G. Durability of Diesel Particulate Filters

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Contractor: Oak Ridge National Laboratory, Oak Ridge, Tennessee
Prime Contract No.: DE-AC05-00OR22725

Objective

- Identify and implement test techniques to characterize the physical and mechanical properties of ceramic diesel particulate filters (DPFs) and to develop analysis tools for predicting their reliability and durability.

Approach

- Identify and implement test techniques to determine the physical and mechanical properties of DPF ceramic substrates.
- Investigate the applicability of probabilistic design tools to DPF ceramic substrates. In particular, the applicability of the Ceramic Analysis and Reliability Evaluation of Structures (CARES) code to predict the reliability of DPF ceramic substrates will be investigated.

Accomplishments

- Completed the stress analysis of DPF beams subjected to flexural loading. The importance of accounting for the cellular structure of the component has been identified.
- Obtained the elastic properties of DPFs using a dynamic mechanical analyzer.

Future Direction

- Organize a round-robin test program to assess the precision of four-point bending test methods to determine the flexural strength of DPF ceramic substrates.
- Assess the susceptibility of DPF ceramic substrates to slow-crack growth using dynamic fatigue and double-torsion test methods.
- Implement probabilistic design tools to predict the reliability and durability of DPF ceramic substrates subjected to arbitrary thermomechanical histories.

Introduction

The pollution emitted by diesel engines contributes greatly to the nation's air quality problems. Even with more stringent environmental regulations set to take effect in 2004 and 2007, existing trucks and buses will continue to emit nitrogen oxides (NO_x) and particulate matter (PM), both of which contribute to serious public health problems.[1] Fortunately, there are several technologies designed to reduce pollution from existing trucks and buses, such as DPFs. A DPF is a ceramic device that collects PM in the exhaust stream. The high temperature of the exhaust heats the ceramic structure and allows the particles inside to break down (or oxidize) into less harmful components. DPFs reduce emissions of PM by 60 to 90% and emissions of hydrocarbons and carbon monoxide by 60 to 90%.

A typical DPF consists of a ceramic honeycomb with hundreds of cell passages partitioned by walls (Figure 1). Each cell passage has a square cell opening at one end and is closed at the other end so that the cell passages are alternately closed at each end. This structure forces the exhaust gases through the porous, thin ceramic honeycomb walls. When the exhaust gases carrying carbon particles flow through the fine pores of the walls, the carbon particles are filtered out. Porosity values in the range of 60% heighten filtration efficiency to more than 90% while reducing gas-flow resistance so as not to affect the engine performance.

The process of diesel PM collection begins as soon as the engine is started and continues while the engine is operating. As carbon particles collect on the ceramic walls of the DPF, the backpressure of the system increases. This problem is alleviated by burning the trapped PM, through a catalytic reaction using exhaust gas heat at 400°C or more. The burning produces carbon dioxide and water vapor that pass through the filter. This process, called regeneration, results in a cleaner filter. The regeneration process depends upon exhaust temperature, oxygen, NO_x content, time, and PM levels.

The key to the successful use of DPFs is to reliably regenerate the filter (e.g., burn the PM that the filter traps or collects). Traditionally, combustion of soot is done in an oxygen atmosphere (air). In air, soot will burn at about 500°C. However, this is not a typical operating temperature for diesel engine exhaust. As a result, to burn soot in air, an ac

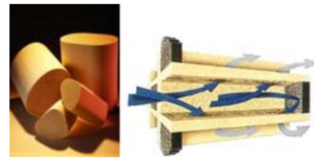

Figure 1. Corning's cordierite-based DPFs.

tive system is required, i.e., one that increases the temperature of the exhaust using some external heat source. But if an active system is not carefully controlled, or if the level of PM collected on the filter walls is too high, a filter may experience an uncontrolled burn where the temperature increases to 600°C or more, resulting in damage to the filter element.

The objective of this project is to develop and implement methodologies to predict the reliability of DPFs. A useful conceptual model for this purpose is the reliability bathtub curve, which describes reliability-related phenomena of a component over its life cycle.[2] A schematic of the reliability bathtub curve is depicted in Figure 2. It consists of three stages: The infant mortality phase is characterized by premature failures due to improper manufacturing or assembly, poor workmanship, or defects introduced during processing. The second stage corresponds to the useful life of the component and is characterized by a constant failure rate. In this regime, failures are typically associated with random, excessive loads. If sufficiently high safety factors are used during the design process, the magnitude of this failure rate should be negligible. The third stage of the bathtub curve is known as the "wear-out" phase, in which the failure rate increases with time as a result of aging phenomena. Aging phenomena include thermal and mechanical fatigue, corrosion, and creep deformation, among others.

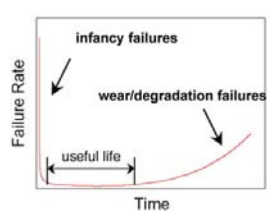

Figure 2. Reliability bathtub curve.

Because of accelerated wear-out, the time at the onset of wear-out is often regarded as the useful life of the component The reliability bathtub curve can be used as a good descriptor of how the failure rate of DPFs evolves over time. Infancy failures of DPFs could be related to manufacturing or process defects (e.g., large pores, inclusions, cracking) or defects introduced during assembly. Failures of DPFs during their useful life will be dictated by the intersection between the spectrum of thermomechanical loads and the distribution of DPF strengths. Such failures could result from excessive vibration, for example, or unwanted thermal excursions during transients associated with regeneration. Wear-out and degradation failures of DPFs could be associated with the growth of microcracks assisted by thermal fatigue, the chemistry of the environment, and/or chemical and microstructural changes in the material due to long-term exposure to elevated temperatures in the exhaust environment and the presence of compounds used for aftertreatment processes.

The objective of this project is to develop life prediction methods for DPFs and, by using those methods, to design more durable and reliable DPFs.

Approach

Designing DPFs that are durable and reliable poses significant challenges. For example, the porosity of DPFs, which allows them to remove PM from the exhaust gas stream, has a deleterious effect on their mechanical strength. This is important because DPFs experience demanding thermomechanical conditions during service, including thermal shocks resulting from rapid heating/cooling and stresses that arise from temperature gradients. The approach to be followed in this project includes identifying and implementing test techniques for non-destructive evaluation of ceramic substrates to assess their integrity. Their physical and mechanical properties and the mechanisms responsible for their degradation in the various stages of the bathtub curve also will be determined and identified. The properties to be analyzed include thermal expansion, thermal conductivity, heat capacity, density, porosity, elastic properties, strength, fracture toughness, and resistance to crack growth at ambient and elevated temperatures in air and in relevant environments. The information generated will be used in turn to implement probabilistic design tools. In particular, the applicability of the CARES code[3] to predict the reliability of DPF ceramic substrates will be investigated. Such probabilistic design methodologies are based on a combination of experimentally-determined strength data, stress analyses of the component using finite-element analysis, and the selection of appropriate failure criteria. The durability (service life) of the component can also be predicted using this framework by considering the mechanisms responsible for the degradation of material strength, such as slow-crack growth or creep.

The implementation of these methodologies has been successful in considering dense structural ceramic components. However, there is limited work on their use to analyze non-structural, porous ceramic components.

Results

To use CARES to predict the reliability of porous ceramic structures, it is necessary, through thorough fractography, to identify the flaws that control the strength of the material. This often amounts to identifying strength-limiting flaws that reside in the volume of the material and on the surface of the component. Often, more than one population of flaws can be identified in the volume or on the surface. Although fractographic analyses are essential for identifying strength-limiting flaws as part of the probabilistic design methodologies, the porous nature of the material and the cellular structure of the component have made fractographic analysis effectively impossible. This is an important issue that will be researched further in the future.

One of the first tasks carried out was focused on analyzing the flexural behavior of beams of various sizes obtained from ceramic substrate DPFs. Special attention was given to determining flexural strength. The maximum tensile stress in a beam when it is subjected to bending is given by

$$\sigma_{max} = \frac{M\,c}{I} \qquad (1)$$

where *I* is the second moment of inertia of the cross-sectional area of the beam, *M* is the moment, and *c* is the distance from the neutral axis to the bottom of the beam, which is subjected to the maximum tensile stress. Figure 3 depicts a schematic of such a beam subjected to 4-point bending (dimensions are in inches), and Figure 4 illustrates the calculation of the maximum tensile stress when the cellular structure of the beam is either taken into account or

Figure 3. Schematic of DPF ceramic substrate 1×1 beam subjected to 4-point bending.

neglected. It was found that when the cross-sectional structure of the beam is neglected, the flexural strength is underestimated by 25%. These results were verified through a finite-element stress analysis (Figure 5).

The discrepancy in determining the flexural strength of beams when the cellular structure of the beam is neglected is further magnified when the cross-sectional area of the beam increases. Figures 6–8 depict the case for a 2×2 beam. In this case, the flexural strength is underestimated by 45% when the cellular structure of the beam is neglected. These

$$\sigma = \frac{Mc}{I}$$

$$M = (0.5)(.15) = 0.075\,lbs \cdot in$$

$$c = 0.041\,in$$

Moment of inertia and stress using beam theory

$$I = \frac{1}{12}(.082)^4$$

Assuming solid cross-section

$$I = 3.77 \times 10^{-6}\,in^4$$

$$\sigma = 815.6\,psi$$

Moment of inertia and stress using actual cross section

$$I = \frac{1}{12}(.082)^4 - \left[\frac{1}{12}(.058)^4\right]$$

$$I = 2.82 \times 10^{-6}\,in^4$$

$$\sigma = 1{,}088.6\,psi$$

Accounting for the cross-sectional area

Figure 4. Stress analysis for DPF ceramic substrate 1×1 beam subjected to 4-point bending.

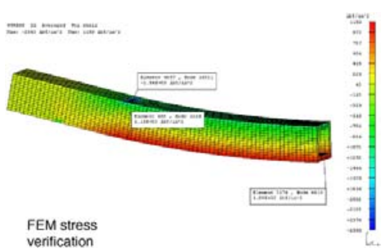

Figure 5. Results of stress analysis using finite elements for a 1×1 DPF ceramic substrate beam subjected to 4-point bending.

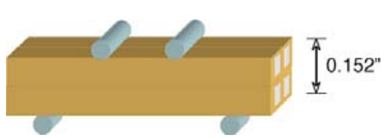

Figure 6. Schematic of DPF ceramic substrate 2×2 beam subjected to 4-point bending.

$$\sigma = \frac{Mc}{I}$$

$$M = (0.5)(.15) = 0.075\,lbs \cdot in$$

$$c = 0.076\,in$$

Moment of inertia and stress using beam theory

$$I = \frac{1}{12}(.152)^4$$

Assuming solid cross-section

$$I = 4.448 \times 10^{-5}\,in^4$$

$$\sigma = 128.1\,psi$$

Moment of inertia and stress using actual cross section

$$I = \frac{1}{12}(.152)^4 - 4\left[\frac{1}{12}(.058)^4 + (.058)^2(.035)^2\right]$$

$$I = 2.423 \times 10^{-5}\,in^4$$

$$\sigma = 235.2\,psi$$

Accounting for the cross-sectional area

Figure 7. Stress analysis for DPF ceramic substrate 2×2 beam subjected to 4-point bending.

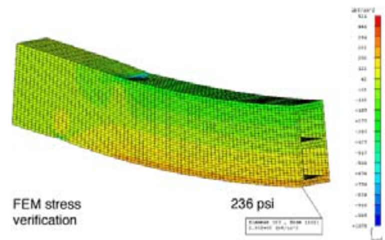

Figure 8. Results of stress analysis using finite elements for a 2×2 DPF ceramic substrate beam subjected to 4-point bending.

results were also verified using a finite-element stress analysis.

As indicated, one of the objectives of this project is to implement probabilistic design methodologies to analyze porous ceramic components with complex cellular structures. One of the questions that needs to be answered is to what extent the meso-structure of the component (cellular structure) can be accounted for, neglected, or simplified, in order to achieve accurate results with numerical expediency. These experimental results indicate that it is necessary to account for the cellular structure of the material, but in order to achieve numerical expediency, local-global techniques will be investigated.

Another important consideration in implementing probabilistic design methodologies requires accurate knowledge of the properties of the material, including their elastic properties. The elastic properties of porous DPF test specimens have been determined with a high degree of accuracy through the use of a dynamic mechanical analyzer. Figure 9 depicts the experimental set-up, which consists of a 3-point bending fixture in which the middle roller is attached to an actuator. A small, cyclic sinusoidal signal is used to stress the test specimen, and the response is recorded to determine the dynamic

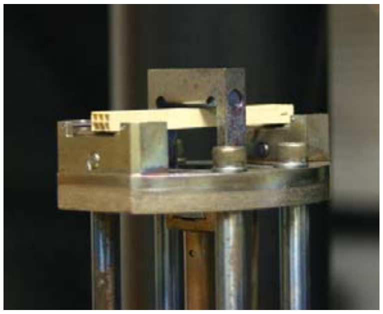

Figure 9. Three-point bending fixture for determining elastic properties of DPF ceramic substrates by using a dynamic mechanical analyzer.

modulus of the material. Figure 10 depicts the cross-sectional area of the beams evaluated, while Table 1 lists the values obtained for the storage and loss moduli of the material. The sensitivity of this test technique makes it ideal for monitoring damage evolution, as determined by changes in elastic properties.

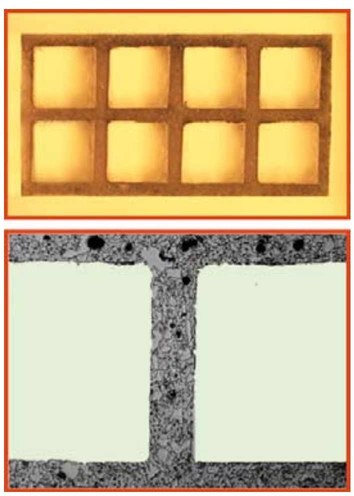

Figure 10. Cross-sectional area of 4×2 DPF ceramic substrate beam.

Table 1. Dynamic modulus properties of ceramic substrate DPF.

Sample	No. of tests	Storage modulus (GPa)	Loss modulus (GPa)	Tan δ
1	4	14.7 ±0.7	0.21±0.03	0.01±0.00
2	6	13.3 ±0.89	0.25±0.07	0.02±0.00
3	5	13.4 ±0.9	0.23±0.04	0.02±0.00
4	5	15.2 ±0.7	0.22±0.04	0.02±0.01
5	5	14.9 ±0.6	0.23±0.03	0.02±0.00
Average		14.2 ±1.1	0.23±0.05	0.02±0.00

Summary

Test techniques have been identified and implemented to determine the physical and mechanical properties of DPF ceramic substrates. Specifically, values for the elastic modulus and flexural strength have been determined by dynamic mechanical analysis and 4-point bending, respectively. A round-robin testing program involving Corning, Cummins, and Oak Ridge National Laboratory has been planned and will be carried out to assess the precision of test methods for determining strength and elastic properties. Work is under way to implement probabilistic design methodologies to predict the reliability and durability of DPFs when they are subjected to an arbitrary thermomechanical history.

References

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