SQUEALING OCCURRENCE OF WORN BRAKE PADS DUE TO FOREIGN PARTICLES EMBEDMENT INTO THE FRICTION LAYERS

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To my beautiful mother, my dear father, my beloved wife and my lovely children.

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ABSTRACT

The disc brake squeal is a very annoying sound and a source of considerable discomfort that leads to customer dissatisfaction. There are various possible mechanisms that could trigger brake squeal generation either from a structural dynamics or tribological point of view. Unlike drum brake design, the disc brake assembly, particularly the disc and the pads are exposed to any unwanted road particle, wear debris and water spray. Their presence into the disc and pad interfaces may create dynamic and physics phenomena induced by friction surface changes which lead to the brake noise and vibration issues. Thus, the objective of this research is to investigate a characterization of the worn surface of squealing brake friction material with the effect of different sizes of foreign particles using laboratory scale brake test rig. The correlation between squeal generation and tribological characteristics of the pad including surface topography, surface roughness, wear, element composition and friction coefficient are established by using squeal index and qualitative analysis. The foreign particles (silica sand and road sand particles) with the sizes of 100-150, 200-300 and 300-400 μm are introduced into the brake disc and pad interfaces. The sensitivity of sand particles in producing squeal noise is also examined at different brake pressures, disc temperatures and speeds. The experimental results show that both sand particles have a significant effect on the brake squeal occurrences. The tribological properties reveal that squeal is more affected by smaller sand particle size. The micrometric particles act as punctual contact surfaces generating more wear debris which are accumulated and compacted inducing a reduction of the friction level. However, the biggest particle size damages the pad surface, reduces the real contact surface and decreases the friction coefficient, yet generates more wear lost. It was found that foreign particles play an important role in reducing the squeal level on the pad surface as well as increasing the value of the squeal index number.

ABSTRAK

Bunyi kiuk pada cakera brek sering menimbulkan ketidakselesaan terhadap penumpang dan pemandu kereta yang membawa ketidakpuasan kepada pelanggan. Terdapat pelbagai kemungkinan terhasilnya bunyi kiuk pada cakera brek samada berpunca dari struktur dinamik ataupun dari kesan tribologi. Tidak seperti rekabentuk brek gelendung, brek cakera terutamanya cakera dan pelapik adalah terdedah kepada partikel asing yang tidak diingini seperti pasir jalan, habuk haus dan percikan air. Kehadiran mereka permukaan cakera brek boleh mengakibatkan fenomena dinamik dan fizik yang disebabkan oleh perubahan permukaan geseran yang membawa kepada bunyi dan getaran. Maka, objektif penyelidikan ini adalah untuk menyelidiki ciri-ciri kehausan permukaan bagi bahan geseran yang berkiuk akibat saiz partikel asing yang berbeza menggunakan pelantar ujian brek berskala makmal. Hubungan antara penghasilan kiuk dan ciri tribologi pada pelapik termasuk permukaan topografi, kekasaran permukaan, kehausan, komposisi elemen dan pekali geseran adalah dibina menggunakan index kiuk dan analisis kualitatif. Partikel asing (partikel pasir silika dan pasir jalan) bersaiz 100-150, 200-300 dan 300-400 μm dimasukkan pada permukaan cakera dan pelapik. Kepekaan partikel asing terhadap penghasilan kiuk juga diperiksa pada tekanan hidraulik brek, suhu cakera dan halaju cakera yang berbeza. Keputusan ujikaji menunjukkan bahawa pasir silika dan pasir jalan memberi kesan besar terhadap penghasilan kiuk brek. Sifat tribologi pelapik brek mendedahkan bahawa kiuk lebih cenderung terhasil pada saiz partikel asing yang lebih kecil. Partikel bersaiz mikrometrik bertindak sebagai permukaan sentuh tepat menghasilkan lebih banyak debu haus yang terkumpul dan padat menyebabkan penurunan tahap geseran. Walau bagaimanapun, partikel asing bersaiz besar akan merosakkan permukaan pelapik, mengurangkan permukaan sentuhan dan menurunkan pekali geseran tetapi menghasilkan lebih banyak kehausan. Penemuan menunjukkan partikel asing memainkan peranan penting di dalam mengurangkan tahap kiuk pada permukaan pelapik dan meningkatkan nilai nombor indek kiuk.

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LIST OF ABBREVIATIONS

Ra	-	arithmetic average
Rq	-	root mean square
Rp	-	maximum peak height
Sm	-	Mean Spacing of Profile Irregularities
NS	-	Roughness Value of new sample
NS	-	New Sample
WPS1	-	without road particle sample 1
WPS2	-	without road particle sample 2
SS	-	silica sand
RP	-	Road particle
S1	-	Sample 1
S2	-	Sample 2
SS100S1	-	Silica sand particle size 100 to 150 μm Sample 1
SS100S2	-	Silica sand particle size 100 to 150 μm Sample 2
SS200S1	-	Silica sand particle size 200 to 300 μm Sample 1
SS200S2	-	Silica sand particle size 200 to 300 μm Sample 2
SS400S1	-	Silica sand particle size 300 to 400 μm Sample 1
SS400S2	-	Silica sand particle size 300 to 400 μm Sample 2
RP100S1	-	Road particle size 100 to 150 μm Sample 1
RP100S2	-	Road particle size 100 to 150 μm Sample 2
RP200S1	-	Road particle size 200 to 300 μm Sample 1
RP200S2	-	Road particle size 200 to 300 μm Sample 2
RP400S1	-	Road particle size 300 to 400 μm Sample 1
RP400S2	-	Road particle size 300 to 400 μm Sample 2

LIST OF SYMBOLS

W	-	Wear
k	-	Wear coefficient
H	-	Surface Hardness (HV)
F	-	Load and Force (N)
S	-	Distance (m)
$\propto$	-	Wear Constant
a, b and c	-	Set of parameter friction pair
K	-	Load cell factor (N)
Tb	-	Brake Torque (Nm)
L	-	Length of Baking Plate (m)
μ	-	Coefficient of friction
F_n	-	Normal force (N)
R_d	-	Disc brake radius (m)
P_{brake}	-	Drake line pressure (Pa)
A_{piston}	-	Brake piston area (m^2)
R_{disc}	-	Brake radius (m)
Md_{brake}	-	Brake torque (T), N.m
P	-	Brake pressure (applied pressure), MPa
$P_{threshold}$	-	Pressure threshold, MPa
A_p	-	Piston area, (mm^2)
r_{eff}	-	Effective rotor radius, (mm)
η	-	Efficiency
Ai	-	Weighting for certain SPL
Ni	-	Number of brake application
Nt	-	Total number of brake application
Ψ	-	Plasticity Index
E'	-	Modulus elasticity

B	-	Mean radius of asperities of pad/disc assembly
γ (SI)	-	Squeal index
$\beta_d \beta_P$:	-	Mean radius of asperities of pad and disc surface (μm)
S_m	-	Mean spacing between profile peaks at mean line (μm)
$(R_P)_{p\,\&\,d}$	-	Maximum height of profile above mean line pad and disc (μm)
σ_p, σ_d	-	Standard deviation of height distribution of asperities pad and disc (μm)
IN	-	Index number of particle composition
ΣE_t	-	Test element composition (weight %)
ΣE_n	-	New element composition (weight %)
ΔSPL	-	Total of Sound Pressure Level (dB(A)
Rz	-	Maximum surface roughness (μm)

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CHAPTER 1

INRODUCTION

1.1 Background

An automotive braking system is a group of mechanical, electronic and hydraulically activated components which use friction materials as a device for slowing or stopping the motion of a wheel while it runs at a certain speed. Brake friction materials are multi-component composites composed of several basic functional parts, abrasives, lubricants, space fillers, fiber or pulp reinforcements, and polymer binders. The requirements of the braking system of the vehicle are becoming more demanding because of strict regulations on safety and performance. Development of brake friction meets many questions till today, such as raw materials selections, friction composite formulations, thermal effects, tribochemistry during the braking, friction layer formation and its role, noise reduction, and environmental friendly components. With the intensity of developing more green technology by automotive manufacturers the challenge insists researchers to develop new product formulations that respond more effectively to the end users. The minimal knowledge about the morphology, chemical composition, and micro-sized particles inside and outside brake components is alarming due to the fact that brake pad manufacturers currently do not have to deal with the development of eco-friendly formulations. Since brake pad and disc are a crucial component from a safety point of view, materials used in brake systems should have stable and reliable frictional and wear properties under varying road conditions: slippery, wet and dry roads, rough or smooth road, wet and dry brakes, new or worn linings, load and pressure, speed and velocity, high durability, temperature, environment, dust and grit particle effect.

Brake Squeal is one of the major problems in the development of new automotive disc brake system and large efforts have been made to reduce it. This is because the nature of brake squeal is mysterious, unpredicted, and often non-repeatable due to its high dependency on a large number of interacting parameters, such as contact conditions, material properties and ever-changing operating conditions (Oberst and Lai, 2011). Brake squeal can be disturbing and annoying to the driver, passengers and people nearby. For car users, this sound quality problem has the highest complaint frequency, effect quality, satisfaction ratings and warranty costs. As a result, car manufacturers and brake researchers start to explore the noise problem not only in the mechanism, theory, and tribological but also in the effect of external source of the surrounding road surface.

Numerous different approaches to the problem solution were considered in the past and many different explanations of squeal origin were proposed (Oberst and Lai, 2011), (Chen, 2009) and (Kinkaid et al., 2003). This is due to brake squeal itself is a challenging subject to tackle not only due to its strong dependence on various parameters, but also the mechanical interactions in the brake system are very complicated. Furthermore, it is well accepted in the brake research community that squealing brakes are due to one or more triggered mechanism such as stick-slip, sprag-slip, negative damping, mode coupling and hammering (Kinkaid et al., 2003), (Papinniemi et al., 2002) and (Chen et al., 2005). However, this theoretical perspective does not demonstrate the whole brake area in which there is a very limited knowledge of what really happens in the material behavior during brake squeal generation. Earlier studies have shown that the friction film of brake discs has a strong influence on the generation of squeal (Rhee et al., 1991). Sound in the squealing brakes is excited by the contact between brake pad and disc. Ericsson et al. (1999) on his wear and contact studies found that direct observation of surface between brake pad specimen and a disc has contributed a positive result into dynamics and mechanical behavior of surface condition.

Researchers in recent years begin to explore tribological behavior of automotive brake squeal phenomena which covers the morphology, chemical composition, abrasive particle, airborne particle, friction and wear, phase composition, third body, wear debris, friction film distribution, health issue and environmental pollution (Hetzlerand and Willner, 2012) and (Yoon et al., 2012). However, not much effort has been made to study the tribological behavior on the influence of small particles with brake squeal phenomenon (Gietl et al., 2010). Despite many investigations over the years to clarify the mechanism causing automotive brake squeal have been done, the exact phenomenon has not yet been fully understood.

In addition, the environmental concerns related to grit particles have only brought more attention in recent years. Road traffic represents a significant source of grit particle released into the environment. Road particle and wear of automotive friction composites is known to be associated with the generation of noticeable amounts of road particles Figure 1.0. When brakes are applied, friction between pads and disc always leads to the release of wear particles. Depending on conditions, released wear debris can be partially attracted to the vehicle brake system. The released wear particles can be categorized as airborne particles (released into the air and typically deposited away from the roadside) and non-airborne particles (deposited on vehicle/ brake hardware or falling on the road surfaces).

(a) (b)

Figure 1.0: The particle and contaminant from the. road surface (a) Road Grit Particle and (b) Particle at contact pad and disc surface

Furthermore, there is little information on the contribution of external particles on brake squeal occurrences available in the open literature. The influence of pad surface characteristics on the generation of brake squeal has recently gained a new interest in many brake researchers as a new insight of understanding squeal occurrence.

1.2 Problem Statement

Today, most car manufacturers have managed to slightly reduce brake squeals through changes in design, careful selection of friction materials and mounting of vibration damping shims on the back plate of the brake pads. However, the mechanism causing brake squeals has not yet been fully understood. Earlier studies have shown that the reaction on the sliding surface has a strong influence on the generation of squeal (Eriksson, 2000) and (Bergman et al., 1999). Rhee et al. (1991) among the early researchers who study the effect of the tribological behavior on automotive brakes believes that the surface changes contribute to a major factor for controlling noise, friction and wear. This is true, where Eriksson et al. (1999) related the squeal phenomenon with that the friction behavior on brake surface is closely related to the formation of plateaus which is due to wear resistance of components. His finding is confirmed by Sheriff (2004) who identified an evidence to prove squeals are generated or eliminated at the surface topography of the pad and disc. Rusli and Okuma (2007) who studied the effect of surface topography of dry sliding surface found that squeal noise tends to be generated on both smooth and rough surfaces.

Despite the fact that brake squeal is caused by different mechanisms, many researchers have not yet reached a comprehensive understanding of the surface behavior during braking operation. Furthermore, research in foreign particles on brake squeal is rather limited since much interest in the past researches were related to the effect of abrasive particle, composition, wear particles, airborne particles, wear debris and friction film, on surface characteristics and vibration (Wahlstrom et al., 2010), (Kim et al., 2011) and (Hinrichs et al., 2011) and only a limited number of research articles considered this aspect (Abdul Hamid et al., 2010 and 2011). Eriksson et al. (2000) and later Bergman et al. (1999) among the early researcher who related the noise effect of brakes contact condition with the wear particles forming during the sliding process between pad and disc. While some researchers had found that the third body formation of trapped material of the pad and disc during the braking process which influence the braking process and brake performance (Osterle et al., 2009). Wahlstrom et al. (2010) and Sanders et al. (2003) has found the effect of airborne wear particle which comes from various sources and occurs in size intervals contribute to the wear mechanism of the vehicle brake. Abdul Hamid (2010) studied the effect of different particle grit size on the accumulation and friction characteristic of brake system and found that the particle size affects the friction performance at certain sliding speed and pressure.

The design of brake system which is exposed to the environment condition such wet, humidity and foreign particles (grid particle, hard particle, airborne particle) with a different size and shapes will affect the tribological characteristics of the brake friction. Furthermore, the location of the disc brake makes it possible for the presence of dust, airborne particles and other environmental particles to enter the brake gap between the pad and disc and it is very difficult to recognize these particles in the surrounding environment. As described in Wahlstrom et al. (2010) external particles also known as debris particles could possibly come from various sources and present in different shapes and sizes. These elements may contribute to a serious tribological problem of braking performance, including squeal generation on the brake interface. Another factor that influences the tribological characteristic is the material transfer between the two brake components. During braking, the interaction between the pad and disc interface which rubs against each other will generate wear particles or wear debris. Researchers have found that some of these particles are compacted and trapped on the brake surface, becoming second body and third body, and others become airborne particles spread to the surrounding. When the contact of two surfaces occurs, the adhesion of the roughness and arbitrary shapes, sizes and heights of surface interaction generates friction force. This process will destroy the interface conditions. Some of the debris particles leave the particles and others will remain forming a new contact patch on the pad and disc interface. The remaining particles (second body and third body) will mix with the external particle which entered into the brake gap agglomerate and form a new surface layer called contact plateaus and friction film several millimeters thick (Kukutschova et al., 2011), (Osterle and Urban, 2006) and

(Ertan and Yavuz, 2010). As a result, the frictional forces and wear behavior of the brake surface change continuously during braking (Sherif, 2004), (Hetzler and Willner, 2012) and (Cho et al., 2003). Coupled with the initial composition and the friction layer evolution, these environmental sources act in synergy and affect the brake performance, particularly squeal noise occurrences. Although numerous researches have related the effects of foreign particles on brake performance, there exists only a limited number of research articles considered with this issue. There is also no recommended standard procedure suitable on the relevant research of tribological behavior of brake system such as the Society of Automotive Engineers Procedures J 886 (a laboratory-scale, coupon test for determining lining friction), J 2430 (a multi-stage dynamometer test for disc brakes), and SAE J 1802 (a test procedure for drum brake linings), (Blau and McLaughlin, 2003).Yet a complete understanding that relate of these particles with the effect on squeal mechanism needs to be found. Thus, research towards it must cover a wide range of area in order to gather full information on the whole aspect of brake behavior. The effect of external particles on braking operation is the most interesting study since not yet fully discover by many researchers in recent years.

1.3 Objectives of Research

The objective of this research aims to:

(i) To investigate the effects of different size of road grit particles on squeal generation using laboratory scale brake test rig. Comparison of squeal generation is also made between pad with and without grit particles.

(ii) To identify correlation between squeal generation and tribological characteristics of the pad based on the surface topography, wear and friction coefficient. Squeal index proposed by Sheriff (2004) and qualitative analysis of elemental composition is performed in order to verify the correlation.

1.4 Scope of Study

In order to achieve the objectives of the research, the following scopes have been determined:

(i) The research is limited to available non organic, asbestos (NAO) brake pads on passenger car.

(ii) The experiment is performed using drag-type brake squeal test rig available at UTM with the power output of 11 kW and hydraulic pressure 20 bars matching with the maximum brake line pressure for squeal occurrence.

(iii) The squeal test procedure is based on surface vehicle recommended practice SAE J2521 test procedure. Since the limited output of power and pressure of the test rig the SAE J2521 test practice is operated between 0 to 15 bars of pressure with initial speed between 3 to 10 km/h and maximum temperature level 100°C as recommended from an SAE test procedure.

(iv) Only two (2) types of grit particles are involved in the study, namely road grit particles and silica sand particles with a size range between 100 to 150 μm, 200 – 300 μm and 300 to 400 μm. These particles were selected due to the common presence of Malaysian road surface. These particles are investigated through laboratory test scanning electromagnetic microscopic (SEM), field emission scanning electromagnetic microscope (FESEM) with energy dispersive X-ray analysis (EDX), optical microscope, surface roughness and hardness test.

(v) Qualitative study is performed to gain an understanding of the data and find the significant correlation of the external grit particle effect of pad surface topography on squeal propensity.

1.5 Significance of Study

The study of surface characterization with the effect of external particle on squealing brake has not been considered by previous researchers. It is, therefore, necessary for current research work to explore and investigate such study in an attempt to identify the root cause of brake squeal in relation to the surface characterization. Having known the main source that excites squeal in the brake system, it is expected that an appropriate brake squeal reduction/elimination solution can be proposed and implemented. Hence, the brake system can become quieter than before.

1.6 Thesis Organization

The thesis consists of five chapters which summarized as follows:

Chapter Two (2) consists of a literature review of the studies of the function of disc brake system, brake material formulation, automotive disc brake noise and the study of brake squeal, The review also discusses on tribological study of brake squeal which consists of surface topography, brake surface contact condition, friction layer, third body and wear debris, wear mechanism, surface roughness, particle characterization and embedment and effect of water and humidity. The review also discusses on a qualitative approach since the studies involved both application (quantitative and qualitative) methods. At the end of the literature, the discussion of vibration studies of brake squeal is also discussed to find the correlation of squeal occurrence with tribological approach.

Chapter Three (3) focuses on the experimental details such as the development of the test rig, experimental apparatus, setting-up and calibration, sample preparations and test procedures. This chapter also explains the external grit particles used in the experiments, the methodology used during the experiments and the analysis involved in analyzing the test result. The overall structure of the analyses conducted is described in this chapter.

Chapter Four (4) presents all the experimental results obtained which consist of the summary of squeal test results, the absolute percentage noise occurrence on sound pressure level, the absolute percentage noise occurrence of different pressure, the absolute percentage of noise occurrence on speed, the analysis of sound pressure level against frequency, the coefficient of friction against sound pressure level, relative humidity against sound pressure level in the form of graphs.

Chapter Five (5) contains discussion on tribological aspects divided into four (4) sections. The first section discusses roughness measurement and the analysis consist of surface roughness average data for brake pad and disc assembly, squeal index analysis, the determination of squeal factor with the generation of squeal noise, the relation between surface profile and the height distribution, statistical study on roughness parameter and its relation to squeal. This is followed by second (2) section discussion on analysis of energy dispersive X-Ray (EDX) composition result, the weight percentage (%) analysis of elemental composition of new and with particle effect. The qualitative analysis through an index number together with the analysis of drain particle outside sliding surface is also discussed. The third (3) section covers the analysis of surface topography and wear debris formation analysis of new pad samples, road particles and silica sand effect. Finally the fourth section discusses on the wear test analysis which consist of new pad samples (original samples), squeal pad without particle effect, squeal pad with road particle effect and squeal pad with silica sand effect.

Chapter six (6) presents the result and conclusion of the study and some recommendations for future work

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