Experimental and numerical study of the thermomechanical and tribological mechanisms involved in dry friction brake emissions

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Abstract

Context

The braking function on land vehicles relies, at least in part, on friction to dissipate kinetic energy. It is well-known that frictional braking systems are a major source of nuisance, especially in urban areas. For instance, the brake pad-disc system may experience friction-induced vibrations, which generate high-intensity, high-frequency noise known as squeal. This phenomenon is seen as an important issue by manufacturers due to the costs associated with customer claims. In addition, it is now established that friction brakes are the cause of significant air pollution related to the emission of fine particulate matter, which poses serious human health risks. The mechanisms behind these friction brakes pollution and emissions remain poorly understood due to their dependence on complex tribological and thermomechanical interactions.

The study of brake emission mechanisms is made difficult by the virtual impossibility of accessing the interface under operating conditions. Consequently, studies to understand the phenomena involved in noise and particle emissions often rely on parametric experimental studies, highlighting the role of loading parameters such as temperature. To go beyond global information, studies are often carried out on simplified experiments such as pin-on-disc systems, and involve in-depth thermal and mechanical measurements as well as surface observations. Various experimental studies have shown, for example, that microscopic and macroscopic contact conditions play a key role in the appearance of emission phases (1). In particular, thermomechanical effects, such as thermal expansion and wear, have a major influence on the location of the contact loading zone on a macroscopic scale (2). Experimental evidence suggests that these effects can be understood by considering the temperature level measured near the surface, which may be a relevant indicator of both squeal occurrences and particle emission rates (3). A great deal of work has also gone into analyzing surfaces and describing the tribological circuit whose morphology and constitution act on excitation mechanisms and wear mechanisms of which particles are a part. From these analyses, load bearing areas can be identified which relate to the contact loading zones identified as relevant indicators. However, surface analyses are carried out post-mortem, which makes it difficult to relate them to the solicitation history.

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Objective and strategy

The aim of this work is to reconstruct the local load history, i.e. the bearing capacity zones resulting from thermomechanical and tribological mechanisms, and to relate them to the particle emission and squeal occurrence phases. The strategy is to conduct highly instrumented experiments to monitor the load bearing areas close to the contact surface (subsurface). Surface analysis (observation and profilometry) are performed before and after each test. Finally, for interpretation purposes, inverse analysis methods are used to derive surface information from the measurements, and direct thermomechanical modeling is also carried out to illustrate some of the phenomena involved.

Methods: Experiment

A pin-disk experiment is used, specially designed to reduce dynamic complexity (minimization of contact joints and adapted geometry) and to facilitate instrumentation (cubic pin). Instrumentation includes measurements of forces, displacements, accelerations, etc. For contact mapping, near-surface thermal instrumentation is included. 16 thermocouples are embedded within the pin, located 2 or 4 mm beneath the contact surface. On the other surface, on the disk side, thermal monitoring is performed using an infrared camera. Additionally, two three-dimensional piezoelectric force sensors and three eddy-current displacement sensors enable a tracking of the pin dynamics. Noise emissions are recorded using a microphone located 1 meter away from the pin-on-disc system. To analyze particle emissions, the contact is encapsulated within a chamber in which an air flow is generated to collect a part of the particles ejected out of the contact. The air flow with the collected particles is directed to an Engine Exhaust Particle Sizer (EEPS) device which analyzes the quantity and size distribution of the collected particles.

Two optical profilometers with focus variation are installed on the test bench for discrete surface monitoring. Between each contact phase, the pin support is rotated to make the 2 contact surfaces accessible for measurement. High-resolution profiles and optical maps are then obtained.

Methods: Models

Models are used to support experiments and interpret measurements. Inverse numerical analysis is first used to trace information from subsurface thermocouples to surface heating and heat flow dissipation areas, which are then associated with contact surfaces. Additionally, to gain deeper insight into the thermomechanical mechanisms involved, a three-dimensional finite element model of the pin-on-disc system is used to perform quasistatic simulations of the thermomechanical coupling. The friction energy dissipation is used as a surface heat source in the contact interface, and the resolution of the transient thermal problem yields the temperature evolution in the pin and disc. This thermal resolution is alternated with a quasistatic resolution of the frictional contact problem accounting for the thermal expansion of the solids, which alters the contact area and distribution of friction energy dissipation over the surfaces, allowing in return to update the source heat flux for the thermal problem. This numerical approach offers detailed insights into the thermomechanical conditions that promote noise and particle emissions. This type of analysis makes it possible to separate the phenomena of contact localization resulting from thermoelastic deformation and thickness variations including wear.

Results

Series of tests were carried out with a variation in speed, force and duration. Evolutions of the squealing phases and particle emissions events are observed with a sensitivity to the first order of the temperature, as expected but also with an influence of the loading history, i.e. previous tests. The overall request information of speed, forces, temperatures nevertheless remain insufficient given the variation in noise and emissions phases. The processing of experimental data made it possible to reconstruct the evolution of the load bearing zones showing significant and very variable variations from one test to another. This information is processed in support of the discrete analysis of the surfaces, on the basis of observations before and after testing, making it possible to reconstruct the history of the evolution of the surface, from initial surfaces which differs from a test to another. It is shown that areas of accumulated powders and compacted plateaus can be associated to the initial surface, before test, and load bearing areas history. Finally, the thermomechanical modeling data, associated with the experiments, make it possible to establish the scenario of the thermomechanical and tribological processes involved. This history is linked to that of the noise occurrences and the emission phases showing that they are related to specific behaviors of the macroscopic contact localization. For example a distinct cyclic radial shift of the contact localization is observed, presumably leading to periodic contact openings and closures. These specific conditions are found to be closely correlated to important emission episodes.

References

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