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Morphology, physical, thermal and mechanical properties of the constitutive materials of diesel particulate filters

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HIGHLIGHTS

- Determination of the microstructural properties of the DPF constitutive materials.
- Investigation of the thermal evolution of the filtering material and the grout.
- Determination of the mechanical properties of the grout.

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ABSTRACT

From experience it is known that the durability of diesel particulate filters (DPFs) may be limited by the high transient thermomechanical stresses created during severe regeneration rather than by mechanical fatigue. This paper, first of a series dealing with the thermomechanical behavior of DPFs, focuses on the morphology and the properties of the constitutive materials, i.e. the filtering SiC and the grout. The filtering material shows isotropic distributions of the SiC grains and the pores. It is characterized by a marked stability of the mechanical and thermal properties in the explored temperature range (up to 1100 °C). The grout with higher porosity is prone to important thermal transformations with no further consequences on filtration and durability. Due to its low thermal conductivity compared to the filtering material, its essential function is the isolation of the SiC bars from each other.

1. Introduction

The Diesel and Hybrid Diesel Cars (HDC) are possible solutions to reduce fuel consumption, CO_2 emissions and thus the dependence on fossil fuel. However, the general automotive emission standards are more and more restricting, especially for Diesel engines. The Particulate Matter (PM) emission (weight and now number) and the durability of post-treatment system to reduce PM must be controlled. In particular, today, all Diesel vehicles must be equipped with such systems.

To reduce the PM emissions of Diesel engines, the current and most efficient solution is the Diesel Particulate Filter (DPF). The DPF is a porous ceramic structure designed to trap the Diesel PM from the exhaust gas owing to wall-flow filtration (Fig. 1). Once the filter is filled in with PM, it must be cleaned. This periodic process is called regeneration. It consists in increasing the temperature in the DPF up to the temperature of soot oxidation. Two strategies exist in order to facilitate the soot oxidation: the first one consists in dispersing noble metals on DPF walls to promote the regeneration, the second one uses a Fuel Borne Catalyst (FBC) (Eolys©) to decrease the soot burn out temperature by about 100 °C, as used on Peugeot and Citroën vehicles.

The program for Diesel Particulate Filter Durability (DuraFAP) aims at improving the durability by limiting the thermo-mechanical stresses in the DPF during a severe regeneration. This situation of severe regeneration can appear when the vehicle stops even when it slows down strongly whereas regeneration was launched. Hence, a high density of heat is confined in the DPF. Thus, a strong variation in temperature within the DPF may be generated when the combinations of all these factors meet.

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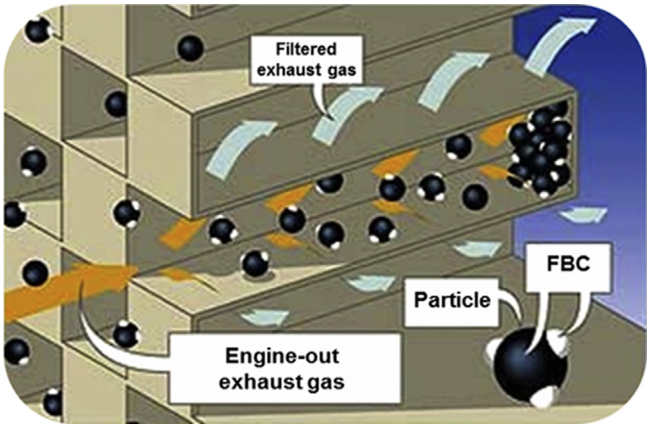

Fig. 1. Wall flow filtration principle used to trap Diesel PM [1].

That requires a proper choice of the constitutive materials of the DPF and of its configuration. The program includes three research chapters: (1) establishment of an experimental methodology to characterize the DPF thermomechanical behavior, (2) improvement of our understanding of the phenomena leading to failure and (3) deriving a numerical model to optimize the DPF conception. This paper deals with the first item on FBC-DPF. In the first section, the DPF and its constitutive materials will be presented. The second section will describe the morphology and microstructure and thermal properties of the constitutive materials and the applied investigation techniques. In the last part, the mechanical properties of the filtering material are assessed and analyzed by using proposed models in the literature for highly porous granular materials. Analysis of the DPF behavior will be performed.

2. General characterization of DPF

The soot mass at the onset of failure, called Soot Mass Limit (SML), is experimentally determined during severe regeneration conditions on engine test bench [2]. A severe regeneration is representative of the most stringent situation of use, met in urban cycle, when the reduced exhaust gas flow is not able to cool the DPF. In such conditions, due to ceramic brittleness, failure of the DPF constitutive material may occur from thermally-induced stresses.

The filtration medium is made up of a set of bars assembled by a grout (Fig. 2a). The bars consist in a honeycomb structure (Fig. 2b) with rectilinear channels. Since the DPF cleans the exhaust gas by forcing it through the walls of the honeycomb structure. They must offer a large specific area and possess interconnected pores small enough to obtain a fine filtration.

The nature of the constitutive material of the honeycomb structure is dictated by the ability to resist high temperature (1100 °C) and high thermal gradients. That requires a particular (and often paradoxical) combination of physical properties: low thermal expansion, low Young's modulus, high strength and high thermal conductivity. As a matter of fact, only a few ceramics can provide such a set of properties. Silicon carbide (SiC) stands out from all other monolithic ceramics. Cordierite ($2MgO–2Al_2O_3–5SiO_2$) is extensively used for catalytic converters but is not able to endure the regeneration temperature. Some properties of both materials are reported in Table 1.

The performance investigation of such filters versus flow rate and particle size showed that a highest filtration efficiencies for particles smaller than 80 nm and larger than 200 nm [7].

The grout binding together the set of bars contributes to accommodate the thermal expansion mismatches between the bars. For given thermal loading conditions, the thermomechanical behavior of a DPF depends on different factors:

- Channels morphology (shape) and dimensions,
- Filtering and grout materials microstructure (grain size, porosity and thickness of the walls), physical and mechanical properties (Young's modulus, coefficients of thermal expansion, strength) and thermal characteristics (heat capacity, thermal diffusivity and conductivity).

The next paragraph deals with the characterization of some of these parameters.

3. Characterization of the constitutive materials

3.1. Materials and specimens

The specimens used to characterize the thermomechanical behavior of the DPF constitutive materials were issued from currently commercialized DPF. Thin specimens of grout ($1.5 \times 28 \times 47$ mm^3) were taken from disassembled bars of the DPF. The SiC constituting the filtration material was investigated by using specimens taken from the external surfaces of the bars (called

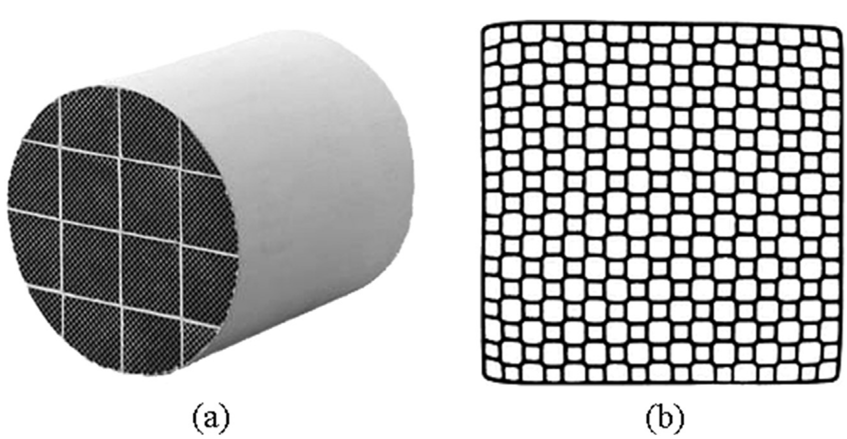

Fig. 2. General view of a DPF (a); section of a SiC bar showing the channels topology (b).