FRICTION MATERIAL (METAL REINFORCEMENT) ANALYSIS OF BRAKE PAD FOR LIGHT RAIL TRAIN SYSTEM

ABDUL RASHID BIN ABDUL RAHMAN

A thesis submitted in
fulfillment of the requirement for the award of the
Degree of Master of Science in Railway Engineering

Faculty of Engineering Technology
Universiti Tun Hussein Onn Malaysia

OCTOBER, 2016

To my beloved parents, siblings and friends for their endless love, support and tolerance

ACKNOWLEDGEMENT

In the name of Allah, Most Gracious and Most Merciful, Praise is to Allah, the guidance that brought this study to a completion.

I would like to take this opportunity to thank Assoc. Professor Dr Hasan Zuhudi bin Abdullah as my supervisor for his support, encouragement, guidance and motivation through the years. My special thanks to my parents, En. Abdul Rahman bin Ibrahim and Pn Roziah Bte Abu Bakar as well as my siblings for the love and their continuous support and willing to share with me all my joy and pain in completing this study.

My heartfelt thanks go to my co supervisor, Dr Zakiah bt Kamdi in providing necessary guidance and help. So does the entire technician involved in this study for their help and advice throughout the project.

I also highly appreciate the cooperation, guidance and unconditional support from KKTSN committee members as well as my fellows, Sakinah, Aisyah, Nik and Natasya.

Last but not least, I would like to thanks those who have directly or indirectly contributed towards the accomplishment of this study.

ABSTRACT

Brake friction material is very important in braking system where they convert kinetic energy of moving vehicles to thermal energy by friction during braking process. The purpose of this research is to determine the optimal friction materials composition of brake pad for light rail train system. Currently all the component of the train system including brake pad is imported from overseas such as Germany. Hence, this research is use to find the new formulation of the mixture ratio that may replace or compete with the commercial available brake pad. Three different testing which are density and porosity test, shore hardness test and wear test were done in order to select which metal is the most suitable for railway application. Different composition were used, (Cu30%$BaSO_4$30%), (Cu25%$BaSO_4$35%), (Cu20%$BaSO_4$40%), (Steel30% $BaSO_4$30%), (Steel25% $BaSO_4$35%), (Steel20% $BaSO_4$40%), (Al30% $BaSO_4$30%), (Al25% $BaSO_4$35%), and (Al20% $BaSO_4$40%) this study to determine the optimal properties with lower wear rate. The selected material were mixed and compacted into desired mould with 5 tons of pressure. The compacted samples were sintered using two different temperatures which is 600^{o}C and 800^{o}C. Steel30% $BaSO_4$30% results in the optimal composition since the result shows the lowest porosity, highest SD reading of shore hardness and the lowest wear rate. The samples were analysed by using Scanning Electron Microscopy (SEM) with an Energy Dispersive Spectrometry (EDS) system to determine the morphology surface and overall composition of the samples. Comparing different sintering temperature, the sintered sample of 800^{o}C shows lower wear rate than the sample sintered at 600^{o}C. This is due to dense sample without crack showing by the samples sintered at 800^{o}C than at 600^{o}C.

ABSTRAK

Bahan geseran untuk brek adalah sangat penting dalam sistem brek di mana ianya menukar tenaga kinetik kenderaan bergerak untuk tenaga haba melalui geseran semasa proses brek. Tujuan kajian ini adalah untuk menentukan optimum komposisi bagi bahan geseran pada pad brek untuk sistem kereta api aliran ringan. Pada masa ini semua komponen sistem kereta api termasuk pad brek diimport dari luar negara seperti Jerman. Oleh itu, kajian ini adalah untuk mencari formula baru dengan nisbah campuran yang boleh menggantikan atau menjadi pesaing pad brek yang sedia ada. Tiga ujian yang berbeza dilakukan iaitu ujian kepadatan dan ujian keliangan, ujian kekerasan dan ujian kehausan untuk memilih logam yang paling sesuai untuk digunakan pada kereta api. Sembilan komposisi, (Cu30%$BaSO_4$30%), (Cu25%$BaSO_4$35%), (Cu20%$BaSO_4$40%), (Steel30% $BaSO_4$30%), (Steel25% $BaSO_4$35%), (Steel20% $BaSO_4$40%), (Al30% $BaSO_4$30%), (Al25% $BaSO_4$35%), dan (Al20% $BaSO_4$40%) digunakan dalam kajian ini untuk menentukan sifat-sifat optimum dengan kadar haus yang lebih rendah. Bahan yang dipilih adalah bercampur dan dipadatkan ke dalam acuan yang dikehendaki dengan 5 tan tekanan. Sampel dipadatkan disinter menggunakan dua suhu yang berbeza yang 600^{o}C dan 800^{o}C. Steel30% $BaSO_4$30% menghasilkan komposisi yang optimum kerana hasilnya menunjukkan keliangan yang paling rendah, bacaan SD tertinggi bagi ujian kekerasan dan kadar haus yang paling rendah. Sampel kemudiannya dianalisis dengan menggunakan SEM dengan sistem EDS untuk menentukan permukaan morfologi dan komposisi keseluruhan sampel. Bagi perbandingan suhu pembakaran yang berbeza, sampel yang disinter pada suhu 800^{o}C menunjukkan kadar haus lebih rendah daripada sampel disinter pada 600^{o}C. Ini adalah kerana sampel padat tanpa menunjukkan retak pada sampel yang disinter pada 800^{o}C berbanding pada 600^{o}C.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURE

LIST OF SYMBOLS AND ABBREVIATIONS

Cu	- Copper
Al	- Aluminium
^{o}C	- Degree Celcius
cm^3	- Cubic centimenters
g	- Gram
kg	- Kilogram
mm	- millimeter
rpm	- Rotation per minute
µ	- micron
%	- percent
LRT	- Light Rail Transit
SEM	- Scanning Electron Microscopy
EDS	- Energy Dispersive System

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of study

Braking system is a crucial part in a rolling stock which where it convert mechanical energy into heat energy through a friction to stop a vehicle (Yoong *et al*., 2010). Brake friction materials play an important role in braking system. They convert the kinetic energy of a moving car to thermal energy by friction during braking process. The ideal brake friction material should have constant coefficient of friction under various operating conditions such as applied loads, temperature, speeds, mode of braking and in dry or wet conditions so as to maintain the braking characteristics of a vehicle (Jang *et al*., 2004). Besides, it should also possess various desirable properties such as resistance to heat, water and oil, has low wear rate and high thermal stability, exhibits low noise, and does not damage the brake disc (Xin, Xu, & Qing, 2007). However, it is practically impossible to have all these desired properties. Therefore, some requirements have to be compromised in order to achieve some other requirements. In general, each formulation of friction material has its own unique frictional behaviours and wear-resistance characteristics.

Friction materials are generally consist of a number of different materials. Sometimes up to 20 or 25 different components are used. These components including:

1. Binder - which holds the other components together and forms a thermally stable matrix. Thermosetting phenolic resins are commonly used, often with the addition of rubber for improved damping properties (Chan & Stachowiak, 2004).

2. Structural materials - providing mechanical strength. Usually fibres of metal, carbon, glass, and/or Kevlar are used and more rarely different mineral and ceramic fibres. Before its prohibition in the mid 80's, asbestos was the most commonly used structural fibre (Maleque *et al*., 2012).

3. Fillers - mainly to reduce cost but also to improve manufacturability. Different minerals such as mica and vermiculite are often employed. Barium sulphate is another commonly used filler (Chan & Stachowiak, 2004).

4. Frictional additives - added to ensure stable frictional properties and to control the wear rates of both pad and disc. Solid lubricants such as graphite and various metal sulphides are used to stabilise the coefficient of friction, primarily at elevated temperatures. Abrasive particles, typically alumina and silica, increase both the coefficient of friction and the disc wear. The purpose of the latter is to offer a better defined rubbing surface by removing iron oxides and other undesired surface films from the disc (Selamat, 2006a).

1.2 Problem statement

Previously asbestos has been widely used as the main material in a brake pad; however it has been avoided due to its cancer-causing nature (Idris *et al*., 2015). The brake pad is a very important component in a railway where a regular replacement needed and it is imported from overseas where it might cause higher maintenance cost (Bouvard *et al*., 2011). Therefore a new asbestos free brake pads need to be developed and manufactured locally to avoid health problem and reducing the production cost and eventually will upgrade Malaysia railway industry level. Thus, the exact formula for the mixture ratio of the brake pad need to be studied to formulate and create a stronger or at same level of properties of the brake pad that had been use commercially by local rolling stock.

1.3 Objective

The purpose of this research is to study the wear behaviour of a brake pad for light rail train system. Currently all the component of the train system including brake pad is imported from overseas such as Germany. Hence, this research is conduct to find the new formulation of the mixture ratio that can generate a better and stronger brake pad for commercial used. The findings of this study will help in identifying which mixture ratio will produce the finest friction material reinforcement that will generate a good brake pad. In this study, a sample of specimen has been fabricated and gone through several testing such as wear test and porosity test. The outcome of this study is expected to be useful in Malaysia railway industry where it can be a starting point for Malaysia to develop our own train from scratches including all component such brake pad.

The objectives of this study are to:

a) Determine the new ratio of the fibre reinforcement used in fabricating the brake pad for light rail train (LRT) to enhance the friction material reinforcement.
b) Compare the porosity and density, hardness and wear behaviour of the fabricated specimen with the commercial used brake pad.

1.4 Scope of study

This study is focus on light rail train system where it has different load and maximum speed compare to heavy train system and it is focus on the range of study such:

i. Fabrication of brake pad with 9 different content of metal fibre used in the mixture which is (Cu30%$BaSO_4$30%), (Cu25%$BaSO_4$35%), (Cu20%$BaSO_4$40%), (Steel30% $BaSO_4$30%), (Steel25% $BaSO_4$35%), (Steel20% $BaSO_4$40%), (Al30% $BaSO_4$30%), (Al25% $BaSO_4$35%), and (Al20% $BaSO_4$40%) by using mould with diameter size 20mm and compacted with 5 tons pressure for every sample after mixing process.
ii. Sintering temperature for this study is at 800^{o}C and 600^{o}C.
iii. The characterisation of mechanical properties of the samples using shore hardness test.
iv. The characterisation of the physical properties of the sample by using density and porosity test.
v. Study the wear behaviour using weight loss test at 5 N pressures for 5 minutes using 200 RPM speed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The growth of railway transportation has been increase significantly this day which require urgent attention in transportation industry. Since railway industry in such a massive demand, it should be manufactured locally. In Malaysia, they only manage to manufacture 80% of the train and some of the component was imported such as alarm system component, seat, wheel, heating, ventilation and air conditioning (HVAC) and brake pad. Brake pad is a component that been change regularly, hence, if it is manufacture locally, it can reduce the cost. This study is particularly studied to produce a local brake pad for railway application.

This study based on previous research in order to improve the outcome of previous researcher. The theoretical analysis of the brake pad from the operation up until the details of materials use in a brake pad particularly the one use for railway application will be discussed in this chapter.

2.2 Brake pad

Braking system is the most important parts in a vehicles where it convert the kinetic energy of a vehicles to thermal energy through friction to stop or slower the moving vehicles (Talati & Jalalifar, 2009). There are basically made up by several parts of equipment and brake pads are one of those that play a very important role where it contact and apply pressure and friction to the brake disc. The pressure and the friction that applied to the brake disc will eventually slow and stop the wheels. Thus, the vehicles will stop running when the wheel stop turning.

Though the operation of brake pad looks simple, but the break pad itself play a huge role where it undergo a great stress every time the vehicles is slow down or stop because it is depends on the speed of the wheels rotate and the amount of weight that the vehicles carry. In (Halderman & Mitchell, 2010) book's explain that there basically two types of brake system which is disc brake and drum brake and both of the system applying the same rule where it slow down or stop the vehicles by engaging hydraulic pistons to press brake pads or brake shoes against the brake disk or brake drums that rotate along the wheels.

Brake pad and brake shoes is actually a different component which have the same function. The main difference between those two is their position in the vehicle. Brake shoes are specially designed to fit in drum brakes, while brake pad are placed on top of brake disk, and act to apply pressure to the discs when applying the brakes (Halderman & Mitchell, 2010). The brake shoes are attached to consumable surfaces in brake systems called lining which use to support the brake shoes. Normally, the shoes are made of two pieces of sheet steel welded together in a T-shaped cross section (Babel, 1933). Brake shoes are more expensive to produce and it is not good for high temperature because it is not durable enough and obviously it is not suitable for railway system because a train running with a huge system and it require equipment that can sustain in high temperature. However, the interesting about brake shoes are it is a solid part that can be relined and reused many time as long as the web (The crescent-shaped piece which contains holes and slots as shown in Figure 2.1) and lining table are not damage.

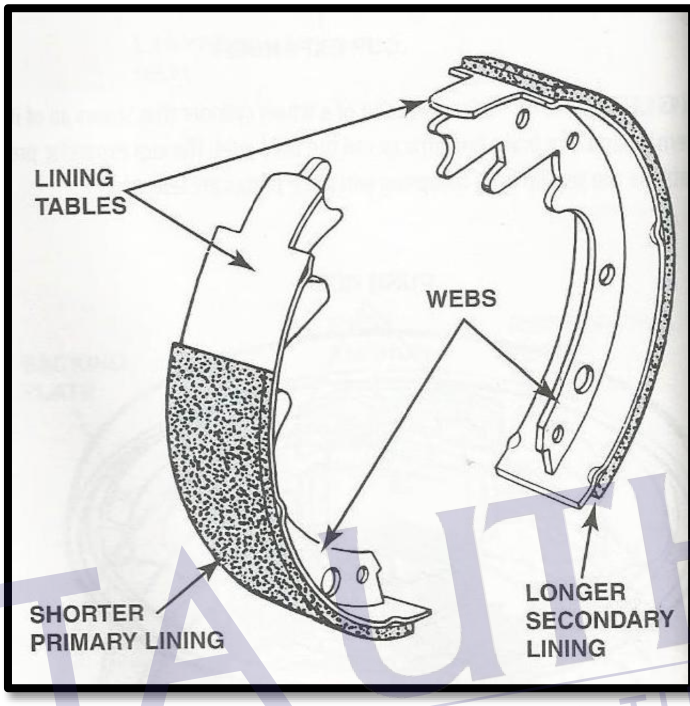

Figure 2.1 : The crescent-shaped piece that attach with lining tables is called web (Jeffrey & Halderman, 2006)

Basically, the design of a brake pad is somewhat much simpler than brake shoes where it consists of a block of friction material that attached to a stamped steel backing plate. Some of the backing plate is installed with a bent tabs that use to prevent noise. Figure 2.2 show the position of the bent tabs that will hold the pad tightly in place so that it can prevent any brake noise. Usually, the edge of the lining material on a brake pad is straight cut to reduce the vibration and noise. As for brake shoes, the lining material can be fastened to the backing plate in several ways to reduce the vibration and noise (Jeffrey & Halderman, 2006).

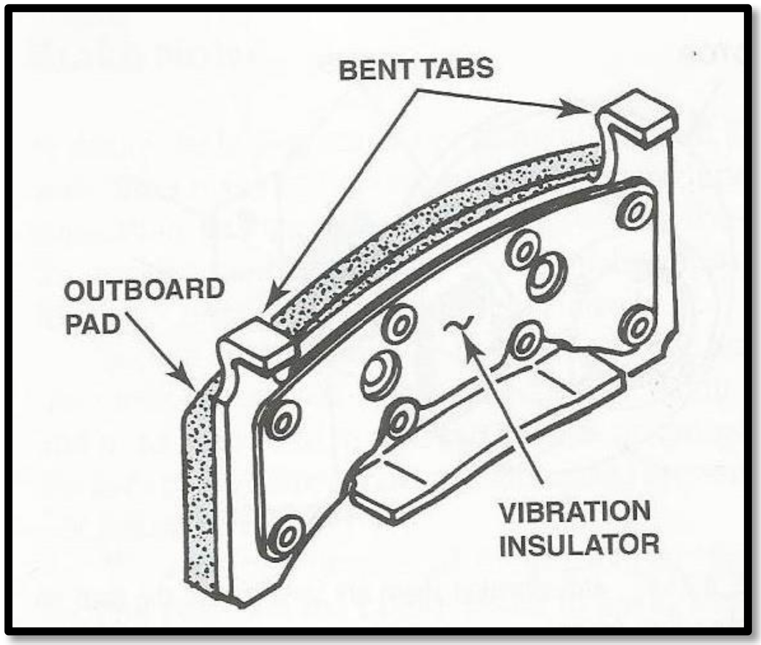

Figure 2.2 : Bent tabs that hold the break pad is use to reduce break noise (Jeffrey & Halderman, 2006)

Brake pads are widely used in a large vehicles including train system. In the early 1970's, disk brake is getting on demand and been broadly produce by automobile manufacturers because it had better braking performance than drum brakes (Idris *et al.*, 2013). Brake pads operate by converting the kinetic energy of the vehicles to thermal energy by friction. It happens when the temperature of the brake pad is increase by the contact with break disc to provide stopping power, thus the break pad starting to transfer small amounts of friction materials to the disc. In general, to ensure the safety of the vehicles, the friction materials are required to provide a firm friction coefficient and a best wear rate at numerous operating speeds, pressures, temperatures and environmental condition in order to reduce the extensive wear, vibration and noise during braking. History shown from the past two decades, asbestos had been a common material used in producing the brake pads due to its durability. However, since 1980s, research show that asbestos is found out as harmful content and was banned from being used as the ingredient in producing brake pads as it can cause severe disease (Liew & Nirmal, 2013).

The asbestos exposure was actually can cause scar tissue to form in the lungs and it's called asbestosis which it gradually will increase the shortness of breath and make a permanent scarring to the lungs (Frank & Joshi, 2014). Besides, asbestos exposure also can lead to lung cancer which normally takes about 15 to 30 years after the exposure. The Occupational Safety and Health Administration (OSHA) have recognised three levels of asbestos exposure in their standard as it is very important to ensure the safety of human being. Any vehicles services company must ensure that the asbestos exposure must less than 0.2 fibres per cubic centimetre (cc) as resolute by air sample and if the level of exposure is exceed the limit, action will be taken by the OSHA organization (Halderman, 2010).

Nowadays, the development of asbestos – free brake pads is increasing through different researcher. There are different kinds of fibres used to replace asbestos such metallic, glass, ceramic and carbon fibres (Solomon, Berhan, & Pad, 2007). Friction materials for brake pad are normally contain metallic ingredient which to improve wear resistance, thermal diffusivity and strength. Most of the vehicles usually using metallic brake pad and made of iron, copper, steel and graphite. Different characteristic of the different type of metallic ingredients can affect the friction and wear of the friction materials (Jang *et al*., 2004). Metallic brake pad s are commonly used because it is cost effective and durable despite that it is also provide great performance and best at shifting heat that generate by friction with the rotor or brake disk.

2.2.1 Application of brake pad for Light Rail Transit (LRT)

Brake pad is the crucial part in vehicles where it faces the greatest wears when every time the pads are pressed against the rotating disc. Thus, it needs a proper maintenance to maintain the effectiveness of the vehicles. The friction material of a break pad plays a very important role where much consideration must be considered such heat resistance and durability. Table 2.1 shows the different types of brake pad materials on various applications where every each of application uses different types of brake pad. Every each of brake pads has different composition based own their application. Heavy vehicles such as train especially the one with high speed need to choose a proper material for break pad because such vehicles faces with great friction wear. Figure 2.3 (a) and 2.3 (b) show the brake pad that use in ampang line Light Rail Transit (LRT) where it is imported from Becorit GmbH Company that base in Germany.

(a) (b)

Figure 2.3: (a) Front view of brake pad that use in ampang line LRT (b) Back view of brake pad that use in ampang line LRT

Table 2.1: Different types of brake pad materials on various applications

Type of vehicle	Brake pad material	Advantages	Ref.
Train/Freight	Semi-metallic and metallic (iron, copper, steel and graphite all mixed together)	High stopping power but expensive High operating temperature Sustain high temperature without fade	(Gultekin et al., 2010a)
Motorcycle	Manufactured using the same materials used in automotive brake pads (ceramic and organic are the one that commonly used)	Organic brake pads does not wear as fast in light weight vehicles	(Kumar & Bijwe, 2011)
Commercial car	Organic Kevlar	Does not pollute the environment as they are easy to dispose Softer compared to other material means quieter	(Kabir & Ferdous, 2012)
Racing car	Carbon fiber Ceramic	Great braking performance High operating temperature Lightweight Sustain high temperature without fade	(Renz, Seifert, & Krenkel, 2012)
Trucks	Ceramic and metallic (iron, copper, steel and graphite all mixed together)	High stopping power but expensive High operating temperature	(Renz *et al.*, 2012)

2.2.2 Type of brake pad for railway application

Brake pad is basically the same even for other application except they have different sizes of brake pad based on the suitability of the application. Brake pad that is use in railway industry is almost the same with the one that regularly use in car. Brake pad for railway is slightly larger than car break pad because it needs a better braking system especially with the high speed train that been use widely nowadays, the needs for a better braking system is vital. The selection of brake disc and pad friction pairing has a significant impact on brake safety and life cycle cost. In choosing a brake pad, especially for railway application, the specific thermal simulation and dynamometer test to ensure

REFERENCES

Angelo, P. C., & Subramanian, R. (2008). *Powder Matallurgy : Science, Technology and Applications*.

Asif, M., Chandra, K., & Misra, P. S. (2011). Development of iron based brake friction material by hot powder preform forging technique used for medium to heavy duty applications. *Journal of Minerals and Materials Characterization and Engineering*, *10*(3), 231.

Astm. (2005). *Dictionary of Engineering Science and Technology, 10th Edition*.

Axén, N., Hogmark, S., & Jacobson, S. (2000). Friction and Wear Measurement Techniques. *Modern Tribology Handbook*, (1987), 493–510.

Berhan, M. N., Solomon, D. G., & David, N. V. (2006). Hardness Test for Light Rail Transit (LRT). In D. G. Solomon (Ed.), *Brake Friction Materials*. Pusat Penerbitan UITM.

Bouvard, K., Artus, S., Berenguer, C., & Cocquempot, V. (2011). Condition-based dynamic maintenance operations planning & grouping. Application to commercial heavy vehicles. *Reliability Engineering & System Safety*, *96*(6), 601–610.

Cai, P., Wang, Y., Wang, T., & Wang, Q. (2015). Effect of resins on thermal, mechanical and tribological properties of friction materials. *Tribology International*, *87*, 1–10.

Callister, W. D., & Rethwisch, D. G. (2007). *Materials science and engineering: an introduction* (Vol. 7). BOOK, Wiley New York.

Chan, D., & Stachowiak, G. W. (2004). Review of automotive brake friction materials. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *218*(9), 953–966.

Chen, X., Wu, S., & Zhou, J. (2013). Influence of porosity on compressive and tensile strength of cement mortar. *Construction and Building Materials*, *40*, 869–874.

Coble, R. L., & Kingery, W. D. (1956). Effect of Porosity on Physical Properties of Sintered Alumina. *Journal of the American Ceramic Society*, *39*(11), 377–385.

Cole, G. S., & Sherman, A. M. (1995). Light weight materials for automotive applications. *Materials Characterization*, *35*(1), 3–9.

Dhakal, H. N., Zhang, Z. Y., Guthrie, R., MacMullen, J., & Bennett, N. (2013). Development of flax/carbon fibre hybrid composites for enhanced properties. *Carbohydrate Polymers*, *96*(1), 1–8.

Eadie, D. T., Elvidge, D., Oldknow, K., Stock, R., Pointner, P., Kalousek, J., & Klauser, P. (2008). The effects of top of rail friction modifier on wear and rolling contact fatigue: Full-scale rail-wheel test rig evaluation, analysis and modelling. *Wear*, *265*(9–10), 1222–1230.

Fei, J., Luo, W., Huang, J. F., Ouyang, H., Xu, Z., & Yao, C. (2015). Effect of carbon fiber content on the friction and wear performance of paper-based friction materials. *Tribology International*, *87*, 91–97.

Frank, A. L., & Joshi, T. K. (2014). The global spread of asbestos. *Annals of Global Health*, *80*(4), 257–262.

Ghosh, S. K., & Saha, P. (2011). Crack and wear behavior of SiC particulate reinforced aluminium based metal matrix composite fabricated by direct metal laser sintering process. *Materials & Design*, *32*(1), 139–145.

Goldstein, J., Newbury, D. E., Echlin, P., Joy, D. C., Romig, A. D., Lyman, C. E., … Lifshin, E. (2012). *Scanning Electron Microscopy and X-Ray Microanalysis: A Text for Biologists, Materials Scientists, and Geologists*. Book, Springer US.

Goodhew, P. J., Humpreys, J., & Beanland, R. (1988). 1. Microscopy with light and electrons. *Electron Microscopy and Analysis*, *2nd editio*, 36.

Gultekin, D., Uysal, M., Aslan, S., Alaf, M., Guler, M. O., & Akbulut, H. (2010a). The effects of applied load on the coefficient of friction in Cu-MMC brake pad/Al-SiCp MMC brake disc system. *Wear*, *270*(1), 73–82.

Gultekin, D., Uysal, M., Aslan, S., Alaf, M., Guler, M. O., & Akbulut, H. (2010b). The effects of applied load on the coefficient of friction in Cu-MMC brake pad/Al-SiCp MMC brake disc system. *Wear*, *270*(1–2), 73–82.

Gyimah, G. K., Chen, D., & Huang, P. (2013). Dry Sliding Studies of Porosity on Sintered Cu-based Brake Materials, 219–224.

Halderman, J. D. (2010a). *Automotive Steering Suspension Alignment*. Pearson Education Ltd.

Halderman, J. D., & Mitchell, C. D. (2010b). *Automotive brake systems*. BOOK, Prentice Hall.

Hentati, N., Kchaou, M., Cristol, A.-L., Najjar, D., & Elleuch, R. (2014). Impact of post-curing duration on mechanical, thermal and tribological behavior of an organic friction material. *Materials & Design*, *63*, 699–709.

Hirsch, J. (2011). Aluminium in innovative light-weight car design. *Materials Transactions*, *52*(5), 818–824.

Holand, W., & Beall, G. H. (2012). *Glass ceramic technology*. Book, John Wiley & Sons.

Hong, U. S., Jung, S. L., Cho, K. H., Cho, M. H., Kim, S. J., & Jang, H. (2009). Wear mechanism of multiphase friction materials with different phenolic resin matrices. *Wear*, *266*(7–8), 739–744.

Hwang, Y. M., Fan, P. L., & Lin, C. H. (2010). Experimental study on Friction Stir Welding of copper metals. *Journal of Materials Processing Technology*, *210*(12), 1667–1672.

Idris, U. D., Aigbodion, V. S., Abubakar, I. J., & Nwoye, C. I. (2013). Eco-friendly asbestos free brake-pad: Using banana peels. *Journal of King Saud University - Engineering Sciences*, *27*(2), 185–192.

Idris, U. D., Aigbodion, V. S., Abubakar, I. J., & Nwoye, C. I. (2015). Eco-friendly asbestos free brake-pad: Using banana peels. *Journal of King Saud University - Engineering Sciences*, *27*(2), 185–192.

Islam, M. A., & Farhat, Z. N. (2011). The influence of porosity and hot isostatic pressing treatment on wear characteristics of cast and P/M aluminum alloys. *Wear*, *271*(9–10), 1594–1601.

Jang, H., Ko, K., Kim, S. J., Basch, R. H., & Fash, J. W. (2004). The effect of metal bers on the friction performance of automotive brake friction materials, Wear 256 (. *February*, *256*, 3–4.

Jeffrey, R., & D. Halderman, J. (2006). *Automotive Brake Systems*. (T. Peyton, Ed.). Pearson Education Ltd.

Johnston, I. F. (1980). Cellulosic material and thermoplastic resin. Gen, Google Patents.

Kabir, E. R. Bin, & Ferdous, E. N. (2012). Kevlar-The Super Tough Fiber. *International Journal of Textile Science*, *1*(6), 78–83.

Kadolkar, P. B., Watkins, T. R., De Hosson, J. T. M., Kooi, B. J., & Dahotre, N. B. (2007). State of residual stress in laser-deposited ceramic composite coatings on aluminum alloys. *Acta Materialia*, *55*(4), 1203–1214.

Kang, S. T., Lee, B. Y., Kim, J.-K., & Kim, Y. Y. (2011). The effect of fibre distribution characteristics on the flexural strength of steel fibre-reinforced ultra high strength concrete. *Construction and Building Materials*, *25*(5), 2450–2457.

Knop, A., Böhmer, V., & Pilato, L. A. (2013). *Phenolic Resins: Chemistry, Applications and Performance*. Book, Springer Berlin Heidelberg.

Kumar, M., & Bijwe, J. (2011). Non-asbestos organic (NAO) friction composites: role of copper; its shape and amount. *Wear*, *270*(3), 269–280.

Liew, K. W., & Nirmal, U. (2013). Frictional performance evaluation of newly designed brake pad materials. *Materials and Design*, *48*, 25–33.

Lin, X., Zhu, M., Mo, J., Chen, G., Jin, X., & Zhou, Z. (2011). Tribological and electric-arc behaviors of carbon/copper pair during sliding friction process with electric current applied. *Transactions of Nonferrous Metals Society of China*, *21*(2), 292–299.

Mahesh A. Sutar, V. V. P. (2015). Experimental Analysis and Investigation of Groove Porosity in Rear Cross Over Brake Disc of FG260 Material. *International Journal of Innovative Research in Science, Engineering and Technology*, *4*(3), 1237–1244.

Makni, Fatma, Cristol, & Anne-lisa. (2015). Heterogeneity Of Organic Brake Lining Materials : Impact Of The Mixing Of Ingredients. *Laboratoire de Mécanique de Lille UMR CNRS 8107, France; 2Université de Sfax, ENIS, LASEM, Tunisie*, 2.

Maleque, M. A., Atiqah, A., Talib, R. J., & Zahurin, H. (2012). New natural fibre reinforced aluminium composite for automotive brake pad. *International Journal of Mechanical and Materials Engineering*, *7*(2), 166–170.

Maleque, M. A., Dyuti, S., & Member, M. M. R. (n.d.). Material Selection Method in Design of Automotive Brake Disc, 3–7.

Nagesh, S. N., Siddaraju, C., Prakash, S. V, & Ramesh, M. R. (2014). Characterization of brake pads by variation in composition of friction materials, *5*(Icamme), 2–9.

Ondik, H. M., Christ, B. W., Perloff, A., Energy, U. S. O. of F., Division, C. for M. S. (U. S.). F. and D., & Division, C. for M. S. (U. S.). M. C. (1982). *Construction Materials for Coal Conversion: Performance and Properties Data*. BOOK, U.S. Department of Commerce, National Bureau of Standards.

Rahimian, M., Ehsani, N., Parvin, N., & Baharvandi, H. reza. (2009). The effect of particle size, sintering temperature and sintering time on the properties of Al–Al2O3 composites, made by powder metallurgy. *Journal of Materials Processing Technology*, *209*(14), 5387–5393.

Renz, R., Seifert, G., & Krenkel, W. (2012). Integration of CMC brake disks in automotive brake systems. *International Journal of Applied Ceramic Technology*, *9*(4), 712–724.

Russ, J. C., Frs, M. A., Kiessling, R., & Charles, J. (2013). *Fundamentals of Energy Dispersive X-Ray Analysis: Butterworths Monographs in Materials*. BOOK, Elsevier Science.

Schienenfahrzeuge. (2013). Brake Discs and Pads. Retrieved from w w w . knorr-bremse . c om

Selamat, M. S. (2006a). How Testing Results can Determine the Best Friction Material Formulation. In D. G. Solomon (Ed.), *Brake Friction Materials* (p. 61). Pusat Penerbitan UITM.

Selamat, M. S. (2006b). Overview on Friction Materials. In D. G. Solomon (Ed.), *Brake Friction Materials* (p. 3). Pusat Penerbitan UITM.

Singh, T. E. J., Patnaik, A., & Satapathy, B. K. (2013). Friction Braking Performance Of Nanofilled Hybrid Fiber Reinforced Phenolic Composites: Influence Of Nanoclay And Carbon Nanotubes. *Nano*, *8*(3), 1350025.

Singh, Y. (2012). Free Vibration Analysis of the Laminated Composite Beam with Various Boundary Conditions. DISS, National Institute of Technology Rourkela.

Solomon, D. G., Berhan, M. N., & Pad, a B. (2007). Characterization of Friction Material Formulations for Brake Pads. *Proceedings of the World Congress on Engineering*, *II*, 2–6.

Straelini, G., & Molinari, A. (2001). Dry sliding wear of ferrous PM materials. *Powder Metallurgy*, *44*(3), 248–252.

Sundarkrishnaa, K. L. (2013). *Friction Material Composites : Materials Perspective*. *Springer Series in Materials Science* (Vol. 173).

Talati, F., & Jalalifar, S. (2009). Analysis of heat conduction in a disk brake system. *Heat and Mass Transfer/Waerme- Und Stoffuebertragung*, *45*(8), 1047–1059.

Talib, R. J., Shaari, M. S., Wan Ibrahim, W. M. A., Kemin, S., & Kasiran, R. (2006). Properties Enhancement of Indigenously Developed Brake Pad for Light Rail Transit. In D. G. Solomon (Ed.), *Brake Friction Materials* (p. 81). Pusat Penerbitan UITM.

Tradekorea. (2008). Steel fibre. Retrieved from http://www.tradekorea.com/product/detail/P262699/steel-fiber.html

Wang, F., & Liu, Y. (2014). Mechanical and tribological properties of ceramic-matrix friction materials with steel fiber and mullite fiber. *Materials and Design*, *57*, 449–455.

Wypych, G. (2000). *Handbook of Fillers*. *Canadian Cataloguing* (2nd Editio). Chem Tec publishing.

Xin, X., Xu, C. G., & Qing, L. F. (2007). Friction properties of sisal fibre reinforced resin brake composites. *Wear*, *262*(5–6), 736–741.

Yoong, M. ., Gan, Y. ., Gan, G. ., Leong, C. ., Phuan, Z. ., Cheah, B. ., & Chew, K. . (2010). Studies of regenerative braking in electric vehicle. In *2010 IEEE Conference on Sustainable Utilization and Development in Engineering and Technology* (pp. 40–45). IEEE.

Zhou, S., Zeng, X., Hu, Q., & Huang, Y. (2008). Analysis of crack behavior for Ni-based WC composite coatings by laser cladding and crack-free realization. *Applied Surface Science*, *255*(5, Part 1), 1646–1653.