



SURFACE VEHICLE STANDARD

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(R) Road Vehicles - Friction Materials -
Elastic Properties Measurements

RATIONALE

This SAE Standard specifies a method for testing and measuring elastic constants in friction materials by precise ultrasonic velocity measurements. This specification has been modified to include the measurement of the out-of-plane modulus as a function of pre-load as well as the measurement of engineering constants as a function of temperature. Finally, methods are formulated to produce all engineering constants as a function of pre-load and temperature.

SAE J2725 has been reaffirmed to comply with the SAE Five-Year Review policy.

FOREWORD

The elastic properties of friction materials are important design parameters because modulus variations may be significant in noise generation of braking systems. Variations in elastic properties as a result of processing and formulation are often a primary determinant of component performance. The purpose of this test procedure is to evaluate the elastic properties of friction materials in brake pads. Data are provided in a format that is directly useful for modeling analysis and simulation.

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1. SCOPE

This SAE Standard specifies a method for testing and measuring elastic constants in friction materials by precise ultrasonic velocity measurements. Measurement methods are also described for measurement of the out-of-plane modulus as a function of pre-load as well as the measurement of engineering constants as a function of temperature. Finally, methods are formulated to produce all engineering constants as a function of pre-load and temperature.

2. REFERENCES (SEE ALSO REFERENCES OF APPENDIX A)

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

Results of Friction Materials Elastic Constant Round Robin Study, Donald E. Yuhas and Paul Sanders, 25th annual Brake Colloquium, Orlando FL October, 2007 SAE # 07BC-40

Yuhas, D., Ding, J., and Venkatesan, S., "Non-linear Aspects of Friction Material Elastic Constants," SAE Technical Paper 2006-01-3193, 2006, doi:10.4271/2006-01-3193.

Elevated Temperature Measurements of Elastic Constants in Polymer Composites, Donald E. Yuhas and Bruce Isaacson, The 43rd International SAMPE Symposium May 31-June 4, 1998, Anaheim California

H.M. Ledbetter and D.T. Read, "Orthorhombic Elastic Constants of an NbTi/Cu composite Superconductor", Jour. App. Phys, #5 May, 1977

Every A.G., "Determination of the Elastic Constants of Anisotropic Solids", NDT International Vol. 27, No. 1, p. 3, 1993

Disc Brake Squeal, Frank Chen, Chin An Tan, and Ronald L. Quaglia eds. Chapter 12 D.E. Yuhas and Marjorie P. Yuhas. Friction Material Elastic Constant Measurements ISBN 10 0-7680-1248-1

3. DEFINITIONS

In this test, the elastic constants of friction materials are determined by measuring both the longitudinal and shear wave speeds propagating at various directions in the friction material. It is important to record and maintain the relationship between the direction of ultrasonic propagation, wave polarization, and the principle axes of the friction material. From the measured ultrasonic velocities, and the symmetry of the friction material, the elastic constants as well as the Engineering constants i.e., Young's moduli, Shear Moduli, and Poisson's Ratios can be calculated.

3.1 COORDINATE SYSTEM DEFINITION

The coordinate geometry referenced to the disc pad shape is shown in Figure 1. The same geometry is used for truck blocks and with a slight modification can be used for drum brakes. In all cases the "3" or "z" axis is the thickness direction and the "1" or "x" direction is along the rotation axis. This coordinate definition is used throughout the gathering of data and the subsequent analysis. Failure to adhere to the appropriate data collection protocol can lead to some unusual and potentially misleading results.

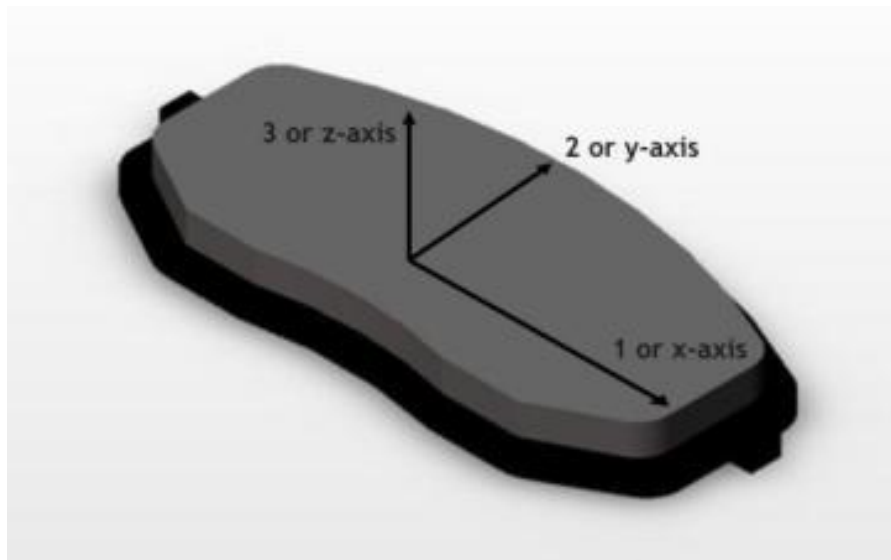


Figure 1 - Brake pad based coordinate system

In the coordinate system shown in Figure 1, the “3” axis is perpendicular to the friction surface, the “1” axis is along the long axis of the pad, and the “2” axis is parallel to the short axis of the pad.

3.2 ULTRASONIC MODES

Ultrasonic – mechanical vibration in the frequency range from 0.1 to 5 MHz.

Longitudinal or compressional wave – ultrasonic wave mode where the direction of wave propagation is parallel to the particle displacement or polarization of the wave.

Shear wave – ultrasonic wave mode where the direction of wave propagation is perpendicular to the particle displacement or polarization.

Using the above definitions and the coordinate system defined in Figure 1, we can define the following wave modes:

V_{33} – Longitudinal mode propagation along the “3” direction with polarization along “3”

V_{11} – Longitudinal mode propagation along the “1” direction with polarization along “1”

V_{22} – Longitudinal mode propagation along the “2” direction with polarization along “2”

V_{31} – Shear mode propagating along the “3” direction polarized along the “1” direction

V_{32} – Shear mode propagating along the “3” direction polarized along the “2” direction

V_{21} – Shear mode propagating along the “2” direction polarized along the “1” direction

V_{12} – Shear mode propagating along the “1” direction polarized along the “2” direction

V_{45} is a shear mode propagating along $j - k$ (the vector $.707j - .707k$) and polarized along $j + k$ (the vector $.707j + .707k$). Here, j is the unit vector along the “2” (or 1) direction and k is the unit vector along the “3” direction. Using the same convention as used for the other modes along the principle axes, this mode would be designated as $V_{.707y-.707z,.707y+.707z}$.

3.3 ELASTIC CONSTANTS AND ENGINEERING CONSTANTS

The equations relating the measured ultrasonic velocities to the material elastic constants and the engineering constants are derived in Appendix A.

4. SYMBOLS AND UNITS

Table 1 - Symbols and units

Parameter	Symbol	Equation	Unit
Initial friction material thickness	X_1, X_2, X_3, X_{45}		mm
Longitudinal Transit time	T_L		microseconds
Longitudinal offset	T_{Lo}		microseconds
Shear Transit time	T_S		microseconds
Shear offset	T_{So}		microseconds
Coupling Force	F_c		kilograms
Longitudinal velocity	V_{ii}	X_i/t	mm/microsecond
Shear Velocity	$V_{ij} \quad i \neq j$	X_i/t	mm/microsecond
Density	ρ		g/cm ³
Temperature	θ		Centigrade
Pre-load force	N		Newton
Sensor Area	A_s		Meter ²
Pre-load Pressure	P	N/A_s	MPa
Unique axis Longitudinal Modulus	C_{33}	ρV_{33}^2	GPa
In-plane Longitudinal Modulus	$C_{11} = C_{22}$	$\rho(<V_{11}, V_{22}>)^2$	GPa
In-plane Shear Modulus	C_{66}	$\rho(<V_{21}, V_{12}>)^2$	GPa
Out-of-plane Shear Modulus	$C_{44} = C_{55}$	$\rho(<V_{31}, V_{32}, V_{13}, V_{23}>)^2$	GPa
First off-diagonal Elastic Constant	C_{12}	$C_{12} = \hat{C}_{11} - 2 \hat{C}_{66}$	GPa
Second off-diagonal Elastic Constant	C_{13}	$C_{13} = \sqrt{\left[\left(2\rho V_{45}^2 - 0.5(C_{22} + C_{33} + 2C_{44}) \right)^2 - .25(C_{33} - C_{22})^2 \right]} - C_{44}$	GPa

5. EQUIPMENT

The test equipment should include:

- Ultrasonic pulser-receiver unit
- Waveform digitizer and display
- Coupling load test fixture
- 2 longitudinal wave ultrasonic sensors
- 2 shear wave ultrasonic sensors
- Micrometer
- Balance
- Ultrasonic couplant
- Propagation Timing Standard
- Test Sample Heater (350 °C) max
- Thermocouple and temperature controller
- Thermal Buffered Shear and Longitudinal Sensors (-20 °C to 325 °C)

6. SAMPLE PREPARATION

For friction materials, the material symmetry is transversely isotropic with the unique axis along the material's thickness direction (axis "3" in Figure 1). We require a minimum of one rectangular sample oriented along the principle axes of the pad and one sample which has been sliced at a 45° angle relative to the "unique" axis of the pad. Figure 2 shows the brake pad cutting diagram.

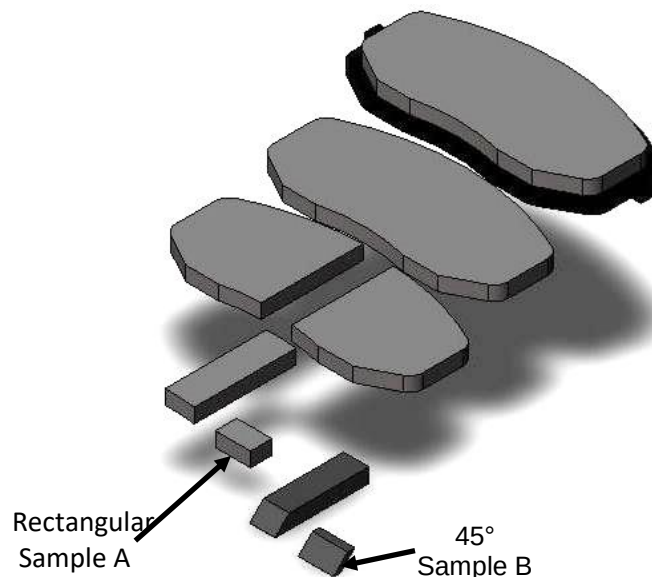


Figure 2 - Typical cutting diagram for brake pad

6.1 Rectangular Samples

The first step in sample preparation is to remove the friction material from the steel backing using a band saw. The friction material is then sliced into a 20 mm wide segment parallel to the “2” direction. From this segment, small, 15 mm by 20 mm by ~8 mm rectangular test specimens are cut. Note that material is discarded from areas near the injection molding sites. Saw cut marks are removed using a belt-sander and efforts are made to produce rectangular test pieces with parallel surfaces. The longest sample dimension, (20 mm), corresponds to the longest dimension of the original pad (“1=x” direction in our defined coordinate system). The smallest dimension (~8 mm) always corresponds to the thickness dimension (“3=z” direction in our defined coordinate system). The parallelism is important for all samples and the variation must be controlled to under ± 25 microns. The above shows recommended sizes for typical automotive disc brake pad. For larger truck blocks, it may be desirable to increase the sample size in proportion by a factor of as much as 3 times. The thickness direction (“3” axis) is the controlling dimension. For drum brake segments, the same rectangular pieces are cut from the segment, however in this case the slight curvature of the surface must be removed by sanding. This is particularly important for the concave surface.

6.2 45° Samples

A second sample type, a cut 45° relative to the thickness direction, is used to obtain the off-diagonal elements to the elastic constant matrix. This is shown as Sample B in Figure 2. This Figure is somewhat misleading in that it suggests that Sample B, (45° Sample) has a large surface area for the face normal to the “3” axis. The 45° sample must be “thinner” than the thickness of the pad from which it came, i.e. thinner than the “3” direction thickness. Typical thickness is 6 mm. Measurements are made on this piece by propagation of waves perpendicularly to the 45° cut surface as indicated by the white arrow in Figure 3. This sample must be cut such that the 45° faces are parallel to one another and the ultrasound can propagate perpendicular to this cut surface reaching the other side before being reflected and refracted by a sidewall.

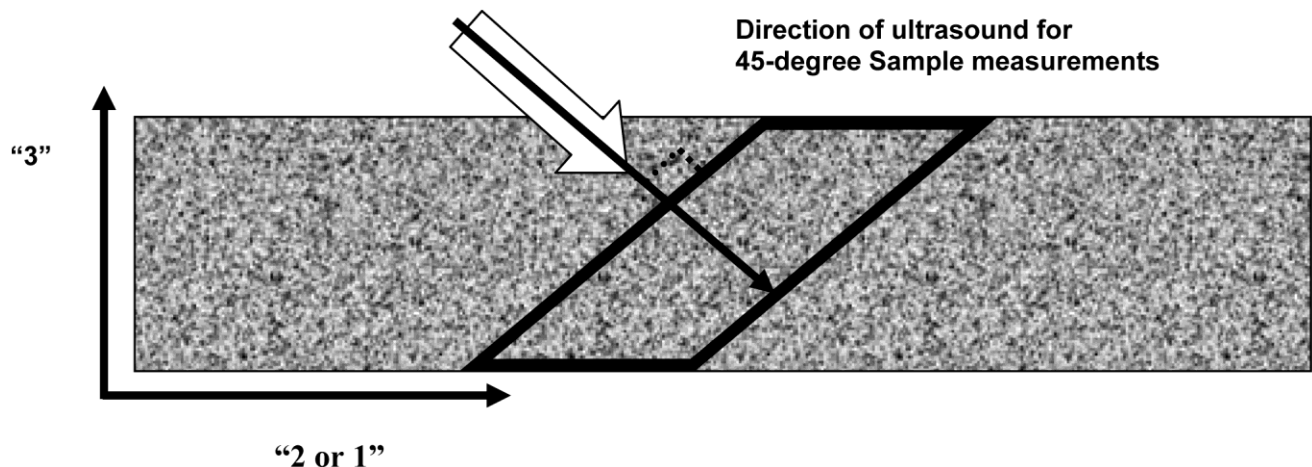


Figure 3 - Direction of ultrasound for 45° sample measurements

Figure 3 shows a friction material in the 3-2 (or 3-1) plane with a dark outline showing a 45° cut, which is appropriate for the transit time measurement.

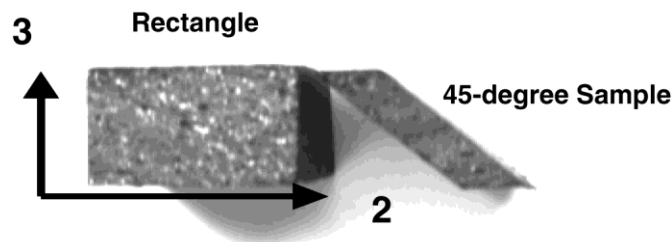


Figure 4 - Cut rectangular and 45° sample

Figure 4 shows a photograph of a typical rectangular and 45° specimen. The thickness of this piece along the “3” axis is generally in the range from 6 to 10 mm. The 45° sample has been oriented so that it appears as it was in the pad prior to slicing. Its thickness, measured normal to the 45° cut surfaces, is only ~6 to 7.5 mm. All coordinate axis designations are referenced to the coordinate system shown in Figure 1.

For all samples, the parallelism should be accurate to ± 25 microns. The surface finish as obtained with 200 grit sandpaper. For the 45° sample, the angular uncertainty is controlled primarily by the cutting fixture. It should be better than $\pm 5^\circ$.

7. EQUIPMENT AND TEST RIG SPECIFICATION

Ultrasonic pulser-receiver unit must have a frequency bandwidth of 90 MHz, be capable of shock excitation of transducer in the frequency range from range of 1 to 10 MHz, and have a dynamic range of more than 90 dB.

Waveform digitizer and display must have an acquisition speed greater than 50 MHz, ability to display of waveforms in real-time, have automatic peak detection, signal averaging, (50 times minimum) and automatic transit time measurement capability. Timing precision of ± 10 nanoseconds is required.

The coupling load test fixture must be capable of supplying and monitoring up to 1000 N (220 pounds) of compressive load to the samples and of maintaining the polarization of the ultrasonic sensors to better than $\pm 5^\circ$. The precision of the load fixture should be ± 20 N (5 pounds). For shear wave transducers, the direction of polarization is indicated on the sensors. The fixture must allow for rotation of each sensor (about the propagation direction) to ensure that the polarization of the sensors are co-linear.

The longitudinal wave ultrasonic sensors must have a center frequency in the range from 1 to 5 MHz and a 10 dB bandwidth greater than 80% and have an active piezoelectric element less than 1.25 cm in diameter.

The shear wave transducers must be linearly polarized with polarization clearly marked. They must operate with a center frequency in the range from 1 to 5 MHz and have a 10 dB bandwidth greater than 80%, and have an active piezoelectric element less than 1.25 cm in diameter.

A propagation timing standard with known (independently measured) transit times for both longitudinal and shear waves must be accurate to ± 5 nanoseconds.

A heater must be such that it can accommodate the cut samples described above. Although not essential, in general the same test samples measured at ambient temperature are used in the elevated temperature test. Because of the small sample size, a heating block with cartridge heating elements will suffice. Generally, a power capacity of a few 100 W is sufficient for heating samples from ambient to 325 °C.

Temperature controller must be capable of controlling the heater over the temperature range from ambient to 325 °C. It must be able to produce a stepwise heating profile with variable hold times from 0 to 20 minutes.

Thermal isolation of the ultrasonic sensors is required to isolate the active elements from the high temperature environment. This can be accomplished by attaching the sensors to a rod of material which has low thermal conduction, near zero velocity-expansion coefficient, and good ultrasonic propagation in the 0.1 to 5 MHz frequency range. Temperature at the active element should not exceed 50 °C.

The balance must have precision better than .01 g.

8. CALIBRATION

The calibration of the system is critical to achieving accurate results. Because of unknown triggering delays in the instrumentation and propagation delays in the piezoelectric sensors, it is necessary to calibrate the system using a test sample where the propagation time is known or measured independently. The ultrasonic system must be supplied with a steel calibration block whose transit time for both longitudinal and shear waves has been measured independently (see Figure 5).