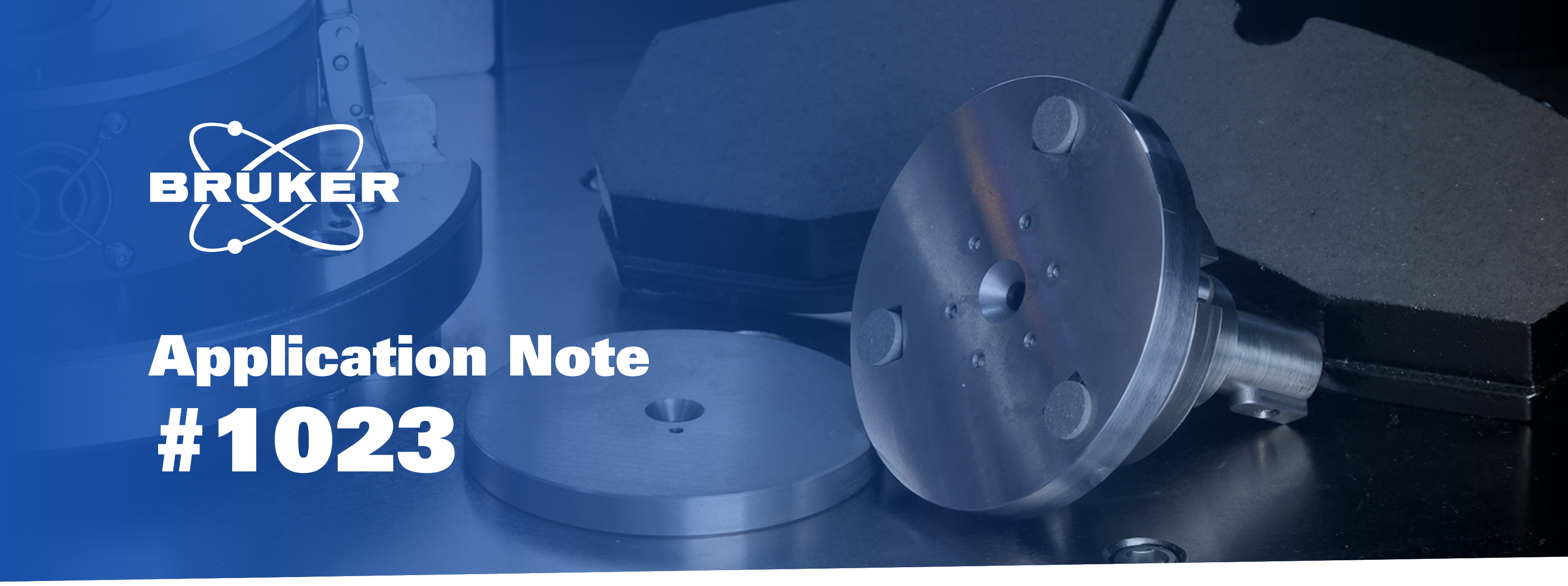

Laboratory-Scale Screening of Brake Wear Particle Emissions

Particle emissions from vehicle brake systems contribute to air pollution and associated health issues, leading to a growing emphasis on understanding and mitigating these emissions. Laboratory testing plays a crucial role in evaluating brake wear emissions and developing effective strategies to reduce these emissions. This application note discusses how Bruker's TriboLab™ HD friction materials tester has been designed and constructed to enable simultaneous brake friction and wear evaluation as well as in-situ brake emission sampling. The sampling is performed under dynamically realistic vehicle braking conditions by using a three-stage cascade impactor to ascertain particle gravimetric mass size distribution.

Understanding Brake Wear Particle Emission Sampling

Brake systems are integral components of vehicles, required for deceleration and stopping. Friction generated during braking induces wear and tear on brake linings, leading to the generation of brake wear particulate matter (PM). These particles are responsible for up to 55% of non-exhaust traffic-related PM10 (particles up to 10 µm in size) emissions.

Toxicological studies indicate adverse health effects from brake wear PM, necessitating rigorous evaluations of brake materials before commercialization. Brake wear PM is a complex blend with emissions and compositions influenced by: (i) brake friction material (NAO, low steel, semi-metallic, carbon composite, or rotor and drum as friction pairs); (ii) brake assembly configuration (disk and drum, size, surface structure, groves); and (iii) driving conditions (initial velocity, deceleration rate, hydraulic fluid pressure, torque, brake temperature). Emission of brake wear PM involves both mechanical abrasion and resuspension of wear particles deposited on brake friction surfaces, complicating the sampling and measurement processes.

Field tests, such as vehicle trials and on-road assessments, enable sampling of brake wear PM under specific braking scenarios, but samples are often contaminated by re-entrained road dust and tire wear particles. Alternatively, brake dynamometers offer a means of assessing brake wear PM in a dedicated facility by simulating deceleration and acceleration without contamination. Such tests are both time-consuming and expensive, not to mention the fact that nonetheless, the availability of commercially viable closed systems capable of collecting brake wear PM for subsequent characterization is limited.

Fast, more cost-effective laboratory scale brake friction material testing is now possible with Bruker's TriboLab HD system, which offers a promising approach to sample brake wear PM from brake pads and rotors without contamination. To achieve this, the brake friction material tester is fitted with an enclosing chamber and particle collection system. In the study presented here, brake wear PM emissions were collected under transient driving cycles using commercially available brake pads and grey cast iron discs. Additionally, the frictional properties of the tribopairs were evaluated using TriboLab HD.

Laboratory Setup for Brake Particle Emission Sampling

TriboLab HD was designed to determine the friction and wear on the brake pad/rotor based on simulated testing protocols, as well as sample brake wear PM emissions via a three-stage cascade impactor. This impactor is connected to the enclosing chamber of the TriboLab HD and integrated with an isokinetic nozzle (Figure 1a).

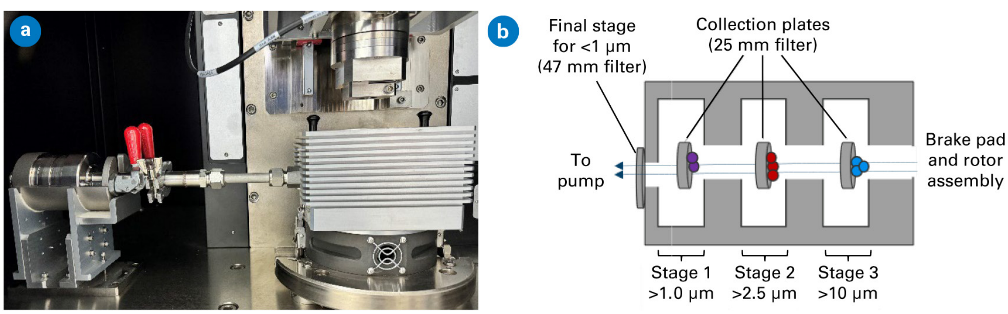

FIGURE 1

(a) Three-stage cascade impactor connected to an enclosing chamber on TriboLab HD, and (b) schematic diagram of a three-stage cascade impactor for PM1.0, PM2.5, and PM10 collection.

A rough pump provides a constant flow rate of 10 lpm to facilitate the extraction of brake wear PM from the TriboLab HD into the cascade impactor. The impactor features three distinct cut-points for the collection of PM fractions: >10 µm, 10–2.5 µm, 2.5–1.0 µm, and <1 µm in size, as illustrated in Figure 1b.

Testing Protocols

AK Master (SAE J2522) test protocol

TriboLab HD was utilized to conduct scaled-down experiments based on the global brake effectiveness SAE J2522 standard. Each section of the SAE J2522 test was conducted as detailed in Table 1. To ensure consistent testing conditions, a closed-loop feedback control system was used to apply and sustain normal load throughout the experiment, with continuous monitoring and recording of normal force, torque, and rotational speed. However, to address inadequate friction-induced heating, an in-stage heater was introduced to facilitate independent temperature control during specific test stages, indicated by asterisks (*) in Table 1.

Section of SAE J2522 (scaled down)		Number of snubs	Average coefficient of friction (μ_{avg})
1.	Green μ	30	0.32
2.	Bedding	64	0.34
3.	Characteristic value 1	6	0.32
4.	Speed/Pressure 40–5 km/h	8	0.35
5.	Speed/Pressure 80–40 km/h	8	0.33
6.	Speed/Pressure 120–80 km/h	8	0.33
7.	Characteristic value 2	6	0.34
8.	Cold application	1	0.36
9.	Characteristic value 3	18	0.33
10.	Fade 1*	15	0.27
11.	Recovery 1	18	0.31
12.	Pressure line at 100°C	8	0.30
13.	Temperature increase 500°C*	9	0.33
14.	Pressure line at 500°C*	8	0.40
15.	Recovery 2	18	0.33
16.	Fade 2*	15	0.38
17.	Recovery 3	18	0.28

TABLE 1

Average effectiveness values obtained using a scaled-down approach on TriboLab HD.

The configuration of the brake pad/rotor disc setup, illustrated in Figure 2, involved securing three 12.7 mm diameter brake pad coupons within a holder and rubbing them against a 95.25 mm diameter cast iron disc. The brake coupons were cut from commercial semi-metallic brake pads while the cast iron disc was machined using CNC milling.

In a validation of proof-of-concept, PMs generated from brake wear were collected using a cascade impactor over the duration of the friction performance evaluation, which lasted approximately 6 hours. Subsequently, the particles were further characterized for particle size and elemental analysis.

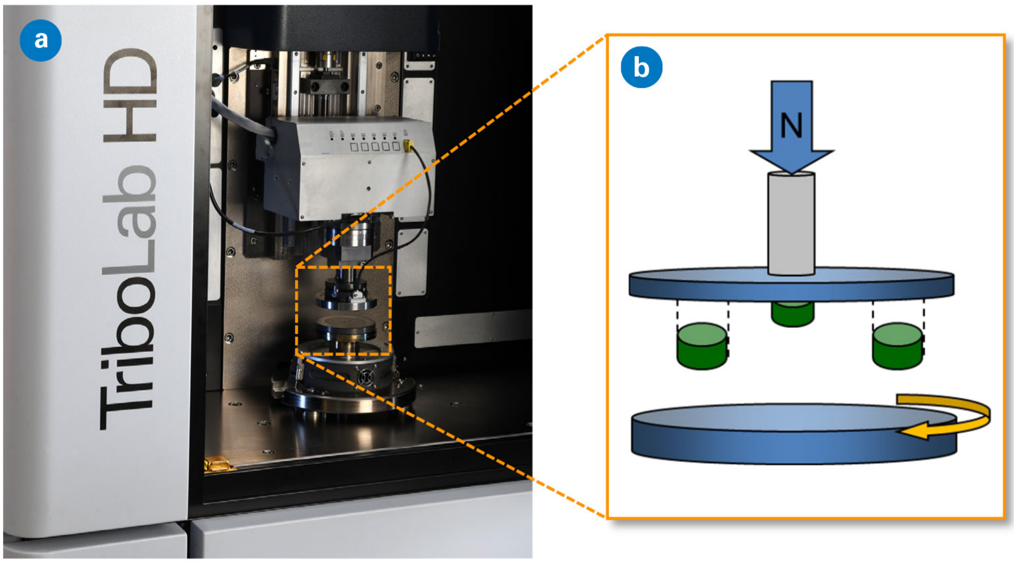

FIGURE 2

(a) Close-up view of brake pad/rotor disc setup on TriboLab HD, and
(b) schematic diagram of three brake pads rubbing against a rotating cast iron disc.

Figure 3 shows the complete scaled-down SAE J2522 test results across a number of braking engagements at varying temperatures (indicated by red line), pressures (indicated by yellow line), and speeds. The effectiveness of brake engagements, assessed through the coefficient of friction (indicated by green line), is determined by calculating the ratio of brake friction torque (indicated by blue line) to the effective radius and applied normal force between the brake pad and rotor disc. The reduced-scale test data revealed notably good correlation between full-scale tests, evidenced by the calculated average coefficient of friction and the behavior and trend of the torque. The camera image in the bottom right of Figure 3 shows the brake wear track and the condition of brake coupons upon completion of the scaled-down SAE J2522 test.

In addition to assessing the frictional properties of the brake pairs, brake wear PM can be collected either at the end of the test for subsequent characterization and analysis, or at specific stages during the simulation of particular braking sequences. PM can also be sampled under custom-defined test conditions, such as at specific temperatures, speeds, or pressures. Figure 4 depicts the brake PM sampled on different stages of the cascade impactor, field-emission scanning electron microscope (FESEM) micrographs, and elemental analysis of the PM from electron-dispersive X-ray spectroscopy (EDS).

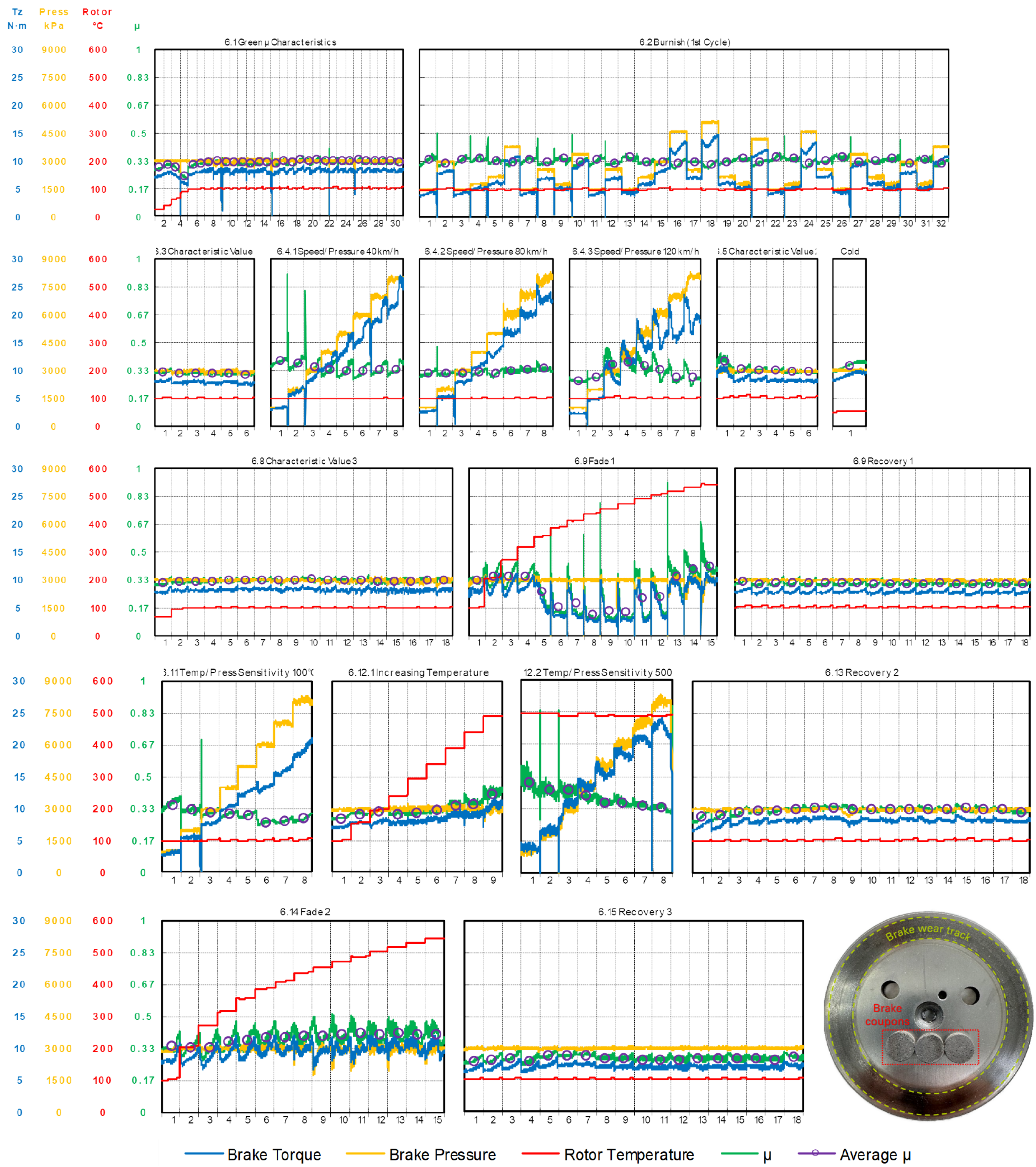

FIGURE 3

Friction performance of semi-metallic brake pad tested against cast iron disc using TriboLab HD. Camera image: Brake wear track on rotor disc and physical appearance of brake coupons after completing scaled-down SAE J2522 test.

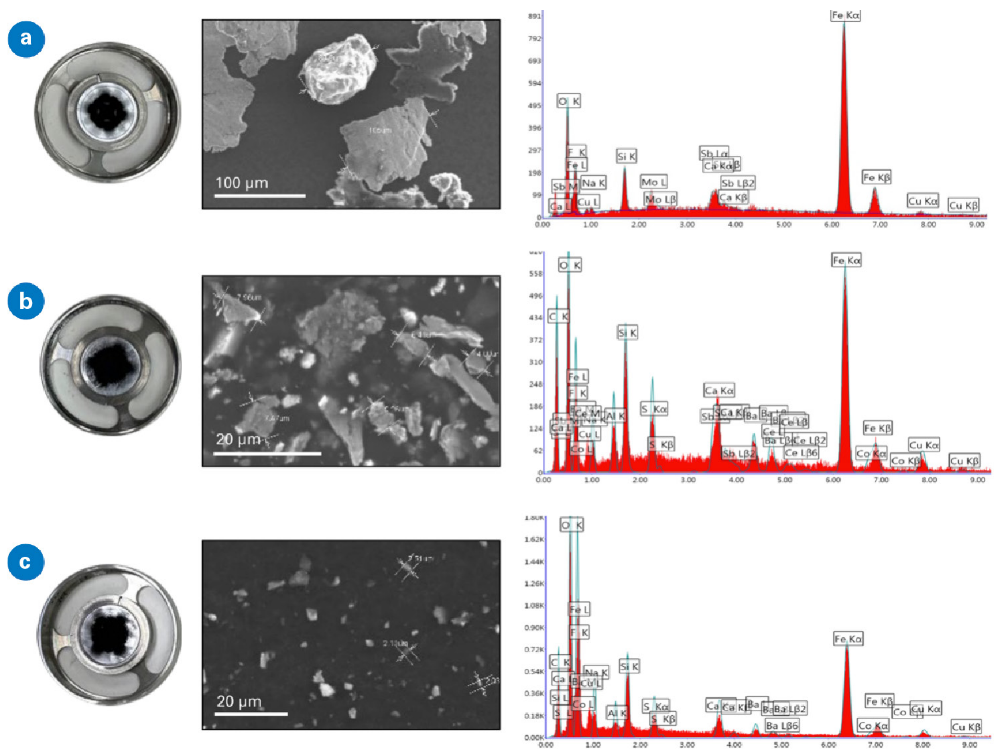

FIGURE 4

(a) PM10, (b) PM2.5, and (c) PM1.0 brake wear PM collected on the three-stage cascade impactor, including micrographs from an FESEM (center column) and elemental analysis using EDS (right column).

GTL speed sensitivity snub test protocol

In a separate study (data courtesy of Greening Associates Inc. and Mike Holly Metals LLC), niobium-alloyed brake rotors (with 0.15–0.25 wt% Nb) and low-metal brake pads were subjected to a series of user-defined speed sensitivity tests on a TriboLab HD system. Before the tests, a burnishing procedure was conducted on the brake pairs to achieve 90–95% of the friction contact area. Subsequently, the brake pairs were subjected to the following speed sensitivity test procedures:

- 20 snubs were repeated at various test speed intervals: 40–0.5, 60–20, 80–40, 100–60, and 120–80 km/hr;
- Each test sequence was conducted at three different unit load values: 0.5, 1.0, and 1.5 MPa.

The brake pairs were allowed to cool down between each test. The purpose of this study was to evaluate the magnitude of brake dust generated by rotor discs with different niobium compositions.

Figure 5 shows the various magnitudes of brake dust accumulated on the TriboLab HD chamber lid at the end of the test. Qualitative findings suggest that the incorporation of niobium with ferritic nitrocarburizing (FNC) improves the wear resistance of the rotor disc. Thus, evaluating brake dust accumulation can serve as a rapid method to screen the wear resistance behavior of rotor discs in the early stages of rotor development.

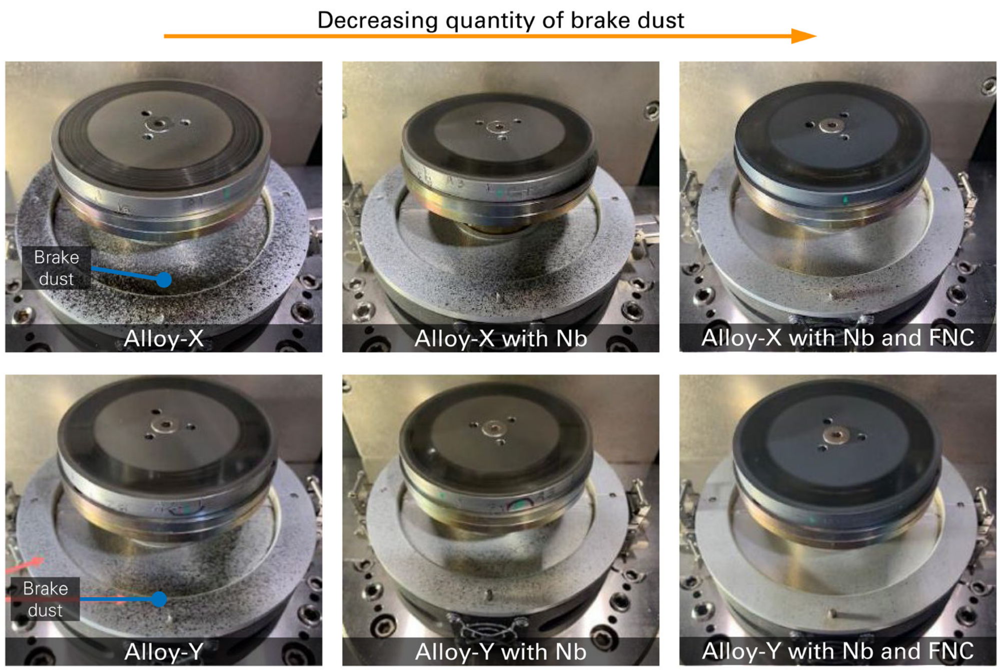

FIGURE 5

Brake dust collected on chamber lid with different niobium-alloyed and FNC brake rotors.

Streamlining Development Processes with TriboLab HD

Data acquired through the Bruker's TriboLab HD platform and particle collection setup can enable friction material developers and brake manufacturers to streamline their development process. By evaluating numerous trial compositions, materials that demonstrated optimal performance in scaled-down studies can be identified, thus saving development time and costs. Only the most promising compositions are advanced to full-scale dynamometer or vehicle stopping tests. Moreover, this setup facilitates in-depth investigations into brake wear PM and potential compositional changes during braking under well-controlled and well-characterized test conditions.

References

1. Brake Dynamometer Standards Committee, SAE J2522., SAE International, (2014).
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3. Holly, M., Brake Colloquium & Exhibition – 41st Annual, (2023).

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