2019-01-2113 Published 15 Sep 2019

Objective Method for Crack Detection in Brake Friction Material

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Citation: Divakaruni, S., Yuhas, D., Vorres, C., and Kaatz, R., "Objective Method for Crack Detection in Brake Friction Material," SAE Technical Paper 2019-01-2113, 2019, doi:10.4271/2019-01-2113.

Abstract

Friction material manufacturing is a complex process where numerous raw materials are mixed, pressed, and cured to make brake pads. It is important to have a consistent manufacturing process that can produce a brake pad that satisfies the vehicle braking requirements. A basic and critical requirement for any brake pad is structural integrity with no internal cracks. In this work a series of processing changes were made to intentionally produce internal cracks in the friction material. Various pad crack detection methods were studied, and their advantages and disadvantages are discussed in detail. One of the crack detection methods used an ultrasonic measuring instrument which gives objective data in the form of calculated modulus of elasticity and signal loss. The details of the machine and how the measurements are obtained are discussed. The modulus calculation is also described. Additionally, random pads with and without cracks were selected and checked using subjective and objective crack detection methods. The comparison analysis is discussed, and authors were able to show the difference between cracked and non-cracked pads using several methods. Conclusions and recommendations are made based on the data from these studies.

Introduction

Brake pad friction material is a complex composite material made from different kinds of chemicals and ingredients. The raw materials can be classified into broad categories (Figure 1) including binders, fibers/reinforcements, abrasives, lubricants/modifiers and fillers. Binders are used to bind all the raw materials together and hold the friction product together as a solid final product. These are typically thermoset phenolic resins that are dry as a raw material during the mixing stage. During the hot press operation they liquefy and re-solidify during the curing process. Fibers/reinforcements provide structural reinforcement and strength to the brake pad. These are responsible for resisting thermal breakdown and wear of the brake pad and can help provide stable friction. These can be organic or metallic materials. Abrasives help increase the friction level, especially at high temperatures, and help clean the rotor surface of corrosion build up. Aluminum oxide, iron oxide, and chromite are examples of abrasives. Lubricants/modifiers balance some of the abrasive effects of the other raw materials. They help develop the transfer layer and help control friction and lining wear rate. Synthetic graphite and tin sulphide are examples of lubricants/modifiers. Fillers cover a wide range of materials that are generally low cost and can enhance or balance out the performance of the friction material. In some cases they are used for adjusting characteristics such as pH, porosity,

FIGURE 1 Examples of Raw Materials [1].

stiction tendency, strength, friction, and NVH characteristics. They can also be used to reduce thermal and chemical reactions within the friction formulation. Mica and calcium hydroxide are some examples of fillers.

In this paper, the authors will discuss common causes of cracks in the friction material related to the manufacturing process. Performance issues related to the cracked friction material are then discussed. Later, existing subjective and objective methods to detect cracks are discussed along with their advantages and disadvantages. The ultrasonic objective method of crack detection is discussed in detail. A study was performed on a set of non-cracked and different levels of cracked pads. All the crack detection techniques were compared to see which method gives the best results to detect the presence of cracks. After the study another set of pads that had random cracks were checked with the different methods to see if any one objective method was superior. Final conclusions and suggestions are made.

Causes for Cracks in a Brake Pad

Figure 2 shows the different manufacturing process steps used to make friction material and brake pads. The steps within the dashed oval line are critical manufacturing processes that need to be properly developed and controlled to avoid cracks. Some of the common causes for cracks in the manufacturing process are;

- **Excess moisture in the raw materials prior to hot press**: This moisture can cause excess vapor release or degassing during the hot press operation resulting in cracked friction material. It is important to store the raw materials and mixed formulation in a controlled environment where humidity and temperature are monitored and regulated.
- **Insufficient mixing or clumps of raw materials**: All raw materials need to be mixed into a homogeneous batch with no clumps remaining. Figure 3 shows a typical friction material mixer. It's important that the plows and choppers are sharp, well maintained, and have proper clearance to the drum of the mixer. In some cases (Figure 4), raw materials must be premixed to breakup clumps prior to being added to the mixer. It's also important to ensure the fibers are opened and the resins are mixed so there is a good blend of all raw materials in the right proportions.
- **Variation in mix volume or weight in each press cavity:** In a multi-cavity press, there will be several cavities, so several pads can be produced at the same time. The volume and weight of the mix needs to be consistent in all the cavities. If the volume or weight of the mix is different from cavity to cavity it can lead to variation in density and the state of cure from pad to pad which can lead to cracks in some of the pads.
- **Inadequate leveling of friction material and/or underlayer in the press cavity:** It is good to have a finger leveler or a rotary leveler for distributing the friction material and under layer uniformly. Uneven distribution can lead to hard and soft spots, and the formation of cracks or voids during the press cure operation.
- **Variation in temperature in press cavities:** Each cavity needs to have a uniform temperature distribution as well as equal temperature from cavity to cavity. The resin and other chemicals melt and flow through the other raw materials during the hot press process. Temperature variation can lead to improper flow of the resins and curing of the friction puck. This causes non-homogeneity in the pad resulting in cracks during cure or subsequent processes.
- **Improper degassing during the hot press cycle:** During the initial pressure and temperature exposure, gases and vapors are released from the raw materials. Those gases and vapors need to be ventilated from the press such that they do not become trapped within the friction material resulting in weak spots or surfaces that will be prone to cracking. It is important to identify the optimum compaction and venting cycle during friction material hot press. Enough time must be given to allow vapors to form with a release and venting cycle so the gasses can escape. Once the resin begins to liquify, vapors that have not been vented can become trapped causing weak spots or surfaces during the solidification or curing process.

FIGURE 2 Critical Processes for Brake Friction Manufacturing

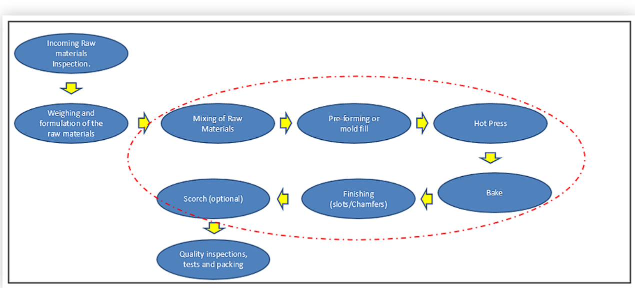


FIGURE 3 Picture of a mixer

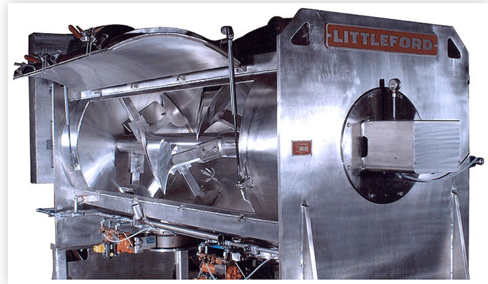


FIGURE 4 Picture of a raw material

FIGURE 5 Illustration of Venting Cycle

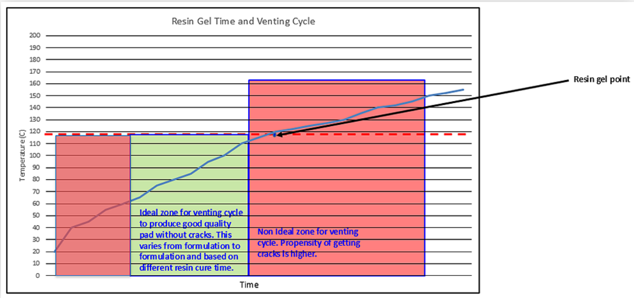


Figure 5 is an example of how the friction material heats up while in the hot press and shows an example region of when venting cycles should be conducted.

- **Stress fracture caused during extraction from press cavities:** Fractures caused during the extraction of the pad from the mold cavity are possible if a proper draft angle is not considered in the mold tooling. In some cases, a mold release agent should be used in the cavity before every pressing cycle such that the friction material does not stick inside the cavity.
- **Residual stresses during or after bake:** A brake pad is a composite material which has the friction material along with underlayer (in most cases) that are bonded to a steel backing plate. When molding these dis-similar materials together there is a possibility of excess residual stresses after curing and baking. The residual stresses between these different materials can cause cracks in the friction material. To reduce stress, it is recommended that backing plates are stress relieved prior to hot press. Also, it is common to cut slots down the center of the friction material on large pads. If the pad is not stress relieved, it has the potential to change in shape when exposed to temperatures or loads [2]. During this shape change in some conditions, cracks can occur.
- **Pad design with sharp corners:** Sharp corners in pad design can be an initiator for cracks due to high stress concentrations.
- **Manufacturing process of pad chamfers:** Caution must be taken during the grinding operation. Improper location of the pad on the grinding/chamfer tool or complicated chamfer designs with sharp corners can cause cracks on the pad surface or along the edges.

Performance Issues due to Cracks

Performance issues with cracked pads include brake noise, excess compressibility, and potentially reduced shear strength. Excess compressibility can cause high brake drag and shorter than expected lining life. In extreme cases, a portion of the friction material can shear off the brake pad. This can cause non-uniform loading of the brake pad which can cause high brake pedal effort and excessive pedal travel. With continued use this can lead to metal-to-metal contact between the backing plate and the rotor causing rotor damage.

Crack Detection Methods

There are several crack detection methods used in the industry. They can be classified as subjective and objective;

Subjective Methods

- **Visual inspection:** These can be either non-destructive or destructive. If the cracks are visible to the human eye along the edge of the pad like shown in Figure 6a, a nondestructive visual method can be used to identify the cracks. If the cracks are internal and not visible from the outside, the pads can be cut and inspected as shown in Figure 6b. Visual inspection, especially the destructive method, is not feasible in mass production. Visual inspections also have the potential for human error as small cracks can be missed. It is also possible for mold line features and surface non-uniformities to be mis-identified as cracks.
- **Tap Test:** This is a commonly used method to detect cracks in the brake pad. Based on the amplitude of the sound that comes from the pad during tapping, the presence of a crack can be detected. At the location of a crack, the tone will be dull or hollow. Without the crack, the sound will be crisp with no dull or hollow tone.

This procedure is commonly used in manufacturing plants, but it is subjective, and in some cases, even experienced operators may not be able to detect small hairline cracks.

FIGURE 6a External Crack

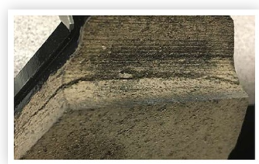
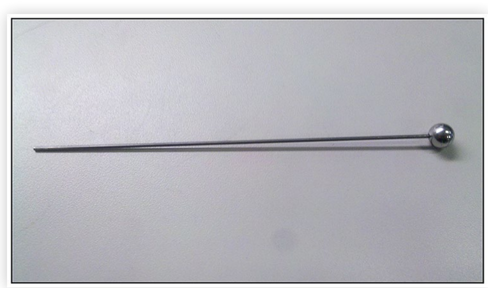


FIGURE 6b Internal crack

FIGURE 7 Picture of a Tap tester



Objective Methods

Compressibility. Compressibility test equipment is commercially available and often found in both research and production environments. It has the advantage of being a global measurement of the entire pad and some equipment has shown to be able to detect the presence of cracks in friction material. The compressibility test is a component test which measures the properties of both the friction material and the steel backing plate. In addition to variation in friction material properties, results are sensitive to dimensional properties of the backing plate. The method is slow and difficult to use in the manufacturing environment.

Grindosonic. The Grindosonic method is a subset of Frequency Response Function (FRF) analysis. This method involves quantitative measurement of the pad resonant frequency and damping of the pad's primary flexural mode. The method is fast, and the equipment is commercially available. It measures the entire pad assembly which may not be adequate to identify cracks which affect the local acoustic response. Care must be taken to control and standardize the excitation method. This method may be an option in production, the data from these studies are discussed further in the paper.

FRF. Frequency Response Function (FRF) analysis enables the investigation of various brake pad resonant frequencies to find those most sensitive to the presence of cracks. The selection of the appropriate mode is determined both by empirical results and knowledge of the mode shapes. It is generally believed that the sensitivity to cracks is diminished if the cracks are located at the acoustic resonance node and maximized at the antinodes. One or more modes can be selected to improve sensitivity and cover the entire pad volume or the most crack prone pad regions. The equipment is commercially available and commonly used in many research applications and requires trained operators. This method may be an option in production. The data from these studies are discussed further in the paper.

FIGURE 8 Schematic of a Compressibility Test Machine

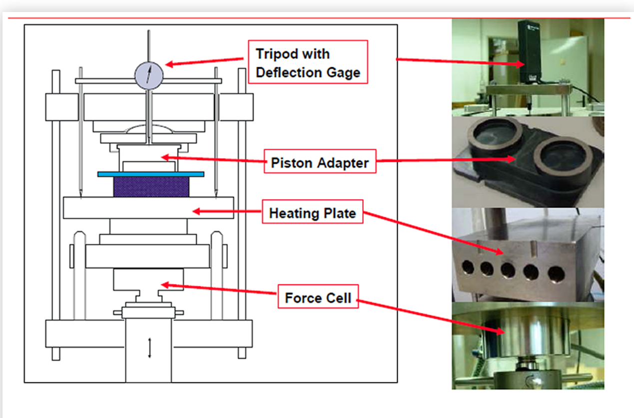


FIGURE 9 FRF hammer and accelerometer.

Ultrasonic. The ultrasonic technique used in this study to measure the dynamic modulus is a through-transmission technique[3-5]. Modulus measurements involve precise measurement of the propagation time of a short ultrasonic pulse. As illustrated in Figure 10, a short burst of high frequency sound, (~ 1 MHz) is generated from the transmitting transducer and propagates through the steel backing, then the friction material and finally to the receiving transducer. Precise measurements are made of the total time-of-flight, ToFpad, from the transmitter to receiver. Ultrasonic velocity is calculated by combining this ToF measurement with the pad thickness. Using a signal digitization rate of 100 MHz, the precision of the ToF measurement is ~10 nanoseconds. Typical ToF for transmission through a brake pad is ~15 microseconds so the baseline precision of the method is on the order of 0.6%. Measurement times for a single position can be made in less than 300 milliseconds. Thus, time required to test multiple positions on a pad is limited only by the parts handling system.

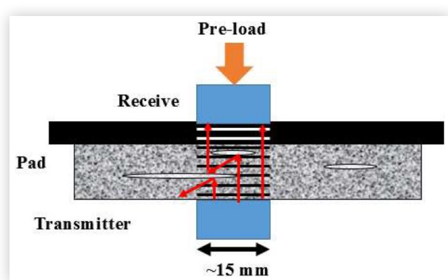
It is desirable to measure the properties of the friction material in an intact, as-manufactured brake pad. As described above, the baseline ToF is comprised of the transit-time through the steel backing, ToFsteel as well as the transit time through the friction material, ToFfm, as shown in Equation 1.

$$ToF_{fm} = ToF_{pad} - \frac{X_{steel}}{V_{steel}} \qquad \text{Eq. 1}$$

Where Xsteel is the steel thickness and Vsteel is the steel backing ultrasonic velocity.

It is relatively straight forward to remove the influence of the steel backing as both the steel thickness and its velocity are known and well controlled. The velocity of the steel is typically 3 to 4 times that of the friction material while the thickness of the steel is about 2 times smaller than that of

FIGURE 10 Measurement configuration for ultrasonic-based modulus & signal loss measurements



the friction material. Thus, the elimination of the steel contribution from the measured ToF is typically a 10% correction. More importantly, because the modulus and density in the steel backing is well controlled, any variation in the ToF can be attributed to the friction material. All modulus data in this study reflect the properties of only the friction material.

The velocity in the friction material is given in Equation 2 by:

$$V = {X_{fm}}/{ToF_{fm}} \quad \text{Eq. 2}$$

Where Xfm= $X_{pad} - X_{Steel}$ is the thickness of the friction material

This velocity in Equation 2 is used to compute the dynamic modulus, E, using Equation 3.

$$E = kV^2 \quad \text{Eq. 3}$$

Where k is a constant related to the Poisson's ratio and historical test data.

In addition to the modulus measurement, the ultrasonic technique can be used to measure signal loss. Signal loss involves measuring the magnitude of the ultrasonic energy loss in propagating through the pad and backing plate.

For the dynamic modulus measurements made in this study a commercially available iETEK measurement instrument depicted in Figure 11 is used. For this system, the transmitting sensor is attached to a stepper motor driven actuator to provide a user-defined preload. The pre-load is measured using a load cell mounted on the bottom surface of the receiving sensor. As illustrated in Figure 10, the ultrasonic sensors are mounted in a co-linear configuration. The brake pad is inserted between the sensors and the user defined preload applied through the sensors. The "footprint" of the sensors is 15mm in diameter. The region influencing the ultrasonic propagation is the cylindrical volume directly beneath the sensors. As such, only a portion of the brake pad is measured for a single position of the brake pad. To obtain an average of the dynamic modulus in the pad, multiple positions are measured in each pad. The iETEK can measure the dynamic modulus using a single user defined pre-load from 100 N to 800 N.

FIGURE 11 iETEK ultrasonic instrument

Studies

Two studies using the above subjective and objective techniques were performed to determine which methods were able to detect the presence of cracks. The studies are described below.

Study 1

Pads were manufactured with baseline manufacturing settings which produced no cracks (A - Non-Cracked Pads). Then pads were intentionally manufactured with cracks by reducing the time that the friction material was under pressure and temperature exposure in the hot pressed before the venting cycle was performed. By varying the time when the vent cycle was performed, three different levels of cracks were produced. In 10 pads the vent cycle was altered to produce severe cracks (B - Cracked Pad Level 1)), 10 pads were altered to produce intermediate cracks (C - Cracked Pad Level 2), and 10 pads were altered to produce mild cracks (D - Cracked Pad Level 3).

Compressibility tests were performed to determine the impact of crack level. SAE J3079/2 was run using the deflection measured during the 3rd loading cycle at 120 bar loading with 0.3 bar preload.

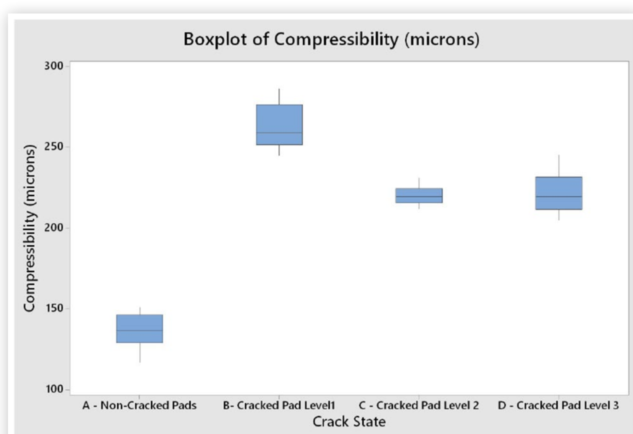
The compressibility data in Graph 1 shows a clear separation between non-cracked pads and cracked pads. The data even showed good separation between severe cracked pads and less cracked pads. SAE J3079/2 was used rather than SAE J2468 such that the deflection occurring between 30 kPa and 500 kPa was included in the measurements. It was believed that including the low load deflection would help for crack detection.

Grindosonic (1st mode) was performed on all these pads and the data is shown below.

The Grindosonic data in Graph 2 did not show separation between non-cracked and cracked pads. The extreme cracked pads had significant variation and some pads had overlap with the non-cracked pads

The iETEK ultrasonic instrument was used to measure the modulus of the pad at 6 different locations as shown below.

GRAPH 1 Compressibility (0.3 bar pre-load up to 120 Bar, K3)



GRAPH 2 Grindosonic (1st mode) vs Crack Level

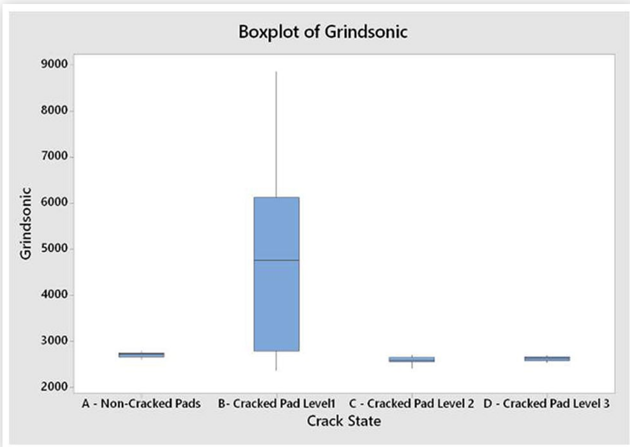
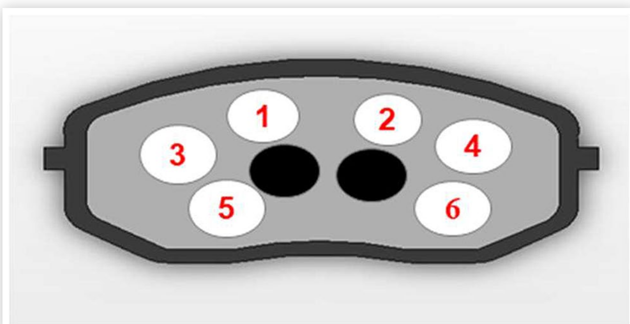


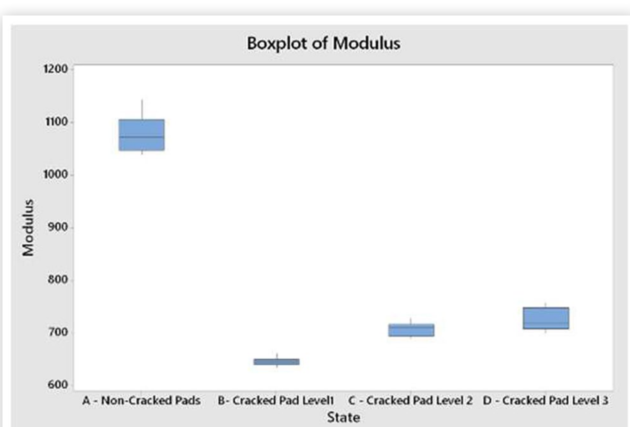
FIGURE 12 6 position/pad, Spatial resolution (15 mm)



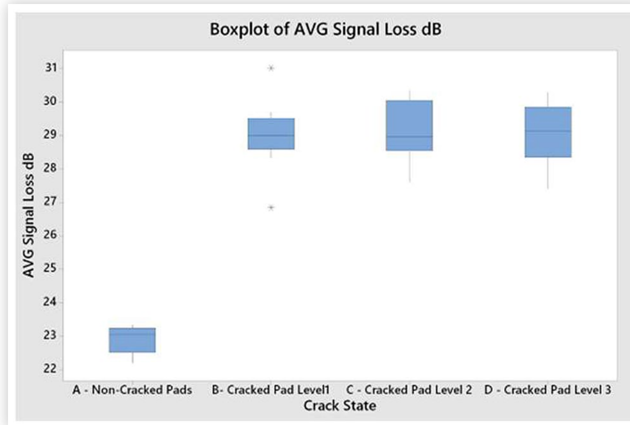
Graph 3 shows good separation between modulus values for non-cracked pads verses the cracked pads. The average modulus was also calculated for each crack level. This method properly rank ordered the crack level.

Signal loss was also measured. Signal loss involves measuring the magnitude of the ultrasonic energy loss in propagating through the pad and backing plate. Signal loss data is presented in Graph 4 which shows good separation between cracked and non-cracked pads, but the rank order of crack level could not be determined.

GRAPH 3 Average modulus vs Crack level



GRAPH 4 Signal Loss vs Crack Level



Study 2

In the second study, pads were taken from a batch that had non-cracked and cracked pads. Compressibility was measured on 20 pads from this batch. During this test, deflection measured during the 3rd loading cycle at 100 bar with 1 bar preload was evaluated. Graph 5 shows test results for 20 pads. The pads with visible cracks had clear separation from pads that did not have cracks.

Both pads 10 and Pad 16 exhibited very high compressibility. Figure 13 shows the images of the cracks on the pads.

Additional tests were carried out on a second set of 24 production pads from this same batch of pads. For this second set, the pads were segregated into 3 categories: 8 pads had visible cracks, 8 pads did not have visible cracks but failed the tap test, and 8 pads had no visible cracks and passed the tap test. All the pads in this study were sorted by subjective and visual method.

FRF data between these groups of pads were measured and compared in Graph 6.

Although there was a clear separation between cracked and passed pads, there was overlap between failed tap test verses passed tap test data. FRF did not show full separation between all the pad groups.

Ultrasonic measurement was performed on these pads at 6 locations as shown in Figure 14.

The average modulus for each pad was calculated and the results are shown in Graph 7.

GRAPH 5 Compressibility

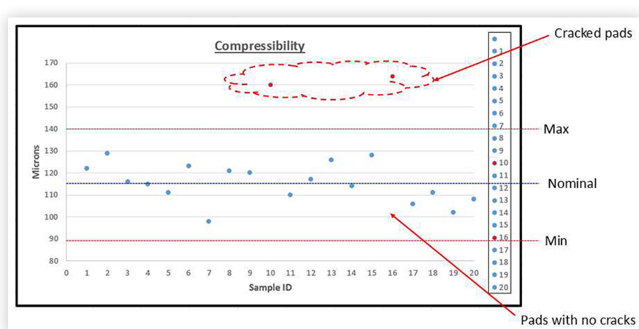


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FIGURE 13 Pads with Cracks

GRAPH 6 FRF (4th mode) vs Pad Group

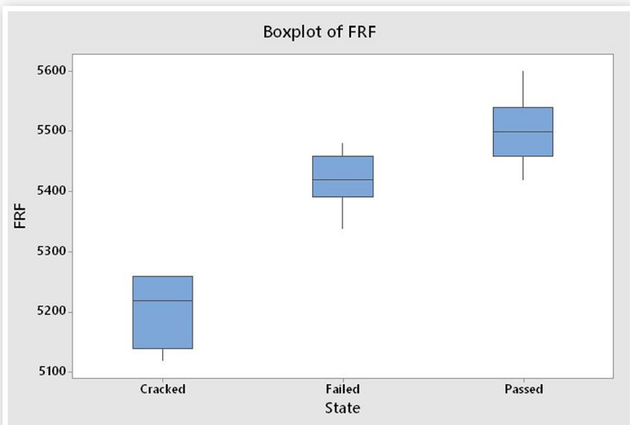
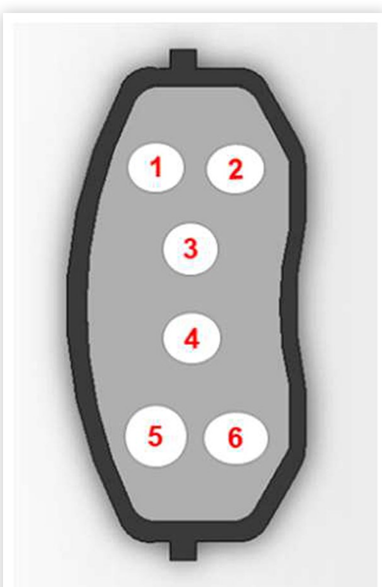
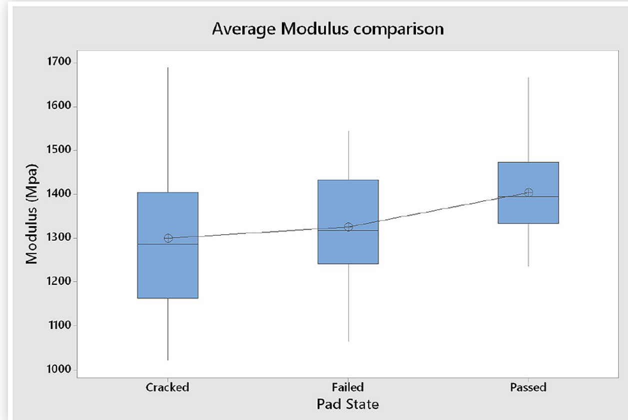


FIGURE 14 iETEK Measurement locations



GRAPH 7 Average modulus vs Pad Group



There was considerable overlap in the average modulus among the groups of pads. This is different from the results of Study 1. After some investigation, it was found that these cracks in Study 2 occurred only near measurement locations 1 and 2 (see Figure 14). In Study 1 the cracks were induced across the whole pad area. Averaging the values in Study 2 did not show the separation. Table 1 shows the measured modulus value for each measurement position.

Based on this data, 1200 MPa seems to be a separation limit between cracked and non-cracked pads. This minimum limit is design specific and may change depending upon friction material and manufacturing process settings. Determining this for different friction materials need further studies and analysis.

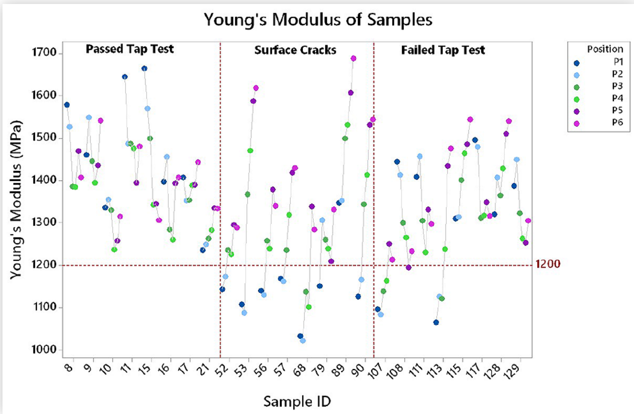
Graph 8 shows the data plotted by position (P1…..P6). Positions P1 and P2 of the cracked pads were below 1200 MPa and for non-cracked pads all points were above that limit. For the group that failed the tap test, some measurements were below the limit mentioned above and some were not. It is uncertain if the pads that failed the tap test had cracks or not.

The signal loss data was also evaluated. Similar to modulus, the average signal loss chart presented in Graph 9 did not show good separation between different pad groups. The signal loss by position presented in Graph 10 showed separation based on the measurement position. One anticipates that the signal loss will be higher in pads with cracks. Higher signal loss is found in position 1 and position 2 of the surface crack group.

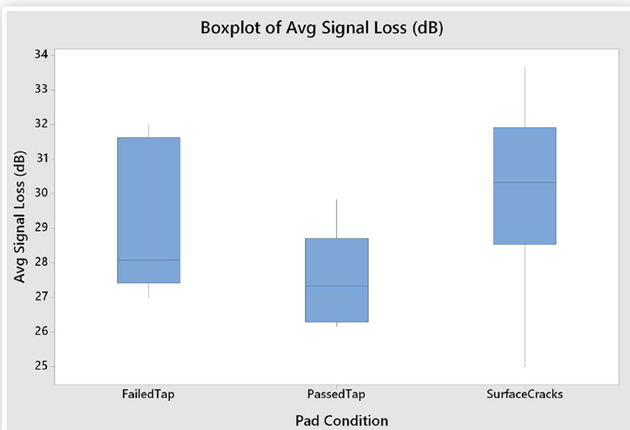
TABLE 1 Pad Group and Modulus by position.

		Young's Modulus (MPa)	Young's Modulus (MPa)	Young's Modulus (MPa)	Young's Modulus (MPa)	Young's Modulus (MPa)	Young's Modulus (MPa)	FRF
	Sample ID	Position1	Position2	Position3	Position4	Position5	Position6	
Passed Tap Test	8_1	1579	1527	1386	1385	1469	1407	5490
	9_1	1461	1549	1446	1395	1436	1542	5540
	10_1	1336	1355	1330	1237	1258	1315	5420
	11_1	1645	1487	1487	1475	1395	1480	5540
	15_1	1665	1570	1499	1343	1345	1307	5500
	16_1	1397	1456	1284	1260	1394	1407	5500
	17_1	1407	1353	1354	1389	1390	1443	5450
	21_1	1236	1249	1263	1283	1335	1334	5600
Surface Cracks	52_1	1144	1174	1236	1226	1295	1289	5220
	53_1	1108	1088	1367	1471	1587	1618	5200
	56_1	1140	1130	1258	1239	1379	1340	5220
	57_1	1168	1162	1236	1319	1419	1429	5260
	68_1	1033	1022	1138	1101	1339	1284	5120
	79_1	1151	1306	1260	1239	1209	1331	5260
	89_1	1348	1352	1499	1532	1607	1688	5120
	90_1	1126	1166	1344	1413	1531	1544	5260
Failed Tap Test	107_1	1097	1084	1139	1164	1251	1213	5430
	108_1	1444	1413	1300	1266	1195	1233	5410
	111_1	1408	1457	1305	1231	1331	1298	5480
	113_1	1065	1126	1121	1238	1434	1476	5340
	115_1	1310	1314	1401	1464	1486	1544	5390
	117_1	1496	1479	1312	1318	1349	1317	5430
	128_1	1320	1407	1365	1428	1511	1540	5470
	129_1	1387	1449	1323	1263	1253	1305	5400

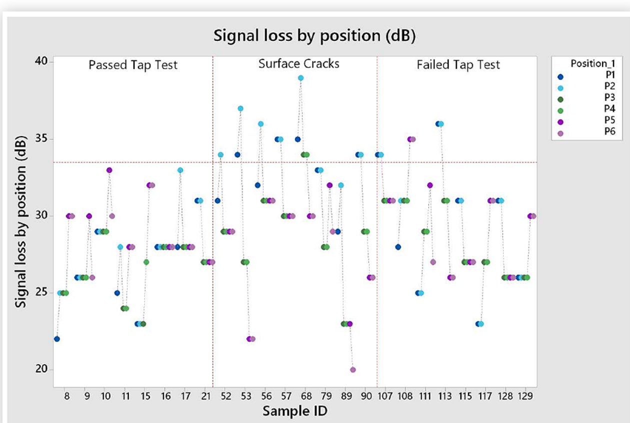
GRAPH 8 Modulus by Position



GRAPH 9 Avg Signal Loss vs Pad Group



GRAPH 10 Signal Loss by position vs Pad Group



Summary and Conclusions

The authors performed two studies to evaluate the effectiveness of several objective methods to determine the presence of cracks in friction material. In study 1, non-cracked and cracked brake pads were prepared specifically for this study. Direct comparisons of test results using compressibility, ultrasonic and Grindosonic methods were presented. In study 2, production pads were tested. Comparative tests were carried out on two sub-groups. In one sub-group of 24 pads, the pads were segregated into 3 categories using a combination of tap test data and surface inspection. These pads were subsequently tested using FRF, ultrasonic modulus, and ultrasonic signal loss methods and the results compared. Compressibility data for this sub-group was not available. In a second sub-group of 20 production pads, compressibility was measured on pads with and without visible surface cracks.

Below are the conclusions for each method.

Compressibility: This method was capable to identify the cracks. The presence of cracks showed an increase in compressibility. The test was performed on compressibility machines designed for low preload (SAE J3079/2 or equivalent) and was run at low preloads. This method may be difficult to implement as a 100% check in a manufacturing environment due to the test setup and cycle time. This method appears good for investigations and small studies.

Grindosonic: The data from the Grindosonic did not show adequate separation between cracked and non-cracked pads during these studies.

FRF: FRF allows for the search of modes which most likely identify the presence of cracks. FRF did not show adequate sensitivity in the study it was used on. This method may also be difficult to implement in production due to test setup and inspection time.

Ultrasonic Modulus: This method was able to identify cracks in both studies. As expected, the presence of cracks decreases the modulus. When cracks were local, positional data was needed. The results correlated well with visual inspections. Less correlation was found with the tap test. This method is fast and non-destructive. It may be feasible for production due to fast setup and cycle time. Further studies and data are recommended.

Ultrasonic Signal Loss: Signal loss test results showed trends similar to the modulus test but were less conclusive.

Recommendations:

An industry standard objective test procedure should be developed for crack detection in friction material. Recent developments in compressibility testing (SAE J3079/2) and ultrasonic measurement and analysis techniques (SAE J3175 work in progress) appear to generate data that can detect cracks in friction material. This study was done on NAO pads and further studies and analysis are required for semi-met and low-met pads. It would be desirable to conduct additional compressibility/ultrasonic comparative studies on production pads to determine the sensitivity. These studies should entail destructive physical analysis along with the surface inspection.

References

1. https://www.akebono-brake.com/english/product_technology/product/automotive/friction_material/.
2. Divakaruni, S. and Chang, H., “Friction Back Plate Design/Manufacturing/Quality-Key Attributes for Better Brake Performance,” SAE Technical Paper 2017-01-2506, 2017, doi:10.4271/2017-01-2506.

3. Sriwiboon, M., Tiempan, N., Kaewlob, K., Rhee, S.K. et al., "Disc Pad Physical Properties vs. Porosity: The Question of Compressibility as an Intrinsic Physical Property," *SAE Int. J. Mater. Manf.* 11(1):57-78, 2017, doi:10.4271/05-11-01-0007.
4. Reder, M., Hoxie, S., Yuhas, D.E., Vorres, C.L. et al., "Variations in Friction Material Elastic Properties Resulting from Performance Tests," in *Proceedings of EuroBrake 2016*, Paper # EB2016-SVM-048, Milan, IT, June 12-15, 2016.
5. Malmassari, C.M., Cucchi F., Yuhas, D.E., Vorres, C.L., and Remiasz, J.R., "Evolution of Brake Noise Performance and its Relation to Variations in Friction Material Elastic Properties," in *Proceedings of EuroBrake 2015*, Paper # EB2015-NVH-011, Dresden, Germany, May 4-6, 2015.

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Acknowledgments

The authors wish to acknowledge the friction suppliers KB Autosys and Federal Mogul, who supported the studies with parts, performed some studies and analysis.

ISSN 0148-7191