Multi Objective Optimization of Nano-composite Non-asbestos Friction Lining Material using Grey Relation Analysis (GRA)

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Abstract. Friction lining materials should possess high coefficient of friction at the same time should have high wear resistance. Moreover, it should be stable at elevated temperature encountered due to sliding friction. One has to think of many functional requirements in order to develop a friction material, which gives motivation to optimize the friction materials for multiple objectives. In this work, three variant (CSP0, CSP15 and CSP30) of friction lining materials with nano-coconut shell powder are developed and subjected chase friction testing. Specimen preparation is done at Universal brakes Jalgaon (MS, India) and Chase friction test is conducted at Indian Friction Material Engineering Company, Delhi (India). The results of the test are then used in multi-objective decision making for the selection using Grey Relation Analysis (GRA). It is applied based on the temperature sensitivity performance of Coefficient of friction (CoF) of the specimens, through six different criterions in parallel. It is observed that CSP30 has ranked 1 according to GRA with six criterions.

1. Introduction

Friction lining materials are the category of material which should wear progressively giving desired frictional effect and also sustain their properties at elevated temperature. This functional requirement motivates to develop the material with more devotion and determination. These are the composite materials with five major components, i.e. binder, reinforcing fiber, filler, friction modifier and additives. In each of the category, more than one material can be used to improve overall properties of the friction material. Till 90’s, the friction lining materials consisted of asbestos as a major constituent, due to its dominant mechanical and physical properties. Environmental issues related to asbestos led to development of non-asbestos friction lining material [1]. Researchers have tried metallic, semi-metallic and non-metallic material to replace asbestos [2-12]. Again, due to ecological issues related to copper, in this decade many countries have banned the use of copper as friction lining materials, which further led to development of copper free friction lining material [13-15]. Nowadays, nano-materials have attracted the scientist to use them in composite material, due to exhibition of desired properties in the resulting material. The friction lining material with nano-material as a constituent shows enhanced tribological and mechanical properties [16]. Nano-metallic compositions in the friction lining material with improved properties are being used and reported by some researchers [17-18]. But, the friction lining material with non-metallic, eco-friendly compositions are still under development.

The sliding speed, braking force and sliding distance are the performance parameters of the automotive brakes. These performance characteristics of the brake depends upon the tribological...
properties of the friction lining material, which slides over the drum or disc surface to provide the braking. Qi et al. (2007) had investigated the interface temperature between the disc and friction lining pad considering these parameters [19]. Ficici et al. (2011, 2014)[20, 21] and Kumar et al. (2013)[22] considered material compositions with these parameters to optimize the tribological behavior using Taguchi method, whereas Kim et al. (2003)[23] optimized the manufacturing parameters of the friction lining material with these operating parameters of the brake. Researchers commonly use Taguchi method to optimize the performance of friction lining material [24-25].

Need of Today’s growing world is to optimize the output with multiple objective for minimum resources, which stimulated the evolution of multi-objective optimization. Grey Relational Analysis (GRA) integrated with Taguchi Design is one of those kinds. Manikandan et al. (2017) had used GRA method to optimize the electrochemical drilling of Inconel 625 for higher material removal and lower surface roughness [26]. Mozammel et al. (2016) optimized the process variables of high-pressure turning of Ti-6Al-4V with coolant for minimum cutting forces and surface roughness, using sole objective and multiple objective approach and compare them with each other [27]. Farhad et al. (2012) optimized the turning process of 50.2 steel for maximum material removal rate and lower surface roughness [28]. Milling parameters of titanium alloy rotor disc with blades channels has been optimized for higher amount of materials removed and life of the cutter, for minimum thickness of residual stress layer [29]. Researchers have applied GRA optimization method to different field of interest [30, 31].

Despite of enormous research in the field of non-asbestos friction lining material, the application of multi-objective optimization to nano-composite friction lining materials for higher coefficient and lower wear is untouched. An attempt to elaborate this, through experimental and statistical techniques is made here, through development of a non-asbestos friction lining material using a nano-coconut shell powder as a filler keeping other compositions fixed and subjecting it to an experimentation design using GRA multi-objective optimization technique.

2. Materials and Methods

This work aims at analysing automotive drum brake using finite element analysis, for nodal deformation of the friction liner surface in contact with drum and validating the outcomes using a mean height measurement of the nodes respective to the surface of the friction liner after experimentation with similar performance parameters. A standard size our wheel automotive drum brake is modeled in software package Solidworks 17.0 available at CAD/CAE lab (Mechanical Engineering Department, MPSTME SVKM’s NMIMS Shirpur, Dist-Dhule, MS), with shoe and friction liner shown in figure 1. Considering the symmetrical geometry of the drum brake, a half model is taken.

In the present study, two friction lining materials to be used in automotive drum brake, are developed varying the nano-coconut shell powder as a filler keeping remaining composition same. Coconut shells are collected, cleaned, crushed and sieved manually up to required size. The sieved powder is subjected to particle size measurement using Malvern Zetasizer. Pdl is the polydispersity which describes the degree of non-uniformity of a size distribution of particles in a powder. It is also called as heterogeneity index, which in our case is 0.618. The compositions shown in table 1, is selected with reference to literature [32-41].

| Sr. No. | Ingredients                        | Weight percentage |
|---------|------------------------------------|-------------------|
|         |                                    | CSP0  | CSP15 | CSP30 |
| 1       | Binder (Phenolic resin)            | 20    | 20    | 20    |
| 2       | Reinforcement (Glass fiber and Steel wool) | 15    | 15    | 15    |
| 3       | Filler                            | Coconut Shell Powder (CSP) | 0 | 15 | 30 |
|         |                                   | Calcium Carbonate (CaC03)   | 35    | 15    | 0    |

Table 1: Composition of the materials
With these compositions, drum brake liners are manufactured at Universal Brakes Ltd, Jalgaon (MS-India). The ingredients are mixed thoroughly using mixer. The mixture is preformed and molded into slab of required shape but of larger size. The friction material slab is then put into an electric furnace for sintering. The grounded piece of linings obtained from the slab are to be bonded over the brake shoe, which is accomplished through a process of bonding and finally a brake liner with shoe is made ready. Chase friction testing is performed for tribological analysis. Fade & recovery are the phenomenon used to demonstrate the actual operating conditions of the brakes, which are utilized here. Table 2 shows the performance parameters of the test.

| Operation cycle | Conditions                                                                                   |
|----------------|-----------------------------------------------------------------------------------------------|
| First fade     | Starting temperature= 91°C, Ending temperature= 289°C, Sliding speed (rpm)= 400, Applied pressure= 1 MPa, times of brakes applied in a cycle=8, gap between two brakes is 10 s, air blower=off. |
| First recovery | Starting temperature= 91°C, Ending temperature= 289°C, Sliding speed (rpm)= 400, Applied pressure= 1 MPa, times of brakes applied in a cycle=5, and gap between two brakes is 10 s, air blower=on.               |
| Second recovery| Starting temperature = 93°C, ending temperature= 345°C, Sliding speed (rpm)=400, Applied pressure= 1 MPa, times of brakes applied in a cycle =10, gap between two brakes is 10 s, air blower=off.                                   |
| Second recovery| Starting temperature= 317°C, ending temperature= 93°C, Sliding speed (rpm) =400, Applied pressure= 1 MPa, times of brakes applied in a cycle =5, gap between two brakes is 10 s, air blower=on.                     |

2.1 Grey Relational Analysis (GRA)

The grey relational analysis is used in this work considering seven criterions listed in table 3 [33-36]. It is a multi-criterion decision making methodology, which is utilised mostly to assess the raw data without any association during the operations. GRA is based on following steps: (1) recognition of evaluating criterions, (2) preparation of operations matrix, (3) preparation of normalized operations matrix, (4) evaluation of grey relation coefficient, and (5) evaluation of grey relation degree.

Step-1: Evaluation criterions are selected from performance parameters of the process under study. There may be n-number of criterions.

Step-2: The operations matrix is generated through criterions and possible ways to solve the problem. If solution ways are A and number of criterions are B then the operations matrix having an order of A x B is to be used.

Step-3: The operations matrix are then normalized between 0 and 1. Each value in the normalised operations matrix is determined using following relations:

Larger the better,
\[
X'_{ij} = \frac{x_{ij} - \min[x_{ij}]}{\max[x_{ij}] - \min[x_{ij}]} \quad (1)
\]

Smaller the better,
\[
X'_{ij} = \frac{\min[x_{ij}] - x_{ij}}{\max[x_{ij}] - \min[x_{ij}]} \quad (2)
\]
Step-4: Grey relation coefficient for each term is evaluated using relation:
\[ \Psi = \frac{\Delta_{min} + \varepsilon \Delta_{max}}{\Delta_{0i} + \varepsilon \Delta_{max}} \] (3)

Step-4: A grey correlation degree is determined using following relation:
\[ \Phi = \frac{1}{N} \sum_{j=1}^{N} [\Psi] \] (4)

Table 3: Details of the criterions

| Criterion                  | Description                                                                 |
|----------------------------|-----------------------------------------------------------------------------|
| Crit-1                     | Coefficient of friction (\(\mu\)) Higher-the-better                         |
| Crit-2                     | Wear (gm) Lower-the-better                                                  |
| Crit-3                     | Friction fade % Lower-the-better                                            |
| Crit-4                     | Friction recovery % Higher-the-better                                       |
| Crit-5                     | Stability coefficient Higher-the-better                                     |
| Crit-6                     | Variability coefficient Lower-the-better                                    |
| Crit-7                     | Friction fluctuation Lower-the-better                                       |

Table 3: Details of the criterions

It is the mean CoF during all the test conditions.

It is interminable material removal from the surface specimen.

Friction fade % = \(\frac{\mu - \mu_F}{\mu} \times 100\), \(\mu_F\) is the upper terminal value of CoF for the fade cycle.

Friction recovery % = \(\frac{\mu_R - \mu}{\mu} \times 100\), \(\mu_R\) is upper terminal value for CoF of the recovery cycle.

It is the ratio between CoF and the upper terminal value of CoF i.e. \(\frac{\mu}{\mu_{max}}\). It revealed how stable system response is.

It is the ratio of top most value and lowest CoF, i.e. \(\frac{\mu_{min}}{\mu_{max}}\). It shows volatility in the system response.

It is the variation in the top most value and lowest value of CoF during actual operation i.e. \(\mu_{max} - \mu_{min}\).

3. Results and Discussions

Figure 1, 2 & 3 shows fade & recovery plots of CSP0, CSP15 and CSP30 respectively. First fade cycle starts from 910C and ends at 2910C, during this cycle CoF first increases, then decreases for all the three materials. First recovery starts when the fade ends and remains till 910C. Preferably second fade and recovery are taken to be of larger range of temperatures.

![Figure 1: Fade & recovery plot of CSP0.](image)

![Figure 2: Fade & recovery plot of CSP15.](image)
Figure 3: Fade & recovery plot of CSP30.

Table 4 shows normal decision matrix with reference sequence which shows average values of the terms used in defining the criteria, taken from the fade and recovery plots. Moreover, they are the values obtain from experimental results. Maximum and minimum values of the criterions are used for further calculations. Table 5 is the difference matrix, which is obtain through their performance factuality i.e larger-the-better or smaller-the-better. Table 6 shows the grey relation coefficient obtain using equation (3). Gray relation grades are shown in table 7. Grey relation degree is obtained through equation (4).

Table 4: The normal resolution matrix

| Formulation | CSP0 | CSP15 | CSP30 |
|-------------|------|-------|-------|
| Crit-1      | 0.400| 0.411 | 0.438 |
| Crit-2      | 10.260| 9.870 | 9.450 |
| Crit-3      | 23.576| 24.579| 29.604|
| Crit-4      | 9.280 | 10.255| 11.052|
| Crit-5      | 94.787| 95.426| 95.842|
| Crit-6      | 77.293| 75.758| 75.847|
| Crit-7      | 0.104 | 0.112 | 0.114 |

Table 5: The difference matrix

| Formulation | CSP0 | CSP15 | CSP30 |
|-------------|------|-------|-------|
| Crit-1      | 0.00 | 0.29  | 1.00  |
| Crit-2      | -1.00| -0.52 | 0.00  |
| Crit-3      | 0.00 | -0.17 | -1.00 |
| Crit-4      | 9.28 | 10.26 | 11.05 |
| Crit-5      | 94.79| 95.43 | 95.84 |
| Crit-6      | -1.00| 0.00  | -0.06 |
| Crit-7      | 0.00 | -0.80 | -1.00 |

Table 6: Grey relation coefficient

| Formulation | CSP0     | CSP15     | CSP30    |
|-------------|----------|-----------|----------|
| Crit-1      | 0.00     | 0.286321  | 1        |
| Crit-2      | 2        | 1.518519  | 1        |
| Crit-3      | 1        | 1.166348  | 2        |
| Crit-4      | -8.279   | -9.255    | -10.05   |
| Crit-5      | -93.78   | -94.426   | -94.84   |
| Crit-6      | 2        | 1         | 1.0585   |
| Crit-7      | 1        | 1.8       | 2        |

Table 7: Grey relation grade
Table 8: ranking of formulations based on GRA

| Formulation | CSP0 | CSP15 | CSP30 |
|-------------|------|-------|-------|
| Crit-1      | 1.0000 | 0.6359 | 0.3333 |
| Crit-2      | 0.2000 | 0.2477 | 0.3333 |
| Crit-3      | 0.3333 | 0.3001 | 0.2000 |
| Crit-4      | -0.0643 | -0.0571 | -0.0523 |
| Crit-5      | -0.0054 | -0.0053 | -0.0053 |
| Crit-6      | 0.2000 | 0.3333 | 0.3208 |
| Crit-7      | 0.3333 | 0.2174 | 0.2000 |

Figure 4 shows wear of the three materials after test runs calculated considering mass before the and mass after the test. It is observe that CSP30 gives least wear among the materials, which ultimately confirm an important aspect of friction materials selection.

4. Conclusions

Development and multi-criterion optimization of friction materials with nano-coconut shell powder led to following conclusions:

1. Chase friction testing is an important tribological testing methodology, which provides the crucial behavior of the friction material to perform in higher operating parameters.
2. The recovery performance remains highest for CSP0, which gets mitigated with higher fade performance.
3. GRA methodology is proved to be useful tool in design of friction materials formulation. Assessment of the friction materials can be done using GRA. Results of GRA have ranked the friction material CSP30 as the best, CSP15 as average and CSP0 as poor amongst the three. Higher percentage of CSP proves to be best for all the criterions.
4. Tribological and mechanical properties of CSP30 is found to be superior.

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