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Relation between mechanical behavior and microstructure of a sintered material for braking application

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A R T I C L E I N F O

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A B S T R A C T

This paper describes an original methodology to characterize the mechanical properties of sintered materials before and after a realistic braking test bench protocol. This characterization consists in a compression test on different samples extracted from friction pins at different states. The compression tests are instrumented with a Digital Image Correlation (DIC). This technique gives local information allowing to link the strain fields with the microstructural mechanisms of the heterogeneous material. Even if the composition of the friction material is complex, it is shown that it can be summarized, at a mesoscopic scale, as a two-component substance. Moreover, the mechanical behavior can be described with an elastic-plastic hardening model combined with an evolution of the properties as a function of the load level. Comparisons between the unused and used materials exhibit strong differences in the evolution of elastic moduli with loading, which has been associated with damage of the virgin material despite densification of the material after the tests. For the used material, two layers can be distinguished with different mechanical properties. These properties vary with the location on the brake pad, and an explanation of this variation is proposed. Results of this study have demonstrated that it is necessary to consider the evolution of a friction material during a braking sequence rather than only properties in a pristine state as commonly done in the literature. The proposed methodology can be applied to a wide class of materials.

1. Introduction

The growing needs for rail transportation results in the continuous increase of masses and speeds. Nowadays there are different programs for high-speed trains to move at maximum service speeds of 320–360 km/h. At the same time, requirements of lightweight structures become more and more noticeable, and such trends lead to evolutions with regard to braking loads. The dissipated energy increases and the mass of the brake system has to be reduced.

These changes involve developments with regard to braking devices to ensure performances and safety at high loading levels. Based on existing technologies this means that the design and materials of friction braking systems have to be improved, which requires a better understanding and control of this safety structure. At the moment, the development of friction materials is still led by empirical methods based on an experimental system of trial and error. This is mainly due to the complexity of the issue.

The development of a friction pad necessarily has to respect different norms. In terms of performance, the industrial partners have certain requirements such as a stable coefficient of friction and a low wear rate at the operating and environmental conditions in question, etc.

To meet these different requirements, a commercial brake lining is a complex composite made up of more than 20 different raw materials. For high-temperature applications (temperatures close to 1000 °C can be reached in railway applications), the composite is made of a metallic matrix obtained by sintering, embedding graphite particles, ceramics, etc. The development and qualification of the friction materials are done by tests on dynamometers, but for an optimized recipe, this black-box approach can be very long and limited. For an optimal design, it would be necessary to develop material characterization methodologies that identify the physical parameters involved in the previously described performances (tribological, mechanical, thermal, etc.) and link them with the formulation of the material.

In this work, we have focused on the mechanical properties. It is well known that they have a main effect on the contact pressure distribution and consequently on the temperature, but also on the tribological performances, on the material strength, etc [1–3]. The aim

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Table 1
Basic composition of the sintered material.

Components	Weight(%)	Typical size
Metallic matrix	70	100–600 µm
Graphite	20	100–1100 µm
Ceramic	10	100–250 µm

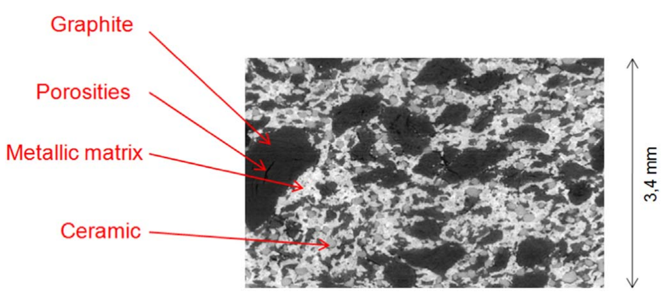

Fig. 1. SEM-micrograph of the sintered material.

is to be able to characterize the evolution of the properties with loading i.e. with the braking sequence. This is rarely mentioned in the literature which considers materials in a pristine state. Indeed, loading levels are so high that materials undergo transformations that very likely change their properties. Another objective of this study was to establish links between the properties, the formulation and heterogeneity of the friction material. This presents a difficulty as, even if the formulation is defined, the distribution and orientation of the components when it comes to their properties are unknown. The matter studied herein is a derivative of an industrial formulation of a sintered material for railway applications with a global composition given in Table 1. This material is made of a iron-copper based metallic matrix embedding graphite and ceramic particles. It is obtained by a sintering 3-step process: mixing of powder, cold pressing and sintering at high temperature (around 900 °C) with a FAST (Field Assisted Sintering Technology) technique. It is clear that the material has a very complex microstructure (as shown in Fig. 1), with a high level of heterogeneity, and components with different characteristic lengths. Moreover, as can be seen in Fig. 1, porosities that could be seen are mainly localized in and around the graphite particles.

Generally, the mechanical behavior of sintered material is considered as homogeneous and isotropic [4–11]. To characterize the mechanical properties, compression tests are carried out on cubic, rectangular or cylindrical samples machined in the brake lining [12–14]. Stress-strain curves, to identify the bulk compressive modulus, are obtained by measuring the force by load cells and the strain from gauges or plateaus displacement. Compressive tests have the advantage of being close to the loading exerted on the lining in a braking system. However, it is a delicate test when the sample heights are low since the thickness of a brake lining is limited (smaller than 30 or 20 mm).

In this study, we propose to take things one step further: first, a very fine instrumented compression test was performed on materials submitted to different braking loadings (i.e. before and after a complete UIC “type” program). For this Digital Image Correlation (DIC) technics were used to measure strain fields. Such a technique made it possible to analyze the test accuracy, i.e., whether the mechanical loading is uniformly compressive. It also gives rich information of local deformation that is interesting for a heterogeneous material [15–21]. With these data, a connection could be made between the microstructure and the strain mechanisms.

Results are shown for two states of the material: before and after the braking sequence detailed in the beginning of the paper. The experimental set-up and DIC instruments are detailed in the second section. Results are shown in the following for the pristine material. For cubes extracted after the test program, different samples were studied to quantify the representativeness. Several differences were seen depending on the location of the sample extraction. They are discussed and highlighted.

Fig. 2. Railway braking test bench - Faiveley Transport Gennevilliers.

2. Test bench program

In order to test the friction material, i.e. submitted to a realistic loading, an experimental campaign was performed on a real-scale railway test bench with an adapted UIC “type” program defined in the worldwide organization for railway cooperation [22]. Several thermocouples were inserted in the brake pads at different depths enabling a rich acquisition to identify the thermal loading encountered during the braking program. Moreover, an infrared camera in front of the disc surface was used to observe thermal localizations. The experimental tests were carried out on a real-scale railway braking test bench from Faiveley Transport Company.

2.1. Presentation of the Faiveley test bench for railway applications

The real scale railway braking test bench from Faiveley Transport Company is presented in Fig. 2. The electric power developed by the test bench motor is above 350 kW at 2400 tr min^{-1}.

The dissipation energy could be simulated with two complementary techniques:

- from the mechanical use of flywheels, which are present on the drive shaft,
- from the power of an electric motor.

The configuration of the bench was fixed to represent the standard TGV train brake system. The various components of this system are presented in Fig. 3.

An unventilated solid disc dedicated to TGV application was used with Faiveley's brake pads making up 10 sectors (presented in Fig. 5). The disc is made of a 28CrMoV5 steel and the friction material is the one previously described. The brake pads and the disc were brought into contact by a pneumatic caliper powered by a pressure control system.

2.2. Additional test bench and brake pad instrumentation

In addition to the standard output data from the test bench (pressure, torque, and disc surface temperature, etc.), it was also possible to obtain results from various complementary acquisition systems. They are illustrated in Fig. 4 and consisted of: