Comparison of Hardness, FRF, Compressibility, and Ultra-sonic Modulus Measurements

2017 SAE Presentation 17BC-0074

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Akebono Brake Corporation
Friction Material Design
Friction Quality Measurements

Pass/Light Truck Brake Pad Quality

• There are diverse opinions within the brake community for determining ongoing production quality of a finished brake pad.

• This presentation compares several industry methods.

• There are two underlying common characteristics assessed across all manufacturers:
  – **Dimensions**
    » Overall thickness, abutment height/length, friction/plate flatness, parallelism, and topography/shape
  – **Friction Modulus**
    » All use some type of measurement in attempt to assess raw materials and processing consistency for modulus.
# Friction Quality Measurements

## Matrix of Main Quality Measurement Types

<table>
<thead>
<tr>
<th>Primary Characteristic Desired</th>
<th>Compressibility</th>
<th>FRF</th>
<th>Rockwell Hardness</th>
<th>Direct Modulus (Ultrasound)</th>
<th>Dimensions</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus</td>
<td>Modulus</td>
<td>Modulus</td>
<td>Modulus</td>
<td>Modulus</td>
<td>Dimensions</td>
<td>--</td>
</tr>
</tbody>
</table>

| What is it measuring           | Approximation of friction modulus and dimensional effects | Primarily plate modulus & secondary friction modulus | Friction surface approximation of friction modulus | Approximation of friction modulus | Friction flatness, plate flatness, parallelism, abutments, etc. | -- |

| Independent intrinsic quality/engineering measurement of friction materials | No | No | Yes | Yes | Yes | Can one compare quality independent of shape, friction formulation, chamfers/slots etc.? |

| In Process Correlation | No | No | Poor/Moderate | Excellent | -- | Can I determine how a part was processed by correlating to previous process measurements? |

| Reference               | SAE J2468 | SAE J2598 | SAE J2654 | SAE Paper 2010-01-1701 | -- | -- |

| Equipment Used for this presentation | Link 1620-H | Zonicbook 618E | Instron Wilson/Rockwell Series 600 | Industrial Measurement Systems | iETEK | -- | -- |
Friction Quality Measurements

Compressibility

- Pad compressibility is made up of two primary components
  - **Friction Modulus**
    » Reciprocal of compressibility without dimensional influence is an approximate measurement of Young’s modulus.
  - **Dimensions**
    » Any friction flatness, plate flatness, parallelism, and topography beyond being “zero” typically contribute to compressibility (i.e. will be part of the deflection in the compressibility). Typical friction flatness, plate flatness, parallelism specifications are in the 100-200 µm (0.10 mm – 0.20 mm) range.
Friction Quality Measurements

FRF, Hardness, Ultrasound

FRF is made up of two main components but in general is attempting to detect changes in friction modulus

- Pressure Plate (primary)
  - Material Properties (Modulus)
  - Plate thickness
- Friction Material (secondary)
  - Material Properties (Modulus)
  - Geometric Properties (slots, chamfers, variation within geometric properties)

Rockwell hardness
- Uses a small scale surface approximation of modulus which is then extrapolated to characterize the entire pad

Ultrasound
- Yields approximation of modulus based on the fundamental relationship between the ultrasonic velocity and the material elastic constants
# Friction Quality Measurements

## Assessing Friction Modulus

<table>
<thead>
<tr>
<th></th>
<th>Compressibility</th>
<th>FRF</th>
<th>Rockwell Hardness</th>
<th>Ultrasound</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acquiring Friction Modulus</strong></td>
<td>Requires machining pads close to ‘zero’ for dimensions or using small coupon size pieces. Commonly referred to as &quot;Specific&quot; Compressibility</td>
<td>Need to account for other geometric variables (pressure plate thickness, friction thickness, slot depth, chamfer size, etc.)</td>
<td>Only rough relationship can be established to modulus</td>
<td>Direct measurement</td>
</tr>
<tr>
<td><strong>Challenges</strong></td>
<td>Lead time to make parts</td>
<td>Sensitivity to changes to friction modulus lower than other factors (plate thickness, dimensions)</td>
<td>Have to know relationship to modulus and can be highly influenced if part is scorched</td>
<td>Newer technology</td>
</tr>
<tr>
<td></td>
<td>Still will have dimensional contributions</td>
<td></td>
<td>Hardness measurement on a single pad is highly variable</td>
<td></td>
</tr>
<tr>
<td><strong>Benefits</strong></td>
<td>Yields combined measurement that gives insights into modulus and fluid displacement</td>
<td>Relatively quick measurement</td>
<td>Can correlate to previous measurements taken in the process (post hot press, post cure, post grind)</td>
<td>Can correlate to previous measurements taken in the process (post hot press, post cure, post grind)</td>
</tr>
<tr>
<td><strong>Reference</strong></td>
<td>SAE Presentation BC201-3</td>
<td>-----</td>
<td>-----</td>
<td>SAE Paper 2010-01-1701</td>
</tr>
<tr>
<td></td>
<td>SAE Paper 2008-01-2572</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Friction Quality Measurements
Repeatability/Environmental/Pressure Plate Plate Sensitivity

- N=10 different pad shapes all current OE production
  - N=9 NAO’s, N=1 Semi-Met
  - N=6 Akebono, N=4 non Akebono
- Measurements:
  - Compressibility SAE J2468 T3/100 bar [microns]
  - FRF SAE J2598 [Hz] (1st bending mode)
  - Rockwell Hardness SAE J2654 [HRR or HRS]
  - Ultrasound Modulus [MPa] (note density = 1.00, reference SAE Paper – 2010-01-1701)

- Run 1 - Pads were dried out 2 hours @ 110°C then measured
- Run 2 - Pads subjected to 25°C @ 80% RH for 24 hours then measured
- Run 3 - Pads were dried out again 2 hours @ 110°C then measured
- Run 4 - 0.40 mm ground off pressure plate, dried 2 hours @ 110°C then measured (simulation of typical min to max plate thickness tolerance and pressure plate flatness almost zero)
Friction Quality Measurements

Repeatability - Run 3 vs. Run 1

- Run 1 - Pads were dried out 2 hours @ 110°C then measured
- Run 3 - Pads were dried out again 2 hours @ 110°C then measured

Note: X & Y scales are same on each respective plot
Friction Quality Measurements

Absolute % Change - Repeatability

% Absolute Change - Repeatability

- Compressibility: 1.79539
- FRF: 0.297067
- Hardness: 4.11681
- Modulus: 1.79527
Friction Quality Measurements

Environmental Sensitivity - Run 2 vs. Run 1

- Run 1 - Pads were dried out 2 hours @ 110°C then measured
- Run 2 - Pads subjected to 25°C @ 80% RH for 24 hours then measured

Note: X & Y scales are same on each respective plot
Friction Quality Measurements

Absolute % Change - Humidity

% Absolute Change - Humidity

- Comp. - Humidity: 3.11794
- FRF - Humidity: 0.752171
- Hardness - Humidity: 5.69179
- Modulus - Humidity: 2.01584
Friction Quality Measurements

Pressure Plate Thickness/Flatness Sensitivity - Run 4 vs. Run 1

- Run 1 - Pads were dried out 2 hours @ 110°C then measured
- Run 4 - 0.40 mm ground off pressure plate, dried 2 hours @ 110°C then measured

### Compressibility - Post Plate Grind vs. Run 1
- \( R^2 = 0.87 \)

### FRF - Post Plate Grind vs. Run 1
- \( R^2 = 0.997 \)

Note: X & Y scales are same on each respective plot
Friction Quality Measurements

Absolute % Change – Pressure Plate Thickness Sensitivity

% Absolute Change - Plate

- Comp. - Plate: 9.8989%
- FRF - Plate: 3.55088%
- Hardness - Plate: 4.88762%
- Modulus - Plate: 5.20253%
Friction Quality Measurements

With “Use” Sensitivity

• N=4 vehicle platforms
• All NAO materials
• Various typical OE dynamometer development tests conducted (Performance, FMVSS, Noise, Wear, Thermal Abuse etc.)
• Measurements of Compressibility, FRF, Hardness, Modulus conducted pre and post test
  • Compressibility SAE J2468 T3/100 bar [microns]
  • FRF SAE J2598 [Hz] (1st bending mode)
  • Rockwell Hardness SAE J2654 [HRR or HRS]
  • Ultrasound Modulus [MPa] (note actual density used, reference SAE Paper 2010-01-1701)

• Can one assess a field returned part for its initial quality metric?
Friction Quality Measurements

Post Dynamometer Test vs. Initial Measurements

Compressibility - Post Test vs. Pre Test

R²=0.56

FRF - Post Test vs. Pre Test

R²=0.99

Hardness - Post Test vs. Pre Test

R²=0.00

Modulus - Post Test vs. Pre Test

R²=0.80

Note: X & Y scales are same on each respective plot
Friction Quality Measurements

Absolute % Change – Post Dynamometer vs Initial

% Absolute Change vs. Measurement Type

% Absolute Change

0 10 20 30 40 50 60 70 80 90 100

Compressibility FRF Hardness Modulus

Compressibility: 13.5202
FRF: 2.26982
Hardness: 16.0978
Modulus: 5.80811
Friction Quality Measurements

Detecting Small Changes Raw Material Properties

• Study was conducted to assess measurement types ability to discriminate between small changes in raw material physical properties
  • Passenger car NAO
  • A baseline mix and derivatives were made by replacing 1 raw material at a time
  • The replacement raw material only differed by a small change in physical properties

• Measurements conducted on finished pad assemblies
  • Compressibility T3/100 bar [microns]
  • FRF [Hz] (1<sup>st</sup> bending mode)
  • Rockwell Hardness [HRR or HRS]
  • Ultrasound Modulus [MPa] (note actual density used, reference SAE Paper 2010-01-1701)
Friction Quality Measurements

Detecting Small Changes Raw Material Properties

Interval Plot of Compressibility [um]
95% CI for the Mean

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Compressibility [um]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Baseline</td>
<td>159.97</td>
</tr>
<tr>
<td>2 - Inorganic Fiber</td>
<td>153.14</td>
</tr>
<tr>
<td>3 - Filler</td>
<td>154.984</td>
</tr>
<tr>
<td>4 - Inorganic Fiber</td>
<td>157.035</td>
</tr>
<tr>
<td>5 - Filler</td>
<td>156.78</td>
</tr>
<tr>
<td>6 - Abrasive</td>
<td>149.335</td>
</tr>
<tr>
<td>7 - Inorganic Fiber</td>
<td>152.33</td>
</tr>
</tbody>
</table>

Individual standard deviations are used to calculate the intervals.

Statistically different mean (95% Confidence)
Friction Quality Measurements

Detecting Small Changes Raw Material Properties

Interval Plot of FRF [Hz]
95% CI for the Mean

Raw Material

Individual standard deviations are used to calculate the intervals.

No statistical difference in means
Friction Quality Measurements
Detecting Small Changes Raw Material Properties

Interval Plot of Finished Hardness [HRR]
95% CI for the Mean

Individual standard deviations are used to calculate the intervals.

No statistical difference in means
Friction Quality Measurements
Detecting Small Changes Raw Material Properties

Interval Plot of Finished Modulus [MPa]
95% CI for the Mean

Individual standard deviations are used to calculate the intervals.

Statistically different mean
(95% Confidence)
Friction Quality Measurements

Detecting Small Changes Raw Material Properties

Correlation Between Measurements

Compressibility [um]

FRF [Hz]

Finished Hardness [HRR]

Finished Modulus [MPa]

R²=0.06

R²=0.09

R²=0.13

R²=0.25

R²=0.09

R²=0.56

R²=0.25

R²=0.13

R²=0.09
## Friction Quality Measurements

### Summary Matrix

<table>
<thead>
<tr>
<th></th>
<th>Compressibility</th>
<th>FRF</th>
<th>Rockwell Hardness</th>
<th>Direct Modulus (Ultrasound)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Repeatability</strong></td>
<td>1.80%</td>
<td>0.30%</td>
<td>4.11%</td>
<td>1.80%</td>
</tr>
<tr>
<td><strong>Sensitivity to Humidity</strong></td>
<td>3.11%</td>
<td>0.75%</td>
<td>5.69%</td>
<td>2.02%</td>
</tr>
<tr>
<td><strong>Sensitivity to Plate Tolerance/Plate Flatness</strong></td>
<td>9.90%</td>
<td>3.55%</td>
<td>4.89%</td>
<td>5.20%</td>
</tr>
<tr>
<td><strong>Changes &quot;with use&quot;</strong></td>
<td>13.52%</td>
<td>2.27%</td>
<td>16.10%</td>
<td>5.81%</td>
</tr>
<tr>
<td><strong>Sensitivity to friction modulus</strong></td>
<td>Excellent w/o dimensional component</td>
<td>Poor</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>Independent instrinsic quality/engineering measurement</strong></td>
<td>No (shape dependent)</td>
<td>No (shape dependent)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>In Process Correlation</strong></td>
<td>No</td>
<td>No</td>
<td>Poor/Moderate</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

- Direct modulus measurements on finished brake pad needs a formal testing procedure
- Direct modulus on finished brake pads should be considered as a primary assessment of friction quality along with dimensional measurements
Friction Quality Measurements

Acknowledgments

- Friction Team at Akebono Engineering Center
- Friction Team at Akebono Brake Glasgow
Thank you

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