure (A) include 50 tonnes (level 1) and 60 tonnes (level 2); molding temperature (B) include 150^{o}C (level 2) and 170^{o}C (level 2); molding time (C) is set at 300 second (level 1) and 600 seconds level 3).

Four quality objectives of friction materials specimens are chosen, including hardness, specific gravity, wear and fade. Typically, large value of physical properties (hardness, *h* and specific gravity, *sg*) and small values of tribological properties (wear, *W* and fade, *f*) are desirable for the manufacturing operation. The experimental results are then transformed into a signal to noise (S/N) ratio. Taguchi proposes the use of the S/N ratio to measure quality characteristics deviating from the desired values. There are three categories of quality characteristic (output performance) in the analysis of the S/N ratio, i.e. larger-the better, nominal-the-best and smaller-the-better. The S/N ration for each level of process parameters is computed based on the S/N analysis. In spite of the category of the quality characteristic, process parameter setting with the highest S/N ratio corresponds to better quality characteristics. Therefore, the optimum level of the process parameters is the level with the highest S/N ratio with minimum variance. Statistical analysis of variance (ANOVA) is performed to observe the most significant controlled factor for the manufacturing operations. Based on the S/N ratio and ANOVA analyses, the optimum combination of process parameters can be predicted. A confirmation run is conducted to verify the optimal process parameters obtained from the design parameter.

2.2 Measurement of Physical Properties

Surface hardness of the friction material specimen was measured using a Rockwell hardness tester (Mitaka TH300) in S scale. Specific gravity or density was measured using specific gravity meter (Shimadzu). The hardness and specific gravity test followed the standard test procedures MS 474: PART 2:2003 and MS 474: PART 1: 2003 respectively, develop by International Standard Organization, Malaysia Standard Department.

2.3 Measurement of Friction Performance

The friction and wear tests were performed using Chase dynamometer in accordance with SAE-J661. The specimens were cut to a dimension of 25 x 25 x 7 mm and then attached to the brake mechanism on brake drum. In this test, each specimen was pressed against a rotating brake drum with a constant speed of 417 rpm under the load of 647 N and subjected to test sequence in Table 3.

Table 3: Friction and wear test program

Block	Temperature (°C)	Remarks
Burnish	82 - 93	Continuous braking 20 minutes
Baseline I	93	Intermittent braking 10 s ON, 20 s OFF, 20 applications
Fade I	93 – 288	Continuous and heater ON
Recovery I	260 – 93	Continuous and cooling ON
Wear	193 -204	Intermittent braking 20 s ON, 10 s OFF, 100 applications
Fade II	93 – 343	Continuous and heater ON
Recovery II	316 – 93	Continuous and cooling ON
Baseline II	93	Intermittent braking 10 s ON, 20 s OFF, 20 applications

The wear was expressed as in term of thickness loss, $W = (t_o - t_1)/t_o$ x 100%, where t_o and t_1 are the average thickness loss of the specimen before and after chase, respectively. Brake fade, f was obtained by calculating the decrement of the friction coefficient after the highest friction coefficient during friction test.

3. RESULTS AND DISCUSSION

3.1 Physical Properties

The results of the physical properties (surface hardness and specific gravity) measurements of the friction materials are shown in Table 4. The average hardness of the friction material was 76.63 $\pm$ 2.63 in Rockwell hardness S scale and the average specific gravity was 2.25 $\pm$ 0.14 g/cm^3.

In this study optimization is achieved by using S/N ratio larger-the better quality characteristics. The largest hardness and specific gravity would indicate the ideal situation. Friction materials with high surface hardness may reduce wear rate which indicates poor life. At high molding pressure, the densities increases and the pores between brake friction materials were reduced. High specific gravity reduces the wear and improves the thermal conductivity of material (Esswein Junior et al., 2008; Kurt and Boz, 2005). For the larger-the-better characteristics, the S/N ratio calculated as follows:

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \qquad (1)$$

where n is number of observations in the L8 orthogonal array and y_i is the average of observed data.

Table 4: Experimental results and S/N ratio for physical properties results

Set	*h* (HRS)	S/N ratio (dB)	*sg* (g/cm^3)	S/N ratio (dB)
1	72	37.147	2.25	7.044
2	73	37.266	2.25	7.044
3	71	37.025	2.20	6.848
4	80	38.062	2.18	6.769
5	86	38.690	2.27	7.121
6	80	38.062	2.32	7.310
7	76	37.616	2.21	6.888
8	75	37.501	2.34	7.384

h: hardness; *sg*: specific gravity

Table 5: ANOVA table for surface hardness

Factor	Sum of squares	Contribution (%)	*p*- value
A	0.7016	31.45	0.148
B	0.1153	5.17	0.588
C	0.0213	0.96	0.818

Table 6: ANOVA table for specific gravity

Factor	Sum of squares	Contribution (%)	*p*- value
A	0.1244	37.68	0.105
B	0.0.493	14.93	0.344
C	0.0460	13.92	0.363

ANOVA is used to identify the relative importance of the manufacturing parameters affecting the quality characteristics. The ANOVA analysis for surface hardness and specific gravity are shown in Table 5 and Table 6, respectively. This analysis was carried out for significant level of α = 0.05, for confidence level of 95%. The order of the percentage contribution reflects the relative importance in each factor. The tables suggested that the factor A, molding pressure has the strongest effect on the surface hardness (Kim et al., 2003) and specific gravity, followed by molding temperature and finally molding time. However, all the factors have insignificant effect to surface hardness and specific gravity because their *p*-values are more than 0.05. Hardness and specific gravity test is used as quality control during production of friction materials.

3.2 Tribological Behavior

The eight friction materials developed by L8 OA exhibited the coefficient of friction in the range of 0.321-0.366, that correspond to the Class E (μ:0.25 to 0.35) and Class F (μ: 0.35 to 0.45). Friction materials have to be designed so that the coefficient of friction is maintained over a wide range of stressing condition.

Table 7: Experimental results and S/N ratio for wear and brake fade amount

Set	*W* (%)	S/N ratio (dB)	*f*	S/N ratio (dB)
1	2.36	-7.458	0.038	28.404
2	1.54	-3.750	0.050	26.021
3	2.50	-7.959	0.070	23.098
4	1.92	-5.666	0.075	22.499
5	3.05	-9.686	0.040	27.959
6	2.58	-8.232	0.075	22.499
7	2.69	-8.595	0.044	27.131
8	2.41	-7.640	0.051	25.849

W: Wear; *f*: Fade

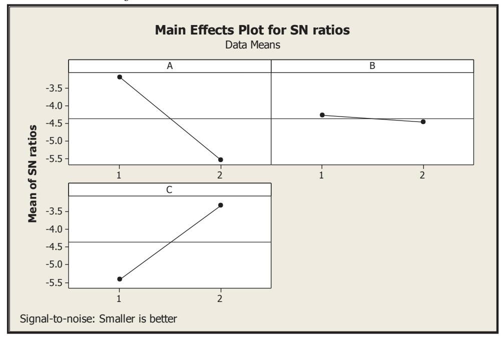


Figure 2 Main effect plots for S/N ratio for wear (*W*) and brake fade amount (*f*)

Table 7 shows experimental results of wear, fade amount and corresponding S/N ratio. In this experiment, smaller value of wear and brake fade amount are desirable. The smaller-the-better characteristics should be taken for obtaining optimal tribological behavior. Wear of friction materials should be minimized as much as possible. Higher wear rate means shorter friction material life and thus, incurred more material and maintenance cost. Lower wear rate would increase the life of the brake pad and higher friction coefficient would offer a better performance. Brake fade was related to thermal stability and thermal diffusivity of ingredients. Large amount of brake fade that organic ingredients decomposed at elevated temperature above 340^{o}C.

The category the-lower-the-better was used to calculate the S/N ratio for both quality characteristics wear (*W*) and fade performance (*f*), according to the equation:

$$S/N = -10\log\frac{1}{n}(\sum_{i=1}^{n} y_i^2) \qquad (2)$$

Based on the results in Table 7, analysis of the results leads to the graph in Figure 2 used to determine the optimal set of parameters from this experimental design. The control factor of molding pressure (A) at level 1 (50 tonnes) provided the best result. Molding pressure of 50 tonnes provide adequate bonding forces as an increase in pressure will cause an increase in energy waste. Similarly, the control factor of molding temperature (B) at level 1 (150^{o}C) provided the best result. This suggest that the wear and fade of friction material increases at high molding temperature was caused by resin decomposition (Lin and Ma, 2000). However, Kim et al., 2003 reported higher molding temperature in their study. Molding time (C) at level 2 (600 second) provided higher S/N ratio than at level 1 (300 second). Molding time of

300 second (C1) explained the insufficient time for the binding process and the weak binding of the phenolic resin between powders even though Ertan and Yavuz, 2010 claimed lower molding time. Figure 2 also shows that the molding pressure (A) has a greatest impact on tribological behavior followed by molding time (C) and finally, molding temperature (B).

Table 8 shows the results of ANOVA for wear, *W* and brake fade amount, *f*. It can be found that molding pressure (A) and molding time (C) are the significant manufacturing parameters for affecting wear and brake fade amount. Molding temperature (C) has an insignificant effect (p = 0.814). Therefore, the optimized combination of levels for the three control factors from the analysis was A1 (50 tonnes), B1 (150^{o}C) and C2 (600 second).

After identifying the optimal levels of all the control factors, the final stage is to verity the tribological properties by conducting the confirmation experiments. The condition A1B1C2 of the optimal parameters combination of the molding process was treated as confirmation run. Three specimens of friction materials were prepared under the optimal parameter set up in the study for the purpose of confirmation run. Table 9 indicates the results of the confirmation run. The mean wear of the confirmation specimens was 1.52% compared with the lowest measurements value in Table 7 was 1.54%. This result indicates that the selected control factor level produced the best wear characteristics.

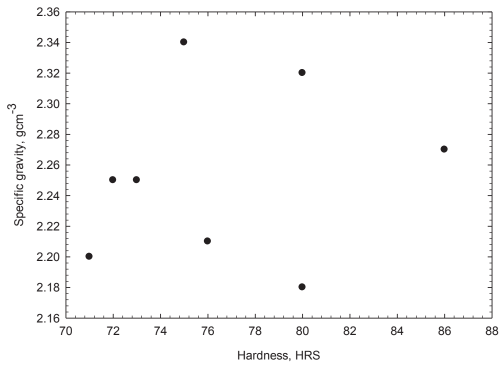
Figure 3 exhibits the correlation among surface hardness, specific gravity and wear of the friction materials studied in this work. The figure clearly indicates that no apparent relationship between hardness and specific gravity or wear. This result point out that friction performance cannot be fully determined by only comparing the physical properties of friction materials. Tribological characteristics are the major determinant to best formulation that could be used as prototype while physical properties act as quality control for consistent composition in actual production process.

Table 8: Results of the ANOVA for wear (*W*) and brake fade amount (*f*)

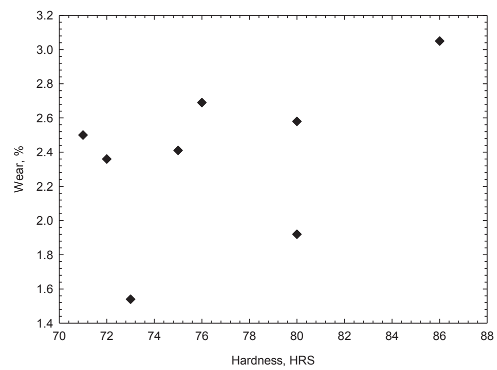
Factor	Sum of squares	*F*-value	*p*-value
A	10.8394	10.13	0.033
B	0.0677	0.06	0.814
C	8.8169	8.24	0.045

Table 9: Results of the confirmation run

Specimen	*W* (%)
1	1.30
2	1.62
3	1.64
Mean	1.52



(a)



(b)

Figure 3 The relationship between physical properties: (a) hardness and specific gravity and (b) hardness and wear

4. CONCLUSION

This study presented an efficient method to determining the optimal manufacturing parameters for improved tribological behavior of friction materials through the use of Taguchi parameter design process. The analytical results are summarized as follows:

1. The molding pressure had the strongest influence on tribological characteristics. From the results evaluated, it was determined that the molding pressure should be held within the optimal limits.

2. The results summarised above suggest optimum manufacturing parameters for which the friction materials composition used in our experiments exhibited the best tribological properties with minimum energy waste. These optimal parameters are 50 tonnes molding pressure (A), 150^{o}C molding temperature (B), and 600 seconds molding time (C).
3. Tribological characteristics are the major determinant to best formulation that could be used as prototype while physical properties act as quality control for consistent composition in actual production process.

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