

## Development of Nano Diamond Polymer Coating on Piston Skirt for Fuel Efficiency

2011-01-1401

Published  
04/12/2011

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doi:[10.4271/2011-01-1401](https://doi.org/10.4271/2011-01-1401)

### ABSTRACT

Various polymer based coatings are applied on piston skirt to reduce friction loss between the piston skirt and cylinder bore which is one of main factors of energy loss in an automotive engine system. These coatings generally consist of polymer binder (PAI) and solid lubricants (graphite or MoS<sub>2</sub>) for low friction property. On the other hand, the present study found that PTFE as a solid lubricant and nano diamond as hard particles can be used to improve the low friction and wear resistance simultaneously.

In the process of producing coating material, diamond particles pulverized to a nano size tend to agglomerate. To prevent this, silane (silicon coupling agent) treatment was applied. The inorganic functional groups of silane are attached to the nano diamond surface, which keep the diamond particles are apart. In addition, the organic functional group in the silane has properly to combine with polymer like PAI or PTFE in the coating solution which improves the bonding energy between nano diamond and the polymer. To find a coating of optimal properties, nano diamond and silane contents as well as the types of silane are controlled. The properties of coating were tested using Ball-on-Plate tribology test machine. As a result, the coating containing 1wt% of nano diamond and 4wt% of amino functional silane compared to the nano diamond contents showed the lowest friction coefficient and wear rate.

The optimized nano diamond polymer coating was applied on real piston and tested using single cylinder rig test machine. The friction force of the nano diamond polymer coating is 21% lower than graphite coating and 7% lower than MoS<sub>2</sub>

coating. Furthermore, in contrast to the MoS<sub>2</sub> coating, the nano diamond polymer coating showed no wear mark after the test. Using the real engine test, the nano diamond polymer coating showed 1.8% decrease in friction force measured as FMEP compared to the MoS<sub>2</sub> coating which is on mass production and nano diamond polymer coating showed superior durability according to the full load and full speed engine test.

### INTRODUCTION

The main issue in the development of automobiles is to improve the fuel efficiency. Due to the limitation of fuel reserves and the trend of restrictions on vehicle exhaust emissions, car makers are being pressed into developing economical vehicles with lower fuel consumption. Only 12% of the energy generated from fuel consumption is used to move the vehicle. The rest of energy disappears as cooling, friction loss, etc. The amount of energy that disappears as friction loss is 15% of generated energy and 10% reduction of this friction loss lead to improve fuel efficiency more than 1.5%.<sup>1)</sup> The main cause of friction loss is the friction between the piston and cylinder liner, which comprises approximately 40% of the total friction loss.<sup>2)</sup> Therefore, there are many ongoing studies on decreasing the friction between two components which can finally decrease CO<sub>2</sub> emission, reduce gas consumption and improve the durability. This study is focused on developing composite polymer coating material with improved low friction property and durability compared to existing coating materials.

Recently, most automotive engines use polymer coatings on the piston skirt to reduce friction and prevent seizing.<sup>3)</sup> These polymer coatings are polymer based composite materials, which consist of a polymeric binder and solid lubricants. Usually, a liquid phase coating material is coated on a piston skirt and cured at high temperatures to solidify polymeric binder as thin film. At the same time, the solid lubricants dispersed in the coating film help reduce the friction during a sliding motion. Currently, at HKMC (Hyundai-Kia Motor Company), PAI (poly amideimide) is used as a binder and both graphite and MoS<sub>2</sub> are used as solid lubricants. However, a low frictional polymeric coating that contains PTFE (polytetrafluoroethylene) as a solid lubricant was developed because the price of Mo is unpredictable and PTFE has lower friction property than MoS<sub>2</sub>. The only weakness of a PTFE containing polymeric coating shows insufficient wear properly for piston skirt applications due to its feeble resistance on shear stress. Therefore, nano sized diamond particles treated with silane were added to improve the wear property.

## EXPERIMENTAL DETAILS

### 1. DEVELOPMENT OF COATING MATERIALS

The polymer coating used on piston skirt demands both low friction and wear resistance. The coating material is made of PTFE as a solid lubricant and silane treated nano sized diamond particles which dispersed in PAI solution used as binder. Diamond particles that are used as a filler to improve the wear resistance were produced using the explosive method.<sup>4)</sup> Normal carbon, which is exposed to high temperatures and pressure by TNT explosion in the chamber changes its crystal properly to diamond. These diamond particles are 3~4nm size, but they exist as 2~3 $\mu$ m due to its tendency to agglomerate. To control the particle size, diamond particles dispersed in NMP (n-methyl-2-pyrrolidone) are pulverized to nano size by bead milling using 0.3mm zirconia beads.<sup>5)</sup> These nano diamond particles with hydrophilic surface were combined with silane coupling agent. As a result, the diamond particles were dispersed in solvent without agglomeration. Among the silane used, ATS ( $\gamma$ -Aminopropyl-trimethoxysilane) has another role in strengthening the bonding force between the diamond particle and polymers such as PTFE and PAI. The silane treated nano diamond particles were mixed in PTFE containing solution (DAIKEN, Japan) that included PAI. The developed coating material which contained 1wt% nano diamond and 4wt% silane compare with the contents of nano diamond shows best performance. The tribological properties were tested using Ball-on-Plate friction and wear test.

### 2. DEVELOPMENT OF COATING PROCESS AND ADHESION TEST

Adhesion between the piston surface and coating film is an important factor in the coating properties. To improve adhesion, the bare surface of the piston skirt was etched by alkali ionized water. And then the coating was applied on piston skirt using screen printing method. Finally, coated the pistons were heated at 210°C for 30 minutes to harden the coating. As a result, the nano diamond polymer coating formed on the piston skirt with a thickness of 10 $\pm$ 1 $\mu$ m. The adhesion of coating was checked using a modified cross-cut tape test (modifying ISO 2409). The coating surface was cut into 100 squares, 1  $\times$  1 mm<sup>2</sup> in size, and then this piston was boiled at 85°C and ultra sonic energy was applied for 30 minutes in the bath. After that, a transparent tape with an adhesive force of 48g/mm was applied on cut area and removed from the surface. The area of removed coating becomes the standard for an evaluation of adhesion.

### 3. EVALUATION OF APPLIED COATING

The frictional property of the developed coating was tested using a high frequency friction machine (TE77, PLINT) under the following test conditions: point contact mode, 50N, 3Hz and with oil. To compare the friction torque, a single cylinder test machine was used in the range of 600 ~ 2000 rpm: [Figure 1](#). Also, a motor rig test for a real engine, which is the target for the U2 diesel engine, was performed under following condition: 90°C of oil temperature, 90°C of coolant temperature and speed range from 1000 to 4000 rpm. From this test, the friction torque is measured by FMEP (Friction Mean Effective Pressure) and compared to MoS<sub>2</sub> polymer coating. Finally, a full load and full speed endurance test was performed for 320 hours to ensure the durability of the coating with a 1,600cc gasoline engine.

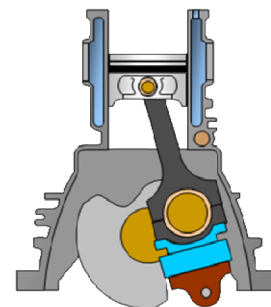


*Figure 1. A schematic diagram of single cylinder test machine*

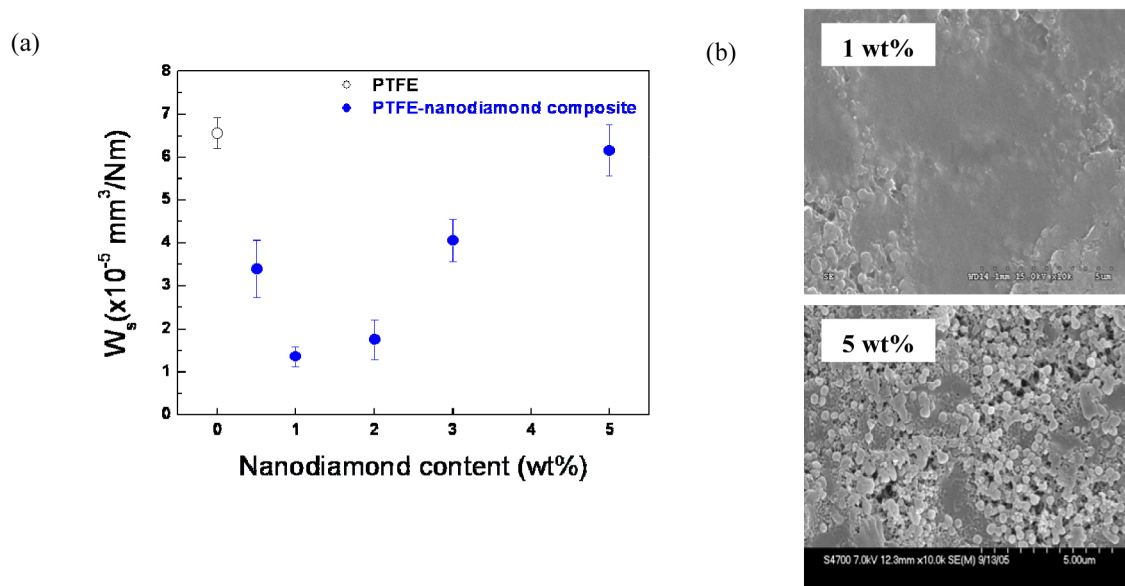


**Figure 2. (a) Wear rate according to the diamond particle contents and (b) SEM images of the coated surface at 1wt% and 5wt %**

## RESULTS AND DISCUSSION

### 1. EFFECTS OF DIAMOND PARTICLES ON THE COATING MATERIAL

Figure 2 shows the variation of wear rate as a function of the content of nano diamond. These results revealed a 10 times of improvement in wear property compared to the pure PTFE coating. The specific wear rate ( $W_s$ ) showed lowest value at 1wt% of diamond particle. However, it showed a drastic increase over 3wt% due to the agglomeration of particles. The agglomeration of nano diamond might contribute to the abrasive action and reducing the reinforcement effect.

Previous studies showed that a decrease in nano diamond sizes did not always improved the tribological properties of a nano diamond filled PTFE coating.<sup>5)</sup> The deterioration effect was observed with approximately 100nm nano diamond particles. The different wear behaviors depending on the size of nano diamond were explained by the competition between the cracking and reinforcing effect. From the results, the optimum particle size range was from 200 to 300nm.

### 2. EFFECTS OF SILANE COUPLING AGENTS

Diamond particles which are pulverized to a nano size have a strong tendency to agglomerate, which leads to worsen the tribological properties due to the enlargement of particle size or local differences in diamond contents (the effects of size and contents of diamond particles are shown in Figure 2). To suppress the agglomeration of diamond particles, silane coupling agent is used. Silane is a chemical agent which

contains organic and inorganic functional group in it. The inorganic functional group in silane tends to combine with the dangling bond at the surface of the diamond particles.<sup>6)</sup> Therefore, silane surrounds the diamond particles which reduce the chance to agglomerate between particles and this is confirmed by a sinking experiment. In addition, the organic functional group of silane combines with the polymer such as PAI and PTFE. This improved the coherence between the diamond particles and polymers in the coating material. Therefore, the wear rate is decreased drastically and the friction coefficient is lowered compared to non-silane treated coating material. There are many kind of silane which is distinguished by the kind of organic functional group. On this investigation, three Types of silane such as GTS( $\gamma$ -Glycidioxypropyl trimethoxysilane), MTS( $\gamma$ -Mercaptopropyl trimethoxysilane), ATS( $\gamma$ -Amino trimethoxysilane) were tested. Among them, the coating material treated with ATS, which contains amino functional group, shows the wear rate and friction coefficient due to the strong coherence between the diamond particles and polymer: Figure 3. This is due to the unshared electron pairs in the N-H bond of amino functional group, which have strong coherence between diamond and polymer that leads to improved wear resistance and reduced friction coefficient: Figure 4.

Theoretically, the coating shows best tribological properties when silane exists at a ratio of 1 wt% compares to the contents of diamond particles.<sup>7)</sup> However, on this investigation, it is revealed that the optimal weight ratio of silane was 4wt% compared to the contents of diamond particles. At the optimum points, the highest error bar due to deviation of surface roughness. This means that the amount of silane sufficient to surround the diamond particles is 4 wt