A wear diagnosis for brake pads by evaluation of contact interface

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Abstract
This work examined a used brake pad and another brand new one to compare their contact shape and contact area. Surface roughness measurement and ultrasonic scanning were used to study the contact interface. The 2D maps show the variation in the contact shape, which indicates that the used pad is unevenly worn to a significant extent. The results may suggest the improved pad design and provide the timing of replacement for a brake pad. The contact area shows an increasing trend under different applied forces and the area matrix gives useful information about the degree of wear. Contact pressures were also calculated by the combinations of image analysis software and ultrasonic technique. The contact pressure varies from 0.17 MPa to 3.4 MPa and maps of the distribution of the pressure contour are also shown.

Keywords: Brake pads, Contact interface, Contact pressure, Wear diagnosis, Ultrasound

1. Introduction

Almost all ground transportation vehicles control their deceleration using a friction brake system. In this system, the brake pad significantly affects the braking ability. The material of the brake is directly in frictional contact with the rotating disc, which achieves the braking effect. Several factors have an important effect on the performance of a brake pad, such as the friction coefficient, the high temperature durability, the noise level, the thermal conductivity and the brake control. Brake pads must have good wear resistance. However, the frictional and wear behaviors are very complicated and not easily predicted. They depend on various parameters, such as the microchemical structure of the pad, the contact interface, the speed of rotation, the pressure and the contact temperature (Stanford and Jain, 2001).

When the brake pedal is depressed, a force is applied on the brake pad that brings it into contact with the rotating disc. The pad/disc interface can be considered to be a dry sliding contact. During the deceleration process the brake pad remains in contact with the disc, which causes wear on both the disc and the pad. In theory, a brake pad is designed to have average wear on its surface after operating for a period of time. However, there is much evidence that brake pads usually wear unevenly in most cases. This uneven wear means that the pad surface does not conform to the rotating disc, which reduces the braking ability. In this study a contact measurement for a used brake pad is performed and the contact shape and contact area are worked out.

Many studies of brake pads or linings focus on vibrations (Popp, 2005; Akay, 2002) and squealing noise (Giannini et al., 2006; Oberst and Lai, 2011). In these studies frictional force is an important factor (AbuBakar and Ouyang, 2008) that is related to the wear of the lining surface, the operation temperature and the pad life. Some models that use a finite element method have been developed to predict the distribution of the contact pressure in static contact conditions (Hohmann et al., 1999; Söderberg and Andersson, 2009). Two principal experimental techniques have been used to investigate the contact interfaces between any two contact bodies: ultrasonic detection [9] and the use of pressure sensitive films (Ng and Yeong, 2005). However, few studies have measured the contact area between the brake...
pads and the rotating disc. None have used the ultrasonic method. The contact area plays an important role in any study of a pad/disc system and the size of the area also affects a decision to replace brake pads.

Wear in a brake pad has a significant effect on brake operation. Many factors affect pad wear, such as the applied force, the temperature, the degree of conformity of the lining surface and the material properties. There are some direct methods for wear estimation, such as visual inspection, measurements of volumetric changes and those that use surface textures and some indirect methods such as online monitoring (for vibrations and squeal noises) (Sherif, 2004). This study diagnoses wear by measuring the contact area for a used motorcycle brake pad and comparing it with the area for a brand new item, using ultrasonic scanning. A single ultrasonic transducer can conduct a point measurement of reflection. If the transducer moves back and forth across the scanned area, a 2D signal is collected and the map of the reflection is obtained. References (Yao and Chien, 2014; Yao and Zhou, 2013, Lewis et al., 2005; Marshall et al., 2006) describe the detailed processes for the method, both analytically and empirically.

2. The Modeling approach

2.1 The operation of brake pad/disc system.

Figure 1 shows an illustration of a contact for a brake pad/disc system. The life of the brake pads depends on many variables, such as driving style or the wear pattern in the laws of tribology. The principal factor that influences the pad life is the material from which a pad is made, or the frictional material. There are four different types of pads: organic, semi-metallic, metallic, and synthetic. Each of these has its own characteristics that must be considered when estimating the brake pad life.

A brake system converts the kinetic energy of a car’s motion into heat energy via the friction from the pads. When the brake is depressed, the pads are pressed against the disc to decelerate the car. A disc is a simple piece of metal that is specifically designed to work with the pads. The mass of some special disc designs helps dissipate some of the heat energy that is developed during the braking process and extends pad life. The surface also has a specific finish that is smooth enough to match the surface of the pad, but rough enough to allow effective braking.

During braking, the state of the brake pads is significant, because it affects the ability and efficiency of the brake system. Direct measurement is the best method to measure brake pad wear because the wear equation is very complex and is highly dependent on the composition of the brake linings and simulation does not accurately represent real cases. In a study of the wear state of brake pads, a critical diagnosis index is the contact area. Because ultrasonic detection allows the shapes of the contact patches to be determined and so allows measurement of the contact area, it is used in this experiment. The sample pad that is used for the wear state investigation in this work is from a motorcycle brake system. Figure 2 shows photographs of the used brake pad and a new item and the original dimensions. It is easily seen that there are different degrees of wear for the new pad and the used item.

2.2 Ultrasonic scanning.

The transducer calibration technique involves scanning a contact interface in a water bath tank using ultrasonic
waves. Partial or incomplete contact causes a changing ultrasonic response that represents an amplitude plot of the pulses in profile is produced on the oscilloscope. The ratio of the amplitude of the reflected pulse to the amplitude of the incident pulse, known as the reflection coefficient, $R$, is determined by equation (1) (Tattersall, 1973):

$$R = \frac{z_1 - z_2}{z_1 + z_2}$$  \hspace{1cm} (1)

where $z$ is the acoustic impedance of the specific material, which is the product of wave speed and density, and the subscripts refer to the two sides of the interface.

Acoustic impedance is the resistance of a material to the passage of ultrasonic waves and attenuates ultrasound in a material. Air has a very low impedance to ultrasonic waves; the impedance of water greater than that of air. The impedance ratio between two materials is simply the impedance of one material divided by the impedance of the other material. Since the ratio between air and any solid material is very high, most of the pulses are reflected back at the interface between air and any solid material.

The surfaces of a brake pad and a rotating disc are rough on the microscopic scale. The interface between disc and pad is composed of individual asperity junctions and air gaps therefore the pad/disc surface is an incomplete interface. When an ultrasonic wave is transmitted through such a rough interface, it passes through the regions of asperity contact and is reflected back from the air gaps, so the reflected signals serve as a scan of the contact shape across the interface. The detail of the experimental procedures and the relationship between the reflected signals and the shape scan can be found in references (Yao and Wu, 2014; Baltazar et al., 2002).

### 2.3 The spring model of a contact interface

A contact spring model (Gonzalez-Valadez et al., 2010) has been proposed to investigate the response of an incomplete interface to an ultrasonic wave. The interface behaves like a series of flexible springs corresponding to the two bodies. The reflection coefficient is determined by the stiffness of the interface spring, $K$, the angular frequency $(2\pi f)$ of the ultrasonic wave, $\omega$, and the acoustic impedance, $z$:

$$R = \frac{z_1 - z_2 + i\omega(z_1 z_2 / K)}{z_1 + z_2 + i\omega(z_1 z_2 / K)}$$  \hspace{1cm} (2)

The stiffness, and hence the reflection coefficient from equation (2), varies with contact pressure. Measurement of the reflection coefficient gives information about the degree of contact at an interface and the distribution of the contact pressure.

This study investigates the contact interface for both a retired brake pad and a new item and then compares them using ultrasonic scanning and surface roughness measurement. If the shape and size of a contact region can be determined, the wear behavior for a brake pad can be predicted, which gives useful information for the future design of
brake pads.

3. Apparatus and Experimental Procedure

3.1 The measurement of the surface roughness

This study investigates the difference in the shape of the contact for a used brake pad and a new item, due to wear. The change in surface roughness when the brake pad is used for a certain period of time is important. In order to determine the difference between the new and the used brake pads, a surface profilometer, SJ-400 stylus (shown in Figure 3) was used for the measurements. The diamond stylus moved down to the brake pad and then moved laterally across the lining face for a specified distance of 1.0 mm. A series of digital signals were converted from the analog signals generated by the profilometer. These data were stored and then analyzed to calculate the roughness using SURFPAK software. The surface roughness was displayed on a PC monitor screen. The unit of the y-axis, which is the measurement for surface roughness, is micrometers (μm) and the unit of the x-axis, which is the measured distance, is millimeters (mm).

Fig. 3  Photographs of the profilometer for the roughness measurement.

3.2 Test Specimens and loading apparatus

The used brake pad was caused to contact with the disc for the ultrasonic scanning experiments. Figure 4 shows a photograph of the contact layout and the loading apparatus. The test specimens consisted of a set of new brake pads and a worn set, which are suitable for motorcycles with 150cc engines and were originally the same size. The brake pad and a steel plate were placed in a frame and a hydraulic cylinder under the pad/plate contact was used to provide a normal load for the specimens. This frame accommodated the contact specimens in a space that consisted of three large stainless steel blocks and four cylindrical supports. In order to ensure the parallel contact of the brake pads, both the frame base of hydraulic cylinder and the plane of the steel plate have been calibrated in parallel with the level meter in advance. A hydraulic cylinder inside this frame applied different normal forces on the contact specimens, in order to study the variation in the contact area.

Fig. 4  A photograph of the specimens in contact and the loading frame, showing the hydraulic cylinder that applies normal loads.
3.3 Ultrasonic instrumentation and scanning procedure

The loading frame, including the test specimens, was placed in a scanning device for ultrasonic scanning. This device consisted of an ultrasonic pulse receiver (UPR), an oscilloscope, a data processing computer and a transducer. Figure 5 shows a schematic layout of the ultrasonic instrumentation and the scanning procedure. The UPR is the principal part of the ultrasound apparatus, which provide a voltage pulse that excites the transducer to produce an ultrasonic pulse. A water bath was placed above the contact specimen. A 5 MHz focusing transducer was immersed in the water bath and was connected to an x-y positioning stage, so that it could be scanned across the interface. The ultrasound focuses down to a finite spot of diameter, \( d \), which is expressed as follows (Marshall et al., 2006):

\[
d = \frac{1.028 l_w c_w}{fD}
\]

where \( l_w \) is the focal length in water (1 inch in this case), \( c_w \) is the speed of sound in water (1481 m/sec), \( f \) is the ultrasonic frequency (5 MHz) and \( D \) is the diameter of the transducer element (0.75 inch). Basically in this case, the spot diameter, \( d \), is 0.4 mm.

The transducer scans over a given region automatically. It moved up and down, to focus the ultrasonic signal onto the interface and to determine the maximum signal amplitude, as shown on the PC monitor screen. When the apparatus had been focused on the surface to be detected, the transducer was moved along the x and y directions in increments of \( dx \) and \( dy \), until the entire region of interest had been inspected. The reflected readings were then taken at prescribed intervals across the interface. The dimensions and resolution of the scan varied and were selected according to the specimen geometry and the degree of ultrasonic accuracy required. Figure 6 shows a photograph of the apparatus.

![Fig. 5 A schematic layout of the ultrasonic instrumentation and the scanning procedure.](image)

![Fig. 6 A photograph of the ultrasonic instrumentation.](image)
There are three typical methods in ultrasonic test. A-scan is a detection method that displays the returned signal in term of distance or depth of penetration at one point. B-scan is to scan a particular cross-section along a line of the specimen. C-scan displays the images composed of A-Scans captured during the XY-scanning in a plane view. Figure 5 also shows a schematic of the movement of the transducer. It combines a number of A-scan processes to produce a C-scan effect and results. A Labview program was written to perform a Fast Fourier Transform (FFT) of the signal, to perform a series of post-processing tasks and to produce useful data. Using the collected and stored data, the reflection amplitude signals for different applied forces were obtained and these were then processed to plot the contact images, using MATLAB.

4. Results

4.1 The reflection amplitude map

Figure 7 shows the scanning amplitude 2D maps, and compares the contact patches for the used brake pad and a brand new item under various normal loads. These pictures clearly show the different shapes of the contact regions for the used and the new brake pads and the variation in the size of the contact is very clear. The 2D maps show the variation in the contact shape, which indicates that the used pad is unevenly worn to a significant extent, so only two arc-shaped regions are still in contact; the remainder of the lining materials is completely worn. Originally, almost all the pad surface of the brand new pad is in contact. However, there is uneven wear in the lining materials for the used pad during the braking process and the pictures of the used pad indicate the probable wear region and the size of contact area.

![Fig. 7 A comparison of the 2D contact pictures for the used brake pad and a brand new item, under various normal loads.](image)

![Fig. 8 The concept of a contact area for different contrast ratios.](image)
4.2 Image processing using the software package

When the scanning process was complete and the data had been captured, the tens of thousands of digital readings for the amplitude of the reflected signals were arranged into a matrix, according to their x-y coordinates. This matrix was then used to plot the contact image, using the “surface” function in MATLAB. Theoretically, the size of the contact image increases from zero contact to full contact when the force is increased. The signal values for the reflected amplitude data show the formation process for the shape of the image, depending on whether the contact is light or heavy. Before performing the area calculation, the contrast ratio was defined as the contact layer from light to heavy, to show the image size for different collected signals. Figure 8 shows the concept and an example of variations in the image for different contrast ratios of 10%, 30%, 60% and 90%. A comparison with the original contact image shows that the size of the contact image increases as the contrast ratio increases from 10% to 100%.

![Figure 9](image1.png)  
**Fig. 9** Contact area vs contrast ratio for worn and new brake pads, under different loads.

![Figure 10](image2.png)  
**Fig. 10** The area increasing matrix for the worn brake pads, for an increasing contrast ratio and under five different loads.


Table 1 Contact area for different contrast ratios, under five different loads. Unit: mm²

| Loads | Status | 10%  | 20%  | 30%  | 40%  | 50%  | 60%  | 70%  | 80%  | 90%  | 100% |
|-------|--------|------|------|------|------|------|------|------|------|------|------|
| 30 N  | new    | 324.3| 388.2| 431.1| 465.5| 496.3| 522.9| 548.0| 575.9| 602.5| 628.8 |
|       | used   | 4.89 | 6.82 | 9.75 | 14.68| 19.05| 23.96| 29.43| 35.65| 43.02| 52.38 |
| 60 N  | new    | 491.3| 579.0| 635.5| 681.3| 724.1| 761.2| 794.7| 828.4| 860.9| 892.1 |
|       | used   | 92.07| 113.4| 127.2| 140.6| 151.4| 161.6| 172.3| 184.7| 195.0| 212.8 |
| 90 N  | new    | 567.1| 657.9| 726.2| 784.9| 839.8| 879.5| 913.7| 944.8| 975.5| 1020.9|
|       | used   | 115.9| 143.0| 162.1| 178.2| 192.5| 206.5| 222.0| 240.8| 264.7| 291.8 |
| 120 N | new    | 623.9| 901.8| 1045.5| 1132.6| 1200.1| 1236.7| 1268.3| 1297.7| 1328.7| 1357.8|
|       | used   | 286.5| 322.1| 348.3| 370.0| 387.1| 402.8| 418.7| 435.8| 455.0| 478.9 |
| 150 N | new    | 1201.5| 1363.5| 1444.2| 1493.9| 1528.5| 1549.1| 1562.3| 1573.1| 1587.9| 1599.0|
|       | used   | 433.3| 468.8| 491.1| 509.1| 523.7| 537.7| 551.1| 565.3| 580.3| 598.0 |

Fig. 11 The area increasing matrix for the new brake pads, for an increasing contrast ratio and under five different loads.
The shape of the images was determined for contrast ratios 10% to 100%, in 10% increments and the contact area was then calculated using the image processing software package, Power Image Analysis (PIA). Firstly, the length in the x-direction was defined as the same width for each scanned image. The distance was 30 mm. The contact images were chosen using a block selection tool. The areas of the selected contact patches were automatically calculated in a digital format and shown on the screen. Using these procedures, the contact areas were calculated and they are listed in Table 1. Figure 9 shows the curves for the increase in the area for the used and the new pads. It is seen that the size of the area for the worn pad is much less than that for the new item because most of the lining materials disappear due to severe wear. Figure 10 and Figure 11 respectively show the area matrices for the worn and new brake pads. This verifies the degree of wear for the used brake pad.

4.3 The results for the surface roughness measurement

The measurements for the average surface roughness, Ra, for the surface of the used and the brand new brake pads are shown in Figure 12, which includes a comparison of these results. During the process, three positions on the left, center and right regions of the used and the new pads were used for the roughness measurements. The curves for the worn exhibit two obvious peaks and the right are higher than the left. This is in good agreement with the result for the scanning map, which shows that two arc-shaped curves remain on the worn pad’s surface. The curves for the new pad are horizontal and level, which reflects the fact that almost the entire surface of the pad appears in the scanning contact images.

In Figure 12, the upper right corner of the roughness curves show the specific details of local roughness. The roughness values, $Ra$, of three positions (the left, center and right regions) are $6.123$, $6.980$ and $8.217 \mu m$ for the used pad and $4.634$, $3.915$ and $3.503 \mu m$ for the new pad, respectively. In the meantime, the difference between the highest and the lowest values for the worn pad are approximately 40 to 60 $\mu m$ but this difference is only 20 to 30 $\mu m$ for the new pad. This verifies that there is uneven wear and shows that the average roughness for the worn brake pad is greater than that for the brand new pad in this case.

![Fig. 12A comparison of the surface roughness for the surface of the used and the brand new brake pads.](image)

4.4 Estimation of Contact Pressure
Because the amplitude of the reflected signal is affected by differences in the intensity of the contact between the interfaces, the different amplitudes for the reflected signals can be used to determine the different contact pressures via data processing. The amplitude of the reflected signal is affected by the size, the number and the distribution of the surface asperities. A calibration process was used to determine the relationship between the contact pressure and the reflected amplitude (Yao and Wu, 2014). The contact pressure is approximately deduced by assuming that the pressure is linearly proportional to the signal amplitude.

In experimental design, the step movement of the transducer was set to be 0.2 mm which was used to scan a 69 mm x 31 mm square area for the worn pad so that the signal matrix has 346 x 156 cells. The applied force and the area of each cell are known, so the constant the pressure distribution for each cell can be worked out. Figure 13 shows the result for the worn pad under five different axial loadings. The figure shows that when the axial force increases, the pressure map shows greater conformity and the maximum pressure is about 3.4 MPa. Figure 14 shows another pressure map for the brand new pad under five axial loads. This distribution map shows that the maximum pressure for the new brake pad is approximately 0.17 MPa under an applied axial force 150 N.

Fig. 13 Maps of the pressure (Pa) distribution for the worn brake pad for five axial loadings with a 100% contrast ratio: (a) F=30 N (b) F=60 N (c) F=90 N (d) F=120 N and (e) F=150 N.

Fig. 14 Maps of the pressure (Pa) distribution for the new brake pad for five axial loadings with a 100% contrast ratio: (a) F=30 N (b) F=60 N (c) F=90 N (d) F=120 N and (e) F=150 N.

5. Discussion
This study uses ultrasonic pulses to scan the contact interfaces for both a retired brake pad and a new pad, under normally applied forces. Under normal circumstances, the pad surface should be entirely in contact with the brake disc and the contact force should be evenly distributed over the entire pad surface, so the wear on the pad lining is approximately even. However, because there is uneven wear on the pad surface, the scanning pictures show that there are two major thin separate contact patches on the retired brake pad, which is different from the original shape. This demonstrates that the pad experiences uneven forces during its working life.

The experiments show that a single ultrasonic transducer can identify the contact area between the brake pads and the disc plate using regional scanning. The measurements for contact area show there is wear in the retired pad and the variation in the location of the wear is easily determined. The scanning images demonstrate the wear process for the retired brake pad, and this information allows optimization of the brake pad design. The thickness of the pad linings is usually checked periodically or the pad surface is inspected to decide whether the brake pad is still serviceable. This study provided another method to decide the correct timing for changing brake pads.

The scanning data was collected and post-processed and the contact area was then calculated using image processing software. The 2D contact images for the contact area measured for the static condition are useful for wear diagnosis and to improve pad design. For the 3D images, the reflected signal amplitudes provide an easy way to study contact intensity, to identify the regions that are most likely to wear during the pad’s life. However, this is a laboratory based static study. In actual operation, the brake pad is in contact with the spinning disc, so pad/disc contact is a transient phenomenon that depends on the location of the transducer.

6. Conclusion

This study uses ultrasonic scanning to investigate the contact interface for both used and new brake pads. Ultrasound is used to determine the contact images for normally applied forces. The scanning results show that there are two major separate contact arc-shaped curves for the used pad and the disc plate. A comparison of the size of the area for the new brake pad and a used item is also presented. This method can be used to diagnose uneven wear in a brake pad of the same type. Under normal circumstances, the contact patches for the used brake pad should have similar images to the original shapes and approximately similarly sized areas. However, this study shows that the used pad has two curved strips of contact patches, which are different from the original shape. This may be due to manufacturing tolerances or uneven wear in the working life.

This study uses ultrasonic detection. Although it is a known method, its application for measuring brake pads is novel and this is the first time that contact images have been obtained using this method. The contact areas for both the used and the new brake pads are calculated using an image analysis software package and a comparison is made between them. The result shows that the contact areas vary from 4.89 mm² to 598 mm² for the used pad and from 324.3 mm² to 1599 mm² for the new pad, depending on the applied force and the definition of the contrast ratio. The area matrices for both used and new brake pads are also presented.

The surface roughness for both the used and the new brake pads is measured using a profilometer. The results show that the roughness depends on the wear on the lining surface, which is incurred during repeated braking. A map of the contact pressure shows the contour of the pressure distribution, which is not evenly distributed over the contact regions. It depends on the surface asperities and the roughness, which plays an important role in real contact, contact pressure and wear. In general, only the average pressure can be obtained from the pressure distribution equation, which is the normal load divided by the contact area. However, the pressure distribution in a real dynamic braking process is complex and its analysis requires a more precise model. In this quasi-static study, because the variation in the ultrasonic signals reflects degree of ease or difficulty with which the pulses pass through the contact interface, the distribution of the contact pressure can be determined.
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