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New Technology with Porous Materials: Progress in the Development of the Diesel Vehicle Business

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ABSTRACT

The long time of twenty years has passed since Diesel Particulate Filter (DPF) was proposed before the practical use. The main factors that DPF has been put to practical use in this time, are the same time proposal of the evaluation method of SiC porous materials linked to the performance on the vehicle, and that the nature of thermal shock required for the soot regeneration (combustion of soot) in the DPF is different from the conventional requirement for the rather rapid thermal shock. For the requirements, these include demonstrating utmost the characteristic of SiC's high thermal conductivity, and overcoming the difficulty of thermal expansion of SiC-DPF by dividing the filter into segments binding with the cement of lower Young's modulus, and the innovation of technology around the diesel exhaust system such as Common-Rail system. As the results of these, the cumulative shipments of SiC-DPF have reached about 5 million, and it goes at no claim in the market.

Key words*: *Silicon carbide, Diesel motor vehicle, Exhaust emission, Diesel particulate filter, Catalyst, Porous material

1. Introduction

Active application research has been carried out on ceramics in the hope of developing materials that could be used under severe conditions in which metals and metallic materials originally could not be used. Among the various types of ceramics studied, SiC has been found to be a chemically stable superior material with strong covalent bonds and a very high sublimation temperature of about 2000°C or higher. Since SiC has superior properties, high heat-resistance, corrosion resistance, high strength and resistance to wear. Moreover, since the material has a high modulus of elasticity and the constituent atoms are light and the difference in their atomic weights is small, it is easy for harmonic vibration to occur. As a result, one characteristic merits of SiC material compared to other ceramics is that it has high thermal conductivity.[1] Hence, the material is widely used in many applications that take advantage of these characteristics, including mechanical seals, wear-resistant sliding parts such as bearings, high-temperature structural material, and jigs used in semiconductor manufacturing equipment.[2]

Since diesel engines, as internal combustion engines, are *lean burning and high compression self igniting engines*, they have good thermal efficiency and their fuel consumption is about 30% superior to gasoline engines. Another advantage of diesel engines that is not very well known is the fact that a wide range of fuels can be used in such engines, because the temperature inside the pistons rises to as high as 500°C prior to ignition due to high adiabatic compression. On the other hand, one shortcoming of such engines is the inverse relationship between the amount of particulate matter (PM) and NOx emissions generated during operation, which is a result of the diffusion combustion process used in these engines to burn fuel. In addition, it is very difficult to reduce NOx in a high oxygen atmosphere.

Fig. 1 shows the increasingly stringent regulatory requirements being placed on PM and NOx emissions from automotive diesel engines each year. PM emission levels are to be suppressed to less than 5 mg/km by 2010. This is equivalent to levels for gasoline engine driven vehicles.

If PM could be completely removed from the exhaust gas of diesel engines, then it would be possible to focus only on reducing NOx emissions down to a certain level through engine control based on the trade off relation between PM and NOx emission levels. Then, exhaust gas performance would be equivalent or superior to that of gasoline engines, and it would be possible to enjoy low CO_2 emissions due to high efficiency, which is the greatest advantage of diesel engines.

This paper deals with design and performances of Recrystallized SiC DPF (R-SiC DPF). The design was based on the concept of optimal amount of PM loading. The performances described here include their thermal shock fracture resistance, cyclic fatigue behavior, and filtration efficiency.

2. Materials used

Fig. 2 shows the outline of the making process of SiC

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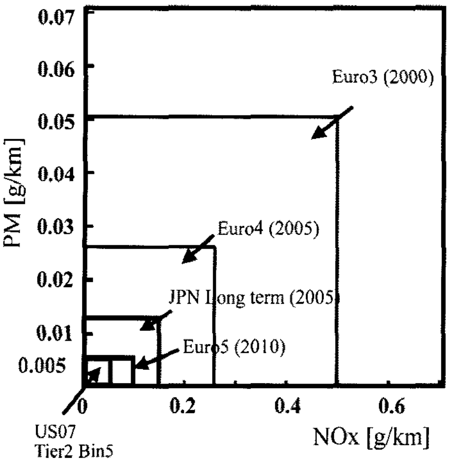


Fig. 1. World wide regulation trend for diesel passenger car emission.

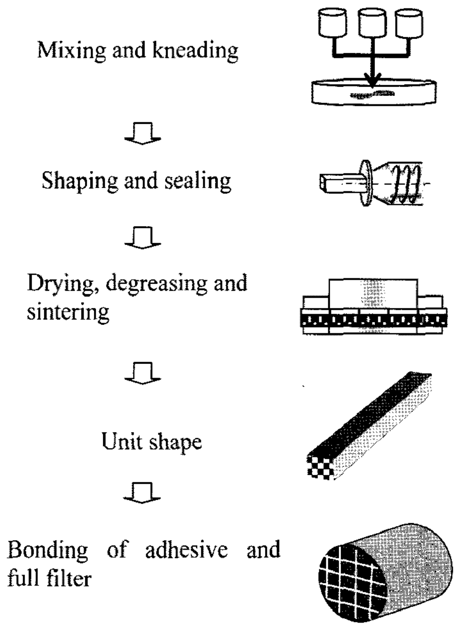


Fig. 2. Outline of forming process of recystallized SiC porous material.

porous materials. Recrystallized SiC can be formed by mixing comparatively coarse SiC powder having uniform grain sizes on the order of 10 to several tens of mm with fine SiC powder which have grain sizes smaller than 1 μm and then heating the resulting mixture to temperatures of more than 2000°C. Then, it is possible to form SiC porous material that has a continuous and evenly distributed pore structure by sintering, grain growth and re-crystallization. Fig. 3 shows the appearance of fine powder being assimilated into course grain during the firing process. Fig. 4 shows the SiC porous material that could be obtained through this process.

Compared with cordierite, which is well known as a high thermal shock resistant material, SiC porous material can be formed as porous body with a very uniform pore size distribution (Fig. 5). Thus, an attempt has been made to take an innovative approach to controlling diesel emissions by

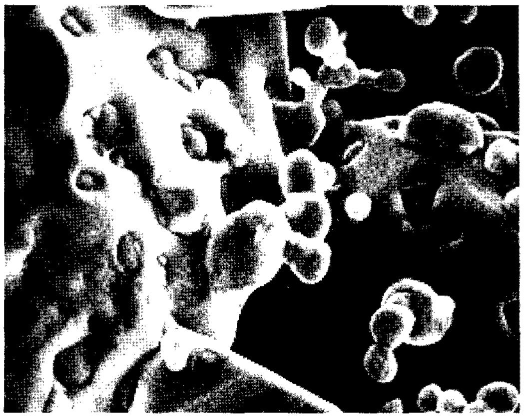


Fig. 3. Fine SiC powder taken into coarse powder in firing process (~1600 deg.C).

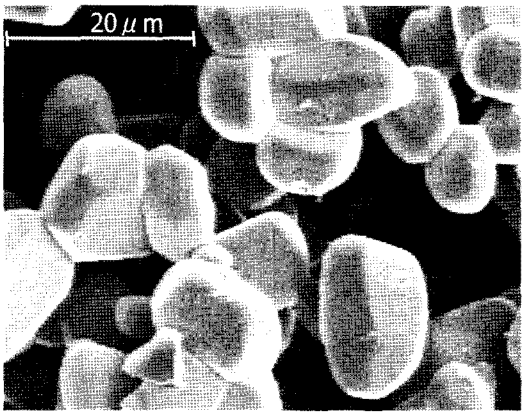


Fig. 4. Structure of recystallized SiC porous material fired at high temperature (>2000°C) pore diameter/porosity = 9 μm/42%.

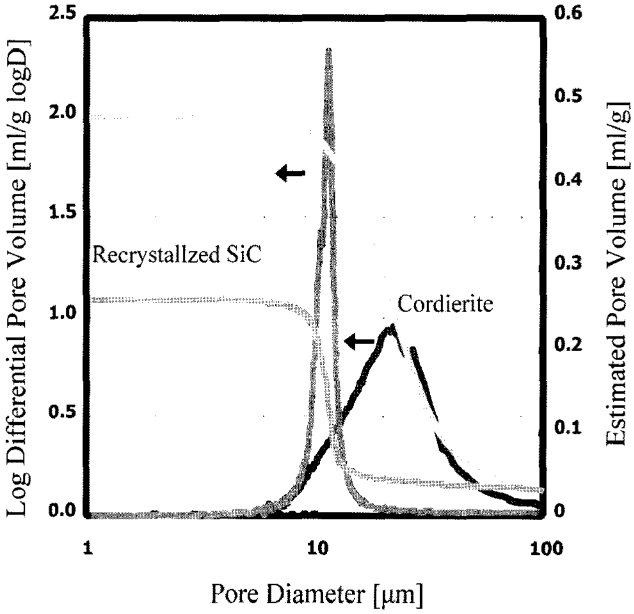


Fig. 5. Comparison of pore structure between recrystallized SiC and cordierite.

taking advantage of the characteristic high thermal conductivity as well as the uniform pore distribution and of SiC porous material.

There are four major types of harmful substances in diesel emissions: CO, HC, PM, and NOx. Since CO and HC are gases, they can be oxidized by a gas phase catalytic reaction. Because PM consists of solid particles, they can be trapped in a filter and then can be removed by oxidation with heating. The method of using the recrystallized SiC porous material for the filter is described below.

3. Optimization of the amount of PM regeneration

As the exhaust gas temperature of diesel is typically about 150°C, this temperature is far too low compared with the minimum combustion temperature of 600°C needed to burn PM. As a result, some type of system is necessary in order to forcibly regenerate the PM. Since it is very difficult to reduce NOx emissions, they are reduced as much as possible through engine management known as EGR (Exhaust Gas Recirculation), while emissions of PM are generally controlled through the use of a diesel particulate filter (DPF). This is the approach most commonly used to reduce and control such emissions.

3.1. Calculation Procedure

Many requirements need to be suitably addressed in an effective DPF system including fuel consumption loss, purification capability of catalyst, the dimensions of the installation, and filter capability, amongst others. In order to satisfy these requirements, the various specifications for the DPF need to be optimized. Although, some methods have been proposed to optimize the design parameters of a DPF, these are not sufficient because they often go into an endless loop of trying to find the most optimal balance of the combined parameters under the operating conditions desired. In this study, a DPF optimization method has been developed that does not fall into an endless cyclic loop of continual readjustment. This is done by defining the optimal amount of PM to be regenerated at the beginning of the operation.

The optimization method proposed here is based on the concept of minimizing energy loss caused by the DPF system installed in the vehicle. The optimal PM loading capacity is equivalent to the regeneration mileage of the vehicle. In other words, this is a question what is the right timing for regeneration after a vehicle runs a certain mileage.[3] Thus, if the requirements for the DPF are replaced with this optimal regeneration mileage, this would equivalent to asking how many g/l of PM regeneration would be able to minimize the energy loss of the DPF system.

In the DPF system, there is a significant gap between PM regeneration temperature and the actual exhaust gas temperature of a vehicle running on the road. Therefore, PM is trapped in the DPF system, and an oxidization process is then followed by the forced regeneration described (Fig. 6).

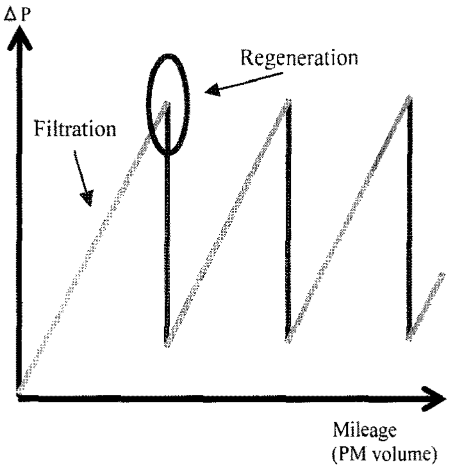
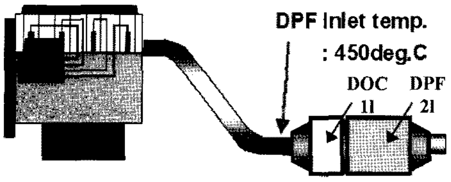


Fig. 6. *Filtration-regeneration cycle on vehicle DPF system.*

In this trapping - regeneration process, two types of energy loss occur. One is caused by DPF pressure loss. This results when the DPF system experiences an increase in pressure loss due to the resistance which is generated when exhaust gas passes through the PM layer that accumulates once the PM are trapped. Energy is lost in accordance with this increase in pressure loss. In short, the longer the vehicle runs without PM regeneration, the greater the loss. The other type of energy loss is caused by the forced regeneration of the DPF system. Forced regeneration makes necessary the amount of energy to raise the temperature from the temperature of the exhaust gas by post-injection to the temperature that would make PM regeneration possible. The greater the distance the vehicle runs without undergoing PM regeneration, the smaller the amount of energy required for forced regeneration becomes, as regeneration occurs less frequently. Consequently, there is an optimal value for the PM regeneration volume which is dependant on the relationship between the energy loss caused by DPF pressure loss and the energy loss caused by forced regeneration. Thus, since a major characteristic of diesel engines is their superior energy efficiency, minimizing energy loss generated by the installation of DPF is one of the most important requirements for a diesel engine.

3.2. Results and Discussion

The Fig. 7 shows a model of the DPF system installed on the vehicle which is used for the calculations carried out as part of this study. The normal temperature of exhaust gas is approximately 200°C, but it can increase to as high as 450°C at the entrance of the DPF system by post-injection when the signal for forced regeneration is input into the system.[3,4] In this state, hydrocarbons (HC) and carbon monoxide (CO) in the exhaust gas are oxidized to heat by the DOC (Diesel Oxidation Catalyst) installed before the DPF. Since the accumulated PM burning temperature in the DPF is about 600°C, the amount of energy loss can be calculated from the post-injection amount of energy required to burn the PM. An example of the calculation results is shown in Fig. 8. As



Exhaust gas ave. temp.:0~200deg.C
Exhaust gas temp. by forced reg.:~400deg.C
PM reg. temp.:~600deg.C
Temp.gap:~150deg.C

Fig. 7. Calculation condition of optimal PM load for regeneration on vehicle.

the amount of regenerated PM increases, the amount of fuel consumption caused by pressure loss increases, but the amount of fuel consumption due to post-injection decreases. It is clear from these results that the total fuel consumption is minimized at 10 g/l.

The following items could be clarified based on the calculation results obtained:

(1) The optimal PM loading capacity does not depend on the system.
(2) The optimal PM loading capacity does not depend on the specific gravity, that is, the porosity of the substrate.
(3) The optimal PM loading capacity strongly depends only on the temperature gap.

The fact that the optimal PM loading capacity does not depend on the porosity of the substrate as indicated in (2) above is the reason why DPF can be optimized uniquely. In other words, if the porosity is raised in order to decrease the amount of pressure loss, the amount of fuel consumption due to pressure loss decreases, while at the same time, fuel loss due to post-injection decreases because heat capacity becomes smaller. As a result, the optimal PM loading capacity does not change. This result is a very important piece of information when optimizing the DPF system, because the optimal PM loading capacity is determined independently from the filter specifications.

4. Regeneration and thermal shock resistance of the recrystalized SiC-DPF

4.1. Experimental Procedure

Because the regeneration of PM accompanies the combustion heat, it becomes thermal shock. As the regeneration is repeated, DPF should endure this thermal shock for a long term (10^3 times).

In general, the following equation is used as an index to evaluate the thermal shock resistance of ceramic materials.

$$R=\frac{\sigma(1-\nu)}{\alpha E} \tag{1}$$

where R is the first thermal shock fracture resistance parameter, ν is the Poisson's ratio, α is the coefficient of thermal expansion, E is the Young's modulus. This first thermal shock fracture resistance parameter does not include thermal conductivity, and for the rest part, as the degree of strength becomes higher, or as Young's modulus or the coefficient of thermal expansion become smaller, the value produced becomes greater. The submersion method is used as a common method of evaluating fracture resistance to thermal shock, as shown in Fig. 9. As the heat is quickly removed from the surface of a ceramic material when the material is submersed in cold water, the material will begin to crack due to the differences in temperature that arise between the surface and the interior of the material. Therefore, increased high thermal conductivity does not contribute to a solution to this problem. Rather, materials with superior values of low thermal expansion such as oxides are indicated. However, PM regeneration is not a phenomenon that occurs in a very short time. Regeneration is a phenomenon that takes a relatively long time to complete, such as two to three minutes. In this case, it is more suitable to use the following second thermal shock fracture resistance parameter, R', as shown in Eq. 2.

$$R'=\frac{\sigma(1-\nu)\kappa}{\alpha E} \tag{2}$$

where κ is the thermal conductivity. The soot mass limit

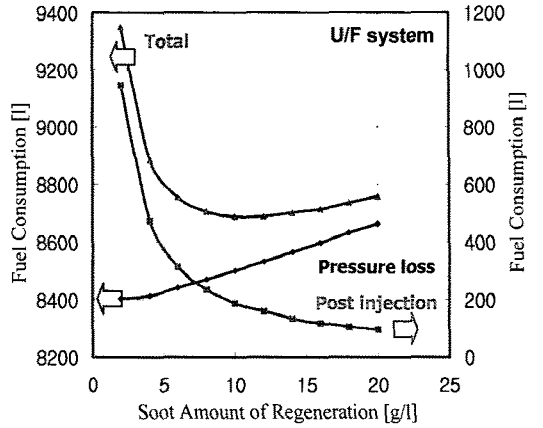


Fig. 8. Calculated total fuel consumption indicates optimal PM load for regeneration. (Optimal PM load = 10 g/l)

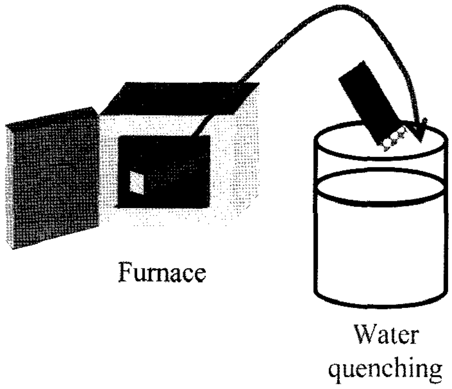


Fig. 9. Water quenching methodology for thermal shock resistance as usual.

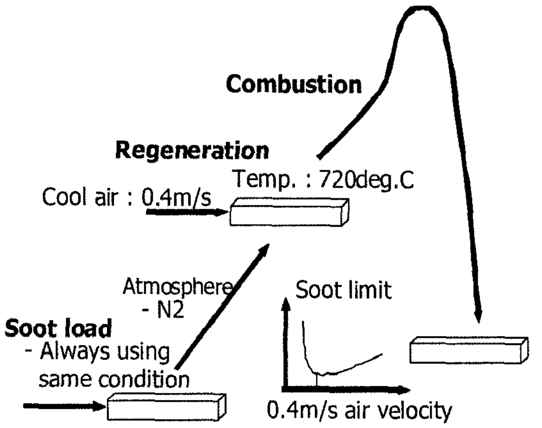


Fig. 10. Soot mass limit methodology for thermal shock resistance on vehicle DPF system. *Printed from SAE paper No* 2000-01-0185

test is proposed as a suitable means of evaluating second degree thermal shock fracture resistance values, as shown in Fig. 10.[5] The procedure may be summarized as follows.

(1) Trap a given amount of PM in the DPF segment of the engine before proceeding.
(2) Raise the temperature up to 720°C in an N_2 inert atmosphere.
(3) Introduce air at ambient temperature (oxygen concentration 21%) into the DPF system at a specific flow rate and start burning the PM.
(4) Maintain the air flow for about twenty minutes until the completion of burning.
(5) Check if any cracks are observable on the segment.
(6) Repeat the procedure until the limit value of the amount of PM with cracking observed and PM amount without cracking observed is obtained.

This regeneration limit test procedure simulates the most severe regeneration conditions that can possibly occur in a motor vehicle. These conditions can occur when the vehicle climbs to the top of a hill and runs down the hill after the PM has been trapped in the DPF installed on the vehicle. In other words, the PM are introduced into the DPF under conditions in which the concentration of oxygen is very low, then the temperature of the DPF rises to near 700°C, and the oxygen at a concentration close to that of the air is introduced at normal temperature. If a DPF installed on a vehicle can survive this severest regeneration evaluation test, the DPF can be expected to have a long distance mileage reliability of more than 240,000 km.

4.2. Results

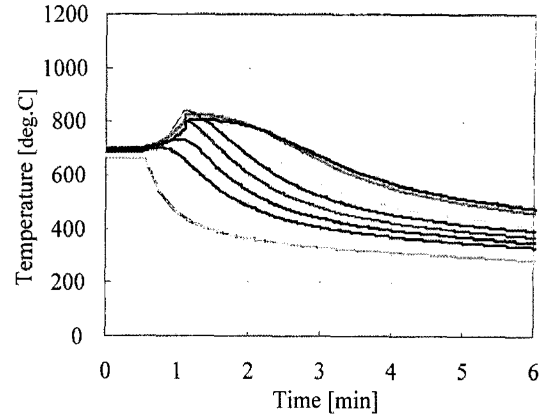
The temperature history during the regeneration limit test using 150 mm segments for R-SiC is shown in Fig. 11. Fig. 12 shows the temperature history for cordierite. The results show that there is a 150°C difference in the maximum temperature.

This means the difference is double in terms of the temperature gradient even though the same amount of PM is present, and a greater thermal load is observed in the case of cordierite. Fig. 13 shows the limit values obtained between the amount of PM causing observable cracks and the amount of PM that does not cause any cracks after tests with arbitrary amounts of PM accumulated on the segment. Eq. 3 and 4 show the chemical and rate equation of oxidation for solid carbon, respectively.

$$C\,(s) + O_2\,(g) \rightarrow CO_2\,(g) \tag{3}$$

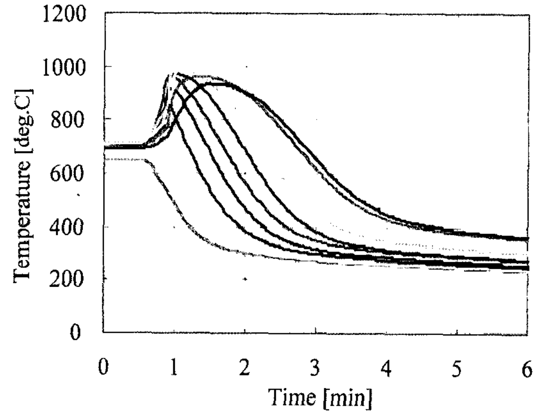
$$k = A\,[C(s)]\,P[O_2]\,\exp\,(-E_A/R_gT) \tag{4}$$

where k is the rate constant, A is the frequency factor, $[C(s)]$ is the carbon concentration, $P[O_2]$ is the oxygen partial pressure, E_A is the activation energy, R_g is the gas constant, and T is temperature. It is helpful to consider the results using the rate equation. The horizontal axis of Fig. 13 indicates



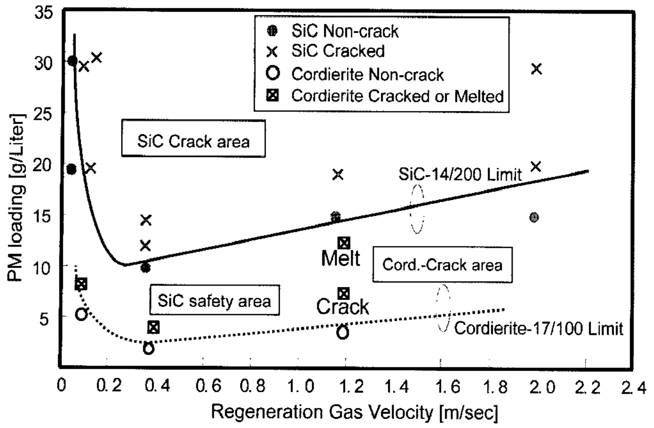
Soot loading : 8.1g/l
Max Temperature : 861 deg.C
Max Temperature gradient : 58 deg.C
Regeneration efficiency : 65%
Thermal conductivity : K=55w/m-k

Fig. 11. Temperature history of R-SiC DPF on soot mass limit test.



Soot loading : 8.0g/l
Max Temperature : 996 deg.C
Max Temperature gradient : 125 deg.C
Regeneration efficiency : 78%
Thermal conductivity : K=0.6w/m-k

Fig. 12. Temperature history of Cordierite DPF on soot mass limit test.



Filter size:34×34×150mm, O_2 Concentration:21%
CeO_2 concentration 0ppm

Fig. 13. Soot mass limit results. *Printed from SAE paper No* 2000-01-0185

the air flow rate of the section. The air flow rate of the section is calculated simply by dividing the amount of air passing through the section by the area. For example, the air flow rate of the section during idling will be around 1.0 m/s due to the relationship between the amount of air passing through the motor and the size of the filter. If the amount of air flow is less than 0.4 m/s, the regeneration limit becomes extremely high when the amount of air flow is smaller. This is explained by the amount of oxygen supply controls the rate in Eq. 4. If the amount of air flow is greater than 0.4 m/s and the air flow rate is increased, the regeneration limit gradually increases because the filter temperature is cooled down by the air flow, and the reaction rate decreases. From this result, it is clear that the minimum value is taken when the air flow speed at the section is 0.4 m/s, so the regeneration limit is defined by the amount of PM which causes cracking at this air flow rate. The crack propagation speed of R-SiC is very fast, as described below, and it is possible to observe the cracking visually.

It is clear from the test results shown in Fig. 13 that the regeneration limit of R-SiC is two to three times greater than the limit for cordierite. It is also clear that the optimal regeneration amount of 10 g/l, derived earlier, can be regenerated safely. Furthermore, one quite distinctive characteristic is that only cracks can be observed in the fracture mode around the optimal PM regeneration amount. In addition, no drastic oxidation or melting was observed. From all these results, it was concluded that it is possible to have reliability if cracking is adequately controlled.

4.3. Discussion

Table 1 shows a comparison between the first and second thermal shock fracture resistance parameters of cordierite and SiC, which are both typical heat resistant engineering ceramics. As can be seen from the results, the ranking is reversed in terms of the first and second parameter. Thus, R-SiC exceeds Cordierite in terms of the second thermal shock fracture resistance parameter because of the superior thermal conductivity of this material.

Table 1. First and Secondary Thermal Shock Resistance for R-SiC and Cordierite

Thermal shock resistance	R-SiC	Cordierite
First: *R*(*K*)	169	1153
Secondary: *R'*(W/m)	3634	369

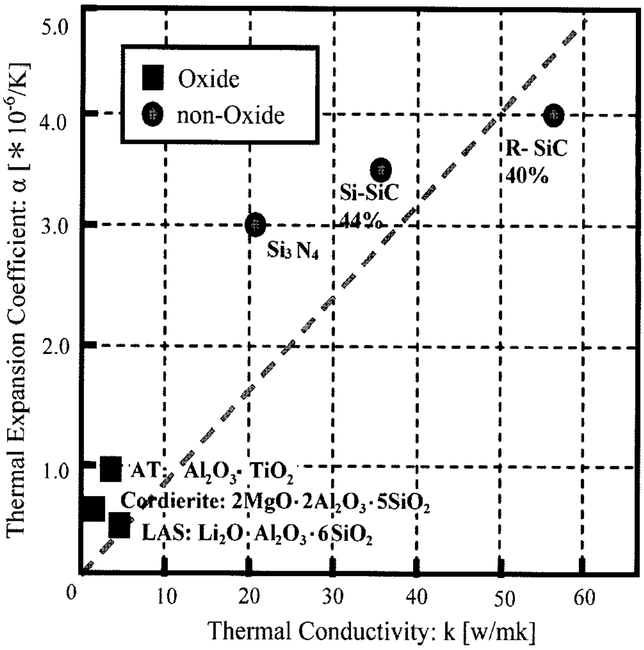


Fig. 14. Relationship b/w thermal conductivity and thermal expansion coefficient on engineering ceramics for high temp use.

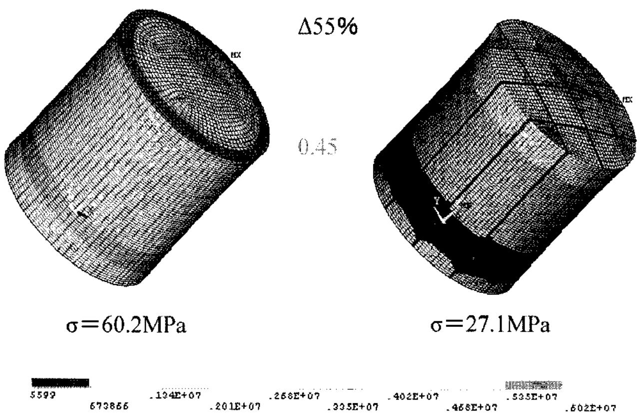


Fig. 15. Von-Mieses stress reduction effect by segmented structure with binding cement on FEM analysis.

As a result, it is believed that the materials used for the DPF should be selected based on the duration of loading caused by thermal shock. Fig. 14 shows the relationship between thermal conductivity and the coefficient of thermal expansion for typical engineering ceramics. From the previous discussion, the materials that have superior thermal conductivity and a smaller coefficient of thermal expansion are required as DPF material. As these two characters have

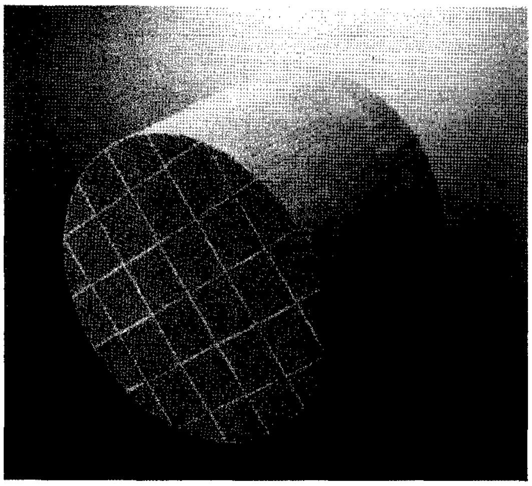


Fig. 16. SiC-DPF.

positive correlation, there is no such material satisfying both characters. Therefore, a segment structure was selected for DPF that could bring about the same effect as reducing the thermal expansion coefficient.[6] The stress relaxation effect of the segment structure is shown in Fig. 15. FEM analysis shows that Von Mises stress can be reduced by as much as 55%. Fig. 16 shows a SiC-DFP designed using a segmented structure.

5. Cyclic fatigue behavior

5.1. Experimental Procedure

Based on the results of the preceding section, it was found that the thermal shock resistance of R-SiC DPF satisfied the optimal amount of PM regeneration in the first time. However, in a motor vehicle, the thermal stress resulting from the regeneration repeatedly puts a load on the filter. Consequently, an assessment was made for the tolerance of the filter against the resulting cyclic stress. The test method used is shown in Fig. 17. The sufficiently strict condition was used in the test that is the test temperature was set at 900°C. The test was carried out by assigning a sine wave to the stress load and adding cyclic stress with a min/max amplitude = 0.1.

5.2. Results

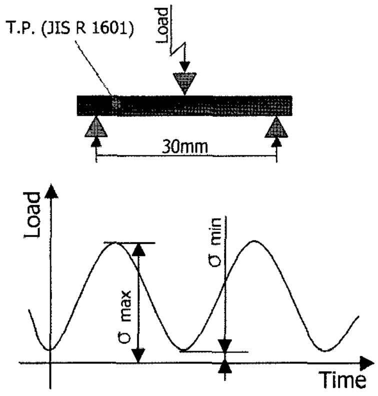
Fig. 18 shows the test results obtained at 900°C. The cycle was repeated 10^3 times giving due consideration to the number of times that regeneration actually occurs in motor vehicles. Under these conditions, the degree of fatigue was found to be quite small at 2.2%. The level of fatigue for cordierite, which is a commonly used engineering oxide ceramic, showed a fatigue level of about 15% after repetition of 10^3 times at normal ambient temperature.[7]

5.3. Discussion

It is well known that cracks will grow in brittle solids such as glass and ceramics at stresses that are lower than the threshold value at which unstable fracturing occurs. This phenomenon is described in terms of the relationship between crack growth speed and the stress intensity factor. Crack growth speed, V, is expressed as follows.

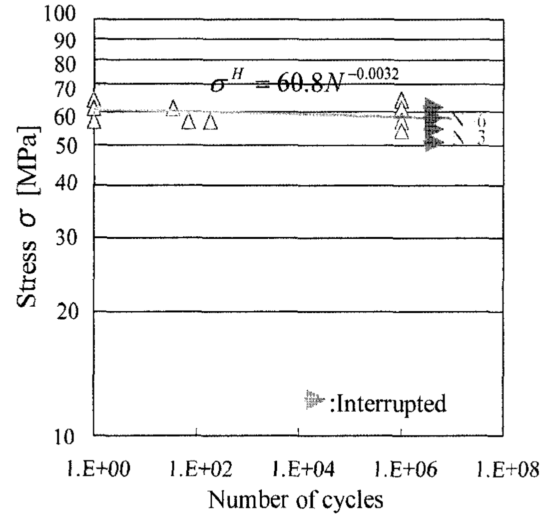
$$V = da/dt = AK_I^n = AY^n\sigma^n a^{n/2} \tag{5}$$

where a is the crack size, t is time, A is constant, K_I is the stress intensity factor, Y is the shape factor, σ is the stress, and n is referred to as a crack parameter or a fatigue parameter. The relationship with the degree of fatigue evaluated earlier is expressed as the slope of 1/n.[8] In other words, it can be said that cracks with a high growth speed conversely do not fatigue. Further, the reverse can also be said to be true, in that no material exists in which the rate of crack growth is small and there is no fatigue. In the case of SiC, n = 80, which is very large. It can be said that SiC is a material very easy to use because there is no fatigue if it is



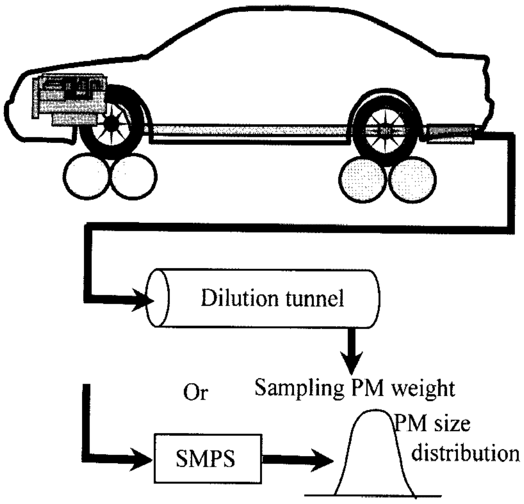
Temp.: 900 deg.C
Atmosphere : air
Frequency : 20Hz
Stress ration : σ min/ σ max=0.1

Fig. 17. S/N fatigue test specification.



Fatigue rate:2.2% at 10^3

Fig. 18. S/N fatigue test result at 900 deg.C. *Printed from SAE paper No* 2000-01-0185



SMPS: Scanning Mobility Particulate Sizer

Fig. 19. PM emission measurement on vehicle roller bench.

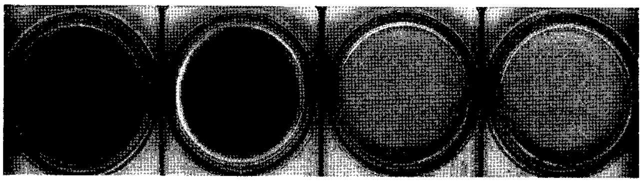
used at a design stress that is slightly less than the level of stress at which crack initiation can begin to occur. From this analysis it was also found that R-SiC is a material that is useful if the way of a crack control could be known. Thus the life proof test of R-SiC-DPF became in hand by the introduction of the concept and methodology of Soot Mass Limit test stated in the previous section.

6. Filtration efficiency

6.1. Experimental Procedure

Research was conducted into the effect of reducing PM by installing an R-SiC-DPF on a diesel motor vehicle.[3] Fig. 19 shows the experimental procedure used in this study. A diesel motor vehicle was placed on a piece of rolling equipment called a roller bench, which made it possible to run the vehicle at the same position. The vehicle was actually run in the MVEG cycle European mode of operation. The amount of PM emitted from the vehicle was then measured using the gravimetric method which utilizes a dilution tunnel and Scanning Mobility Particulate Sizer (SMPS).

In the gravimetric method, the exhaust gas is diluted in a large tunnel called a dilution tunnel, which has a length that is approximately two to three times longer than a motor vehicle. The diluted exhaust gas is then returned to a standard temperature of 25°C at standard atmospheric pressure. Sampling is done using the diluted exhaust gas and the weight of the accumulated PM trapped in the filter is measured. This is the only PM measuring method used as the standard for determining compliance with statutory and regulatory requirements. In the SMPS method, the PM in the exhaust gas is electrified and passed by an electrically charged rod, and classified by their inertia since the PM has mass. The SMPS method makes it possible to measure the number, concentration and weight of PM within a specified range of PM particles in real time, and is a useful method for considering the filter mechanism.



605-DK5	605-HDi	605-HDi+DPF	Air Dilution
Part	**Part**	**Part**	**Part**
0,1 g/km	**0,035 g/km**	**0,004 g/km**	**0,004 g/km**
(IDI)	(DI)	(DI+DPF)	

Fig. 20. Particulate matter emission in mass (MVEG cycle), refer to.[3] *Printed from SAE paper No* 2000-01-0473

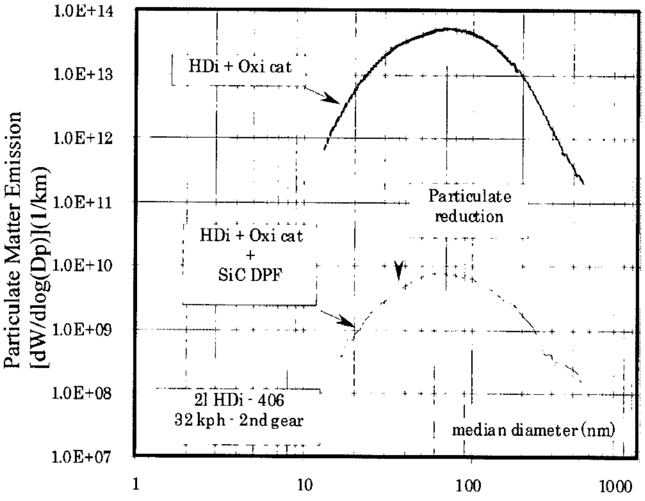


Fig. 21. SiC-DPF reduction of particulate matter on 2LHDi on PSA 406 vehicle (32 kph), refer to.[3] *Printed from SAE paper No* 2000-01-0473

6.2. Results

Fig. 20 shows the results of measurements obtained using the gravimetric method and a photograph of the PM actually accumulated on a filter paper. As can be seen in the figure, if the engine is switched from being an indirect injection (IDI) engine to being a direct injection (DI) engine, the amount of PM emissions could be drastically reduced. Moreover, if an R-SiC-DPF is installed on the engine exhaust pipe, it becomes possible to suppress the amount of PM emitted to revolutionary low levels, because the level of PM emission is decreased to 2 to 4 mg/km which is equivalent to the level of dilution in air only.

The decreasing effect of the total number of particles of PM measured using the SMPS method is shown in Fig. 21. The amount of PM emissions is reduced by three to four orders of magnitude in all ranges from 10 nm to 1000 nm. It is clear that the efficiency of filtration is at a level of 99.98 to 99.99 percent. In addition, using SMPS, it was not possible to differentiate PM particles at the down-stream of SiC-DPF from particles in the air (Fig. 22).

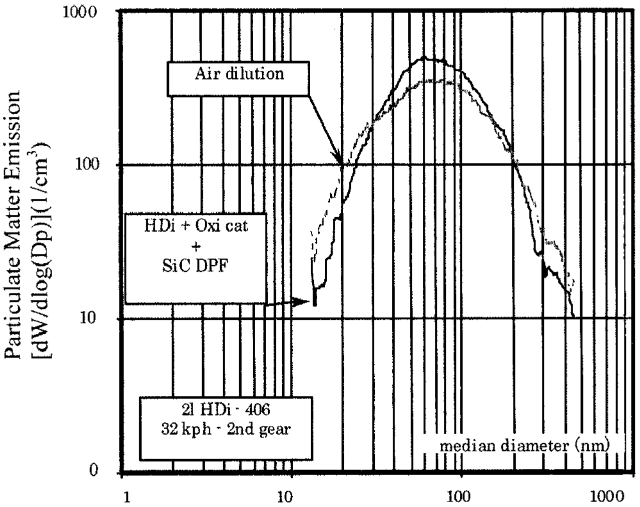


Fig. 22. Comparison of SiC-DPF particulate matter emission with air distribution on PSA406 vehicle 2LHDi (32kph), refer to.[3] *Printed from SAE paper No 2000-01-0473*

6.3. Discussion

According to Opris,[9] there are three types of filtration mechanisms that can be used to filter PM as follows:

(1) inertial impaction,
(2) interception effect, and
(3) adsorption by Brownian motion.

The efficiency of filtration becomes greater in cases (1) and (2) above as the size of the particle diameters of the PM being filtered becomes larger. On the other hand, in the case of filtration mechanism (3), there is an opposite effect in which the efficiency of filtration becomes greater as the diameter of the PM particles becomes smaller. Therefore, it is said that trapping efficiency is worst for the middle range of PM particle diameter size. From the results of this experiment, it was observed that PM leakage is distinctive at a range of around 100 nm, especially for DPFs with higher pore diameter and higher porosity. Thus, a special characteristic of honeycomb type R-SiC-DPFs is that such filters can have a filtering efficiency rate that is especially effective for trapping nanoparticles.

7. Conclusion

1. A re-crystallized porous SiC material was obtained by mixing a coarse powder and a fine powder of SiC at a fixed rate and firing the mixture at a high temperature of 2000°C or more. The material obtained has a uniform pore diameter distribution compared with other materials, and is suitable as a DPF material.

2. The optimum PM amount for the regeneration was defined based on the concept of minimizing the energy loss caused by installing the DPF on the vehicle. The optimal PM amount of loading is the measure of the optimum regeneration distance from the view of vehicle side. By this definition one can optimize uniquely the specifications of DPF system.

3. The heat of soot combustion upon regeneration of PM induces thermal shock within a filter. We devised a method to quantify the thermal shock under the severest conditions in diesel engine simulations. This method made it possible to estimate the critical amount of PM loading (SML). The SML of R-SiC-DPF can afford to generate the optimal PM amount.

4. The thermal shock induced by PM regeneration takes place repeatedly at a certain interval as a vehicle travels. According to fatigue tests carried out on the re-crystallized porous SiC material at 900°C, the degree of fatigue was 2.2% at 10^3 times. This remarkably small degree of fatigue is characteristic of the re-crystallized SiC-DPF. DPF made with other material have never approached this value. If the critical stress (critical amount of PM regeneration) can be known, the re-crystallized SiC-DPF qualifies as a material that's very easy to use.

5. When diesel exhaust gases are passed through the DPF, PM is collected by filtration. We examined the extent of PM collection and found that the filtration efficiency was around 99.99% to 99.98%. The number of particles contained in the exhaust gas after passing through the re-crystallized SiC-DPF was nearly the same as that in the air.

List of notation

A : Frequency factor
a : Crack size
A : Constant
E : Young's modulus
k : Rate constant
K_I : Stress intensity factor
n : Crack parameter
R : First thermal shock fracture resistance parameter
R' : Second thermal shock fracture resistance parameter
t : Time
V : Crack growth speed
Y : Shape factor

Greek symbols

α : Coefficient of thermal expansion
κ : Thermal conductivity
ν : Poisson's ratio
σ : Stress

Abbreviations

DI : Direct Injection
DPF : Diesel Particulate Filter
IDI : Indirect Injection
MVEG : Motor vehicle Emissions Group (European mode of operation)
PM : Particulate Matter
PSA : Peugeot Sociẻtẻ Anonyme
R-SiC : Recrystallized SiC
SMPS : Scanning Mobility Particulate Sizer

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