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Implementation of Digital Logic Method for Selection of Material of Automotive Brake Disc

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ABSTRACT

An automotive brake disc or rotor is a device for slowing or stopping the motion of a wheel while it runs at a certain speed. The widely used brake rotor material is cast iron which consumes much fuel due to its high specific gravity. The aim of this paper is to develop the material selection method and select the optimum material for the application of brake disc system emphasizing on the substitution of this cast iron by any other lightweight material. Two methods are introduced for the selection of materials, such as cost per unit property and digital logic methods. Material performance requirements were analyzed and alternative solutions were evaluated among cast iron, aluminium alloy, titanium alloy, ceramics and composites. Mechanical properties including compressive strength, friction coefficient, wear resistance, thermal conductivity and specific gravity as well as cost, were used as the key parameters in the material selection stages. The analysis led to aluminium metal matrix composite as the most appropriate material for brake disc system. Index Terms— Brake disc; Material selection; Cost per unit strength method; Digital logic method.

KEYWORDS: Composites, Automobile Disc Brake, Digital Logic Method, Material Selection

1. Introduction

In automotive industries, to achieve reduced fuel consumption as well as green house gas emission is a current issue of utmost importance. To reduce automobile weight and improve fuel efficiency, the auto industry has dramatically increased the use of aluminum in light vehicles in recent years. Aluminum alloy based metal matrix composites (MMCs) with ceramic particulate reinforcement have shown great promise for such applications [1, 2]. These materials having a lower density and higher thermal conductivity as compared to the conventionally used gray cast irons are expected to result in weight reduction of up to 50 – 60 % in brake systems [3]. There are several factors to be considered when selecting a brake disc material. The most important consideration is the ability of the brake disc material to withstand high friction and less abrasive wear. Another requirement is to withstand the high temperature that evolved due to friction. In general, the material selection process is performed based on performance indices in chart [5]. As an alternative approach, digital logic methods have been occasionally used in material selection for certain engineering application [6]. The information on the development and application of the materials selection method for the design of automotive brake disc is scare in literature. The main purpose of the present work is to develop a suitable material selection method and apply that for the selection of best candidate material for brake disc application using Ashby's chart and finally rank the materials according to the performance indices using digital logic method.

II. STAGE OF MATERIAL SELECTION

For material selection there are small numbers of methods that have evolved to a position of prominence [9]. Material selection process is an open-ended and normally lead to several possible solutions to the same problem. This can be illustrated by the fact that similar component performing similar function, but produced by different manufacturers, are often made from different materials and even by different manufacturing processes [10]. However, selecting the optimum combination of material and process is not a simple task rather gradually evolved processes during the different stages of material selection. In this investigation, the stages of material selection method are shown using a flow chart in Figure.1.

General material performance requirements
⇩
Initial screening of candidate material
⇩
Material selection using Digital Logic Method
⇩
Optimum material selection

Figure.1 Flow chart of material selection method

III. GENERAL MATERIAL PERFORMANCE REQUIREMENTS

Disc brake systems generate braking force by clamping brake pads onto a rotor that is mounted to the hub. A schematic view of the brake system is shown in Fig.2.The higher the coefficient of friction for the pad, the more brake power will be generated. Coefficient of friction can vary depending on the type of material used for the brake rotor. Typically service brakes are concerned with dynamic coefficient of friction, or the coefficient of friction measured while the vehicle is moving.

$$F_{rotor} = 2C_{f,pad} F_{pad} \quad (1)$$

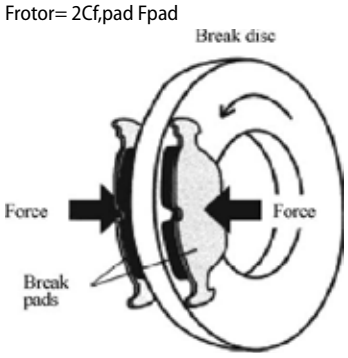

Figure.2 Schematic view of real size brake system

(brake disc and brake pad)

IV. INITIAL SCREENING OF CANDIDATE MATERIAL

Traditional material for automotive brake rotor is the cast iron. The specific gravity or density of cast iron is higher which consumes much fuel due to high inertia. Following section will describe the potential candidate materials those can be used for brake rotor application.

Cast Iron: Metallic iron containing more than 2% dissolved carbon within its matrix (as opposed to steel which contains less than 2%) but less than 4.5% is referred to as gray cast iron because of its characteristic colour. Considering its cost, relative ease of manufacture and thermal stability, this cast iron (particularly, gray cast iron), is actually a more specialized material for brake applications particularly the material of choice for almost all automotive brake discs. [12].

Titanium alloys: Titanium alloys and their composites have the potential to reduce weight of the brake rotor disc component which is about 37% less than a conventional cast iron with the same dimensions and offering good high temperature strength and better resistance to corrosion [13].

Aluminum-Metal Matrix Composite (AMC):
Aluminum alloy based metal matrix composites (MMCs) with ceramic particulate reinforcement have shown great promise for brake rotor applications. These materials having a lower density and higher thermal conductivity as compared to the conventionally used gray cast irons are expected to result in weight reduction of up to 50-60% in brake systems.

Based on the properties, potential candidate materials for automotive brake disc were selected as:

- Gray cast iron (GCI)
- Ti-alloy (Ti-6Al-4V)
- 7.5 wt% WC and 7.5 wt% TiC reinforced Ti-composite (TMC)
- 20% SiC reinforced Al-composite (AMC 1)
- 20% SiC reinforced Al-Cu alloy (AMC2)

V. material selection using digital logic method

The digital logic method can be employed for the optimum material selection using with ranking. As a first step, the property requirements for a brake rotor were determined based on previous discussion. The properties and the total number of decisions, i.e. N (N – 1)/2 = 10, are given in Table 1. The weighting factor for each property, which is indicative of the importance of one property as compared to others, was obtained by dividing the numbers of positive decisions given to each property by the total number of decisions. The total positive decisions for each property and corresponding weighting factor were calculated and are presented in Table 2. From Table 2, it can be seen that friction coefficient and wear resistance have the highest weighting factors followed by thermal capacity, whereas the least important properties are compressive strength and specific gravity hence, obtained lower weighting factor.

Table.1 Application of digital logic method to material selection for brake disc

Decision Numbers										
	1	2	3	4	5	6	7	8	9	10
Compressive Strength	0	0	0	1						
Friction coefficient	1				1	0	1			
Wear resistance		1			0			1	1	
Thermal capacity			1			1		0		0
Specific gravity				0			0		0	1

Table.2 Weighting factors for brake disc

Property	Positive decisions	Weighting factors
Compressive Strength	1	0.1
Friction coefficient	3	0.3
Wear resistance	3	0.3
Thermal capacity	2	0.2
Specific gravity	1	0.1
Total	10	1.0

Table 3 showed the properties of the candidate materials those are used for ranking purposes. In order to complete the DL method, the next step is to scale the properties of the materials based on their respective weighting factor and the scale value is shown in Table 3. For the present application, materials with higher compressive strength, friction coefficient and thermal capacity are more desirable and highest value is rated as 100. Their scaled values are calculated using the following equation (2).

$$\text{scaled property} = \frac{\text{numerical value of property}}{\text{maximum value in the li}} \quad (2)$$

Since lower wear rate and specific gravity are desirable for the automotive brake disc, therefore, their lowest value is considered as 100 and scaled values are calculated using equation (3).

$$\text{scaled property} = \frac{\text{numerical value of prope}}{\text{numerical value of the p}} \quad (3)$$

Other values in Table 4 are rated in proportion. The scaled values and performance index (γ) are given in Table 5 which was calculated using equations (4) [10].

Material performance index, $\gamma = \sum_{i=1}^{n} \beta i \alpha i$ (4)

Where β is the scaled property, α is the weighting factor and i is summed over all the n relevant properties.

Table.3 Properties of candidate materials for brake disc [11, 13]

Property / Material	1 Compressive strength (MPa)	2 Friction coefficient (μ)	3 Wear rate ($\times 10^{-6}$ $mm^3/N/m$)	4 Specific heat (KJ/ Kg K)	5 Specific gravity (Mg/m^3)
GCI	1293	0.41	2.36	0.46	7.2
Ti-6Al-4V	1070	0.34	246.3	0.58	4.42
TMC	1300	0.31	8.19	0.51	4.68
AMC 1	406	0.35	3.25	0.98	2.7
AMC 2	761	0.44	2.91	0.92	2.8

Table.4 Scaled value of properties of each material and corresponding performance index

Scaled properties						
	1	2	3	4	5	Performance Index (γ)
GCI	99	93	100	47	38	81.0
Ti-6Al-4V	82	77	0.96	59	61	49.5
TMC	100	70	29	52	58	56.0
AMC 1	31	80	73	100	100	79.0
AMC 2	59	100	81	94	96	88.6

The performance index showed that the technical capability of the material without regard to the cost. However, if there are a large number of properties to be considered, the importance of cost may be emphasized by considering it separately as a modifier to the material performance index (γ). It is also important to consider the cost of material before making any final design or ranking. Therefore, in this study, the figure of merit (FOM) M is calculated before ranking using the equation (5):

$$M = \frac{\gamma}{C\rho} \quad (5)$$

Where,
C=Total cost of the material per unit weight
ρ = Density of the material

Table. 5 Cost and figure of merit of candidate materials

Material	Relative cost	Performance index	Figure of merit	Rank
GCI	1	81.0	11.25	2
Ti-6Al-4V	20	49.5	0.56	5
TMC	20.5	56.0	0.58	4
AMC 1	2.7	79.0	10.84	3
AMC 2	2.6	88.6	12.17	1

The values of the relative cost, performance index, and figure of merits of the different materials are shown in Table 5. The plot of performance indices against all the candidate materials is shown in Fig. 3. From Fig. 3 it can be seen that AMC 2 (Al-Cu alloy reinforced with 20% SiC) showed higher performance index (γ) followed by gray cast iron (GCI) material.

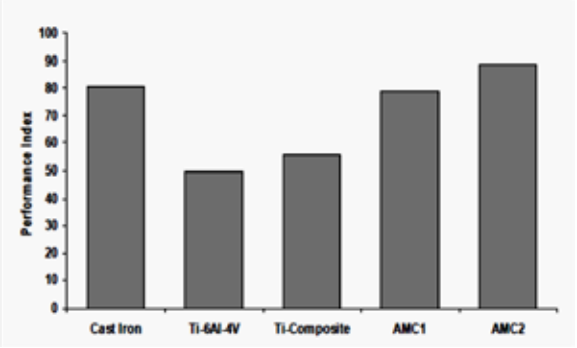

Figure.3 Plot of performance index (γ) against all candidate materials.

VI. OPTIMUM MATERIAL SELECTION

In this section, the performance index, γ, and the total cost, Ct of the candidate material AMC 2 are separately compared against the currently used gray cast iron (GCI). Since the purpose is to improve performance, acceptable candidates must perform at a higher level than the currently used material. If cost is not the objective, the candidate with the highest performance index, γ, can be selected. The percentage increase in performance (Δγ %) and the corresponding percentage increase in cost (Δ Ct %) for both the candidate materials and the currently used material is calculated using equation (6) and (7) respectively and values are summarized in Table 6.

$$\Delta\gamma\% = \frac{100(\gamma_n - \gamma_0)}{\gamma_0} \quad \ldots\ldots (6)$$

$$\Delta C_t\% = \frac{100(C_{tn} - C_{t0})}{C_{t0}} \quad \ldots\ldots (7)$$

Where,
γn and γ0 = performance indices of the new and original materials,
Ctn and Ct0 = cost of the new and original materials, respectively.

Table. 6 The percentage increase in performance (Δγ %) and the corresponding percentage increase in cost (Δ Ct %) for both the candidate materials

Material	Performance index(γ)	Total cost (£/ton) Ct	Δγ %	ΔC_t %
GCI	81.0	830	9.4	167.5
AMC 2	88.6	2220		

VII. CONCLUSION

The material selection methods for the design and application of automotive brake disc are developed. Functions properties of the brake discs or rotors were considered for the initial screening of the candidate materials using Ashby's materials selection chart. The digital logic method showed the highest performance index for AMC 2 material and identified as an optimum material among the candidate materials for brake disc. In the digital logic method, the friction coefficient and density were considered twice for determining the performance index and the cost of unit property. This procedure could have overemphasized their effects on the final selection. This could be justifiable in this case as higher friction coefficient and lower density are advantageous from the technical and economical point of view for this type of application.

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