

Impact of Ceramic Substrate Web Thickness on Emission Light-Off, Pressure Drop, and Strength

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ABSTRACT

The effect of web thickness on emission performance, pressure drop, and mechanical properties was investigated for a series of catalyzed ceramic monolith substrates having cell densities of 900, 600 and 400 cpsi. As expected, thinner webs provide better catalyst light off performance and lower pressure drop, but mechanical strength generally decreases as web thickness is reduced. Good correlations were found between emission performance and geometric parameters based on bare and coated parts. An improved method for estimating the effects of cell density and web thickness on bare substrate strength is described, and the effect of porosity on material strength is also examined. New mechanical strength correlations for ceramic honeycombs are presented. The availability of a range of ceramic product geometries provides options for gasoline exhaust emission design and optimization, especially where increased levels of performance are desired.

INTRODUCTION

The cellular geometry of ceramic honeycomb substrates is a critical design element that affects product performance. Theoretical relationships of cell density and web thickness to product performance have been well documented, as have numerous experimental studies. In principle any combination of cell density and web thickness is possible, but various practical constraints such as manufacturability, strength, durability, and canning have limited product availability to those having the best combination of attributes. Nevertheless, aftertreatment technology continues to demand higher performance substrates to match the needs in the market.

Directionally, thinner webs have been developed to reduce substrate mass, thereby improving light off performance, and to reduce pressure drop. High cell densities are developed to provide high geometric surface area for improved emission performance and precious metal utilization. High cell densities also provide mechanical strength, especially for ultra-thin walls. Correlations of bare (uncoated) substrate geometry have been developed to help explain the relationship between cell density and web thickness to emission performance and pressure drop (1,2). However, the presence of the washcoat and catalyst modifies the geometry and properties of the composite catalyst-substrate system. Correlations of coated substrate properties with performance are fewer, and generally first principle reaction engineering models have been used instead to understand the emission performance of catalyzed substrates (3).

EXPERIMENTAL BACKGROUND

SAMPLE SELECTION

A set of cordierite ceramic substrates were tested, spanning the range of cell densities and web thicknesses currently manufactured by Corning Incorporated. A summary of relevant properties of the bare substrates are shown in Table 1. Identical round substrates of 4.16" (105.7 mm) diameter by 3" long (76.2 mm) were packaged two to a can, and tested in a close-coupled location.

Table 1 Bare Substrate Properties

Product cpsi / web	Bulk Density g / L	OFA %	GSA cm ² /cm ³	Hydraulic Diameter mm
350 / 5.5	317	80.5	26.4	1.22
400 / 3	219	86.5	29.3	1.18
400 / 4	279	82.8	28.7	1.16
400 / 6	395	75.7	27.4	1.10
600 / 2	223	88.1	36.2	0.97
600 / 3	267	83.6	35.3	0.95
600 / 4	338	79.2	34.3	0.92
900 / 2	271	85.6	43.7	0.78

Substrates were coated with a modern washcoat formulation by a commercial coater. The precious metal was a Pd/Rh combination having a target 195 g/ft³ loading, typical of some SULEV formulations.

EMISSIONS TEST PROCEDURES

Catalysts were aged separately from the test vehicle using a CARB rapid aging test-A procedure, described previously (4).

A 2 liter 4-cylinder multi-port fuel injected SULEV vehicle was tested in this study, using a 48" chassis dynamometer. The FTP-75 test cycle and measurement protocol was used. In addition, emissions measurements were taken continuously before and after the close-coupled converter. Excellent agreement was found between the three bag data and the integration of modal data from the continuous analyzers over the corresponding time period. Further details about the vehicle, catalyst aging and test setup used in this study can be found previous work (4).

FTP tests were run in triplicate to improve data quality. In most cases, two separate catalyzed samples were tested for each cell density and web thickness combination. This was done to improve statistical value and account for normal variations in sample preparation.

Emissions data were analyzed using the Minitab statistical software package. Regression analyses were performed on each component of the data; bag 1-3, integrated modal data, and subsets of the modal data.

EMISSIONS RESULTS

LIGHT-OFF FACTOR (LOF)

A light-off factor is defined in the Appendix for bare substrates as;

$$LOF = \frac{B \bullet GSA}{M^* \bullet D_h}$$

Where

$B = a \text{ constant}$

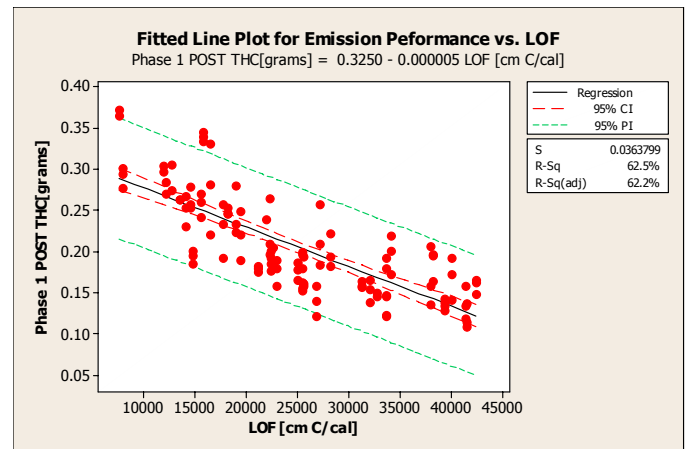
$GSA = \text{geometric surface area, cm}^2/\text{cm}^3$

$M^* = \text{heat capacity, cal/cm}^3 \cdot K$

$D_h = \text{channel hydraulic diameter, cm}$

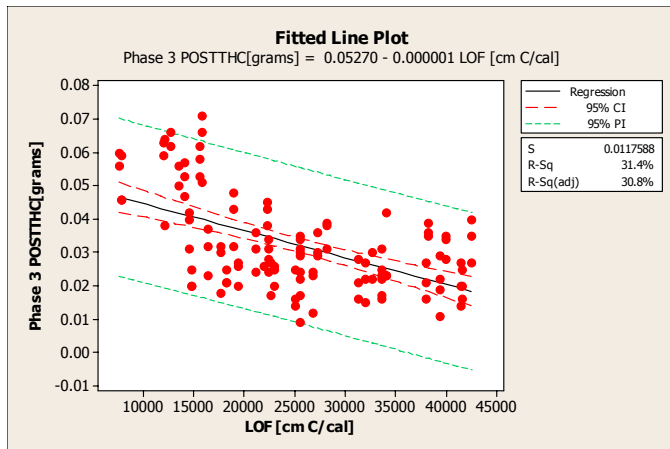
A regression analysis of the integrated modal hydrocarbon emissions over the first phase of the FTP-75 ("Phase-1", 0-505 seconds) versus the bare substrate light off factor is shown in Figure 1, for all substrates and replicate measurements. A reasonably good correlation is apparent, indicating that higher LOF leads to lower hydrocarbon emissions. Since all catalysts in these tests came to operating temperature within the first 60 seconds of the drive cycle, the Phase-1 data includes the true cold-start performance of each substrate combined with performance of the hot catalyst. After the catalysts come to operating temperature, other factors, especially available surface area (GSA in this study) become more dominant contributors to catalyst differentiation, and light-off related thermal mass and heat capacity less so.

Figure 1 Correlation of FTP Phase-1 HC Performance with Bare Substrate LOF



A similar type of regression analysis was performed for phases 2 and 3 of the drive cycle. As expected, the correlation with LOF is not as strong for these later stages of the FTP test since light off performance is not a primary factor after the catalyst becomes fully operational. Data scatter is also a consequence of the relatively low concentration of hydrocarbon in the later stages of the drive cycle. Figure 2 shows the correlation for the 3rd phase of the test, representing bag 3 and the last 505 seconds. The correlation coefficient, R^2 , is poor.

Figure 2 Correlation of FTP Phase-3 HC Performance with Bare Substrate LOF



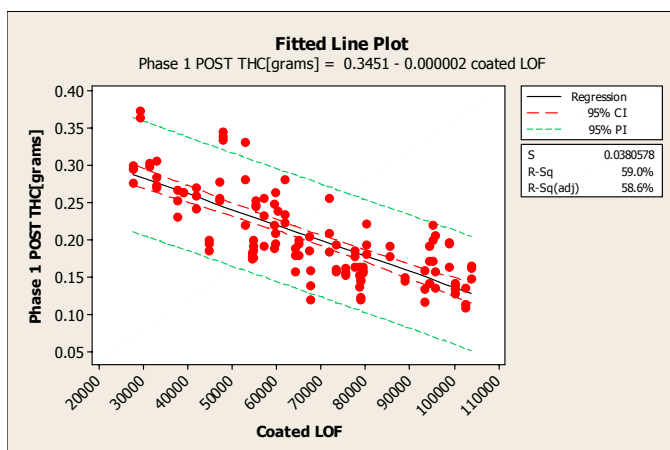
COATED LOF

A coated LOF can also be defined, analogous to bare, by substituting coated geometric properties;

$$LOF_{coated} = \frac{B \cdot GSA_{coated}}{M_{coated}^* \cdot D_h^{coated}}$$

Here we assumed that the heat capacity of the composite washcoat-substrate product is the same as cordierite, which is a reasonable approximation for high alumina content coatings (5). The linear regression of coated LOF versus Phase-1 data is shown in Figure 3. The quality of this correlation is comparable to that for the bare substrate LOF.

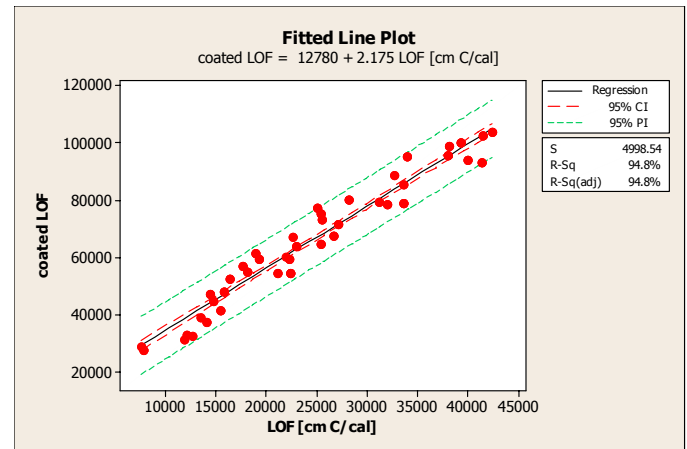
Figure 3 Correlation of FTP Phase-1 HC Performance with Coated Substrate LOF



A comparison of the bare and coated LOF shows that they are highly correlated. This is related to the dominant effect of the bare substrate properties and indicates that either LOF can be used effectively. An improved coated LOF model would need to take into account thermal mass effects of the coating, the catalytic

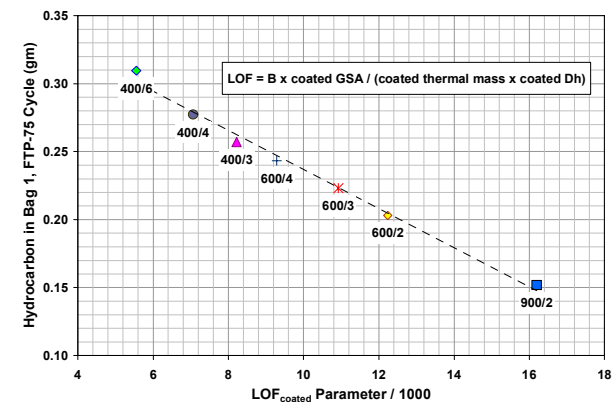
activity of the precious metals, and the exothermic heat release of the oxidation reactions.

Figure 4 Cross-Correlation of Coated and Bare LOF for FTP Phase-1 HC



After averaging the emissions data for each nominal cell density and web thickness product, further correlations can be done to describe the impact of cell geometry on emission performance. Figure 5 shows a good relationship between the FTP-75 Bag 1 hydrocarbon quantity and the LOF_{coated} for various substrate products.

Figure 5 Correlation of FTP Phase-1 HC Performance



CONVERSION EFFICIENCY FACTOR (CEF)

The conversion efficiency factor for bare substrates was defined by Gulati as (1);

$$CEF = \frac{Nu \cdot GSA}{D_h}$$

CEF is similar to the LOF factor with the exception that does not account for thermal mass (M^*) in the equation. This is related to the fact that the heat up of the catalyst is not relevant for steady state conversion efficiency (assumes that the catalyst has reached temperature equilibrium).