The Effect of Micro Dimples Formed on Nylon12/Polyamide-Imide Composite Coatings on Friction and Wear Behavior

Kosuke Suzuki1), Akio Hikasa2) and Nobuyuki Suzuki2)*

1) Department of Mechanical Engineering, Shizuoka University, 3-5-1 Johoku, Hamamatsu 432-8561, Japan,
2) Department of Development, SUZUKI MOTOR CORPORATION, 300 Takatsuka, Hamamatsu 432-8611, Japan
Fax: 81-53-478-2683, e-mail: nobsuzuki@hhq.suzuki.co.jp

To improve the surface performance, Nylon12/Polyamide-imide (PAI) composites were coated on aluminum substrates using a printing technique. Dimples were formed on the surface of the coating with sizes corresponding to the grain diameters of the nylon particles. The objective of this study was to investigate the influence of the dimples on the tribological behavior under oil lubrication. The effect of the sliding speed on the friction coefficient was also evaluated. Friction tests were performed using a ball-on-disk tribometer. The results revealed that the incorporation of dimples significantly improves the tribological properties. Particularly, the friction coefficients of the Nylon12/PAI composite coatings were much lower than that of the PAI-only coating at slow sliding speeds. The dimples played an important role in maintaining the oils under mixed lubrication. The friction coefficients of the Nylon12/PAI composite coatings initially decreased with an increase in the additive amount of nylon particles. However, the friction coefficients gradually increased when the volume fractions of Nylon12 exceeded about 3 to 5 vol. %.

Based on tribological behavior, it was found that an optimum amount of nylon particles exists for PAI coatings.

Key words: Friction coefficient, Friction reduction, Surface texturing, Resin coating

1. INTRODUCTION

The improvement of automobile fuel efficiency is a very important aspect of CO₂ reduction. The reduction of friction losses in an engine's sliding parts is one effective means of improving fuel efficiency. The main sliding parts in an engine include the valve, piston, and bearing systems. Among them, it is estimated that piston skirt contact produces about 25% of the engine's total friction loss [1].

In the sliding parts of an engine, the lubrication provided by the protective oil films can easily be compromised at the time of starting and during high-load driving; consequently, scuffing and scoring may occur. Therefore, automakers apply a resin coating made of polyamide-imide (PAI) and a low-friction epoxy to the piston skirt [2]. In addition to its ability to prevent scuffing, scoring, and seizure, this resin coating is heat resistant, wear resistant, oil and petrol resistant, adhesion resistant, and inexpensive.

Streak grooves are commonly incorporated on the piston skirt [3, 4]. By forming grooves, oil is reserved in the grooves, and the lubrication condition between the piston skirt and cylinder bore improves. As a result, even if the piston reciprocates at high speeds, the oil films are maintained, and scuffing of the piston skirt can be prevented. Research has been presented that improves the sliding properties by designing the surface such that it forms oil reserves [5-11]. Materials such as processable hard metals and ceramics were used in those research studies since it was necessary to process the surfaces by shot peening or laser. On the other hand, it is difficult to process the surface to a micrometer order after applying the resin coating since the resin material used for the piston skirt is soft and weak against heat.

The authors have investigated the surface modification of PAI coatings by particle addition. We have selected the nylon particles as the material that has a low friction coefficient, excellent chemical stability, and high potential for surface modification. In forming the dimples, we found that the dimple size corresponds to the grain diameter of the nylon particles. The authors expect that the dimples affect the tribological properties of the coating in a positive way. The purpose of this paper, therefore, is to clarify the role of the dimples under oil lubrication. Furthermore, based on tribological behavior, we will prove that an optimum amount of nylon particles exists for PAI coatings.
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2. EXPERIMENT

2.1 Coating procedure

Nylon particles were used as additives in the composite coatings. Ny5 and Ny10 powder (Ny12 powder of 5 and 10 μm average grain diameters, respectively) as well as PAI-only and Nylon/PAI composites are available from Dow Corning Toray Co., Ltd. The volume fractions of the Nylon12 powders ranged from 0 to 16.7%. The PAI-only and Nylon/PAI coatings were deposited using the bar coat method. The PAI and Nylon/PAI varnishes were diluted using a solvent (N-methylpyrrolidone). To form a homogenous slurry, a planetary mixer (THINKY, ARE-250) was used to mix the composites. The viscosities of the slurries ranged from 1.8 to 2.0 Pa·s.

Aluminum disk substrates were used to represent the automobile engine pistons. The slurries were applied to the surfaces of the disks and coated homogenously with a scraper. After coating, the specimens were immediately heated in an oven. In order to prevent the generation of bubbles in the resin from the rapid heating, the specimens were heated at 80°C for 30 min and then at 120°C for 30 min. Subsequently, the specimens were cured at 180°C for 120 min. The thicknesses of the coatings were about 35 μm.

The surface textures of the Nylon/PAI composite coatings were measured using a scanning electron microscope (SEM, JEOL Ltd., JSM6360A) and an atomic force microscope (AFM, KEYENCE, VN-8010). In addition, analyses of the SEM images were conducted with analysis software (Asahi Kasei Engineering Corporation, Azokun®) to investigate the area ratio of the dimples formed on the coating surfaces. To calculate the area ratio, first, the number of dimples was counted by image analysis. Secondly, this number was multiplied by the dimple area, which equals the average grain diameter of the nylon particles. Finally, the obtained value was divided by the area of the SEM image. The surface roughness Ra (the calculated average roughness) was measured with a surface roughness meter (Mitutoyo Corporation, SJ-301).

2.2 Friction tests

Friction tests were performed using a ball-on-disk tribometer (Shinto Scientific Co., Ltd., TRIBOGEAR, TYPE: 20) with oil lubricants. Fig. 1 shows the schematic of the tribometer. The indenter consists of a ball bearing. During the test, the friction force is measured with a load cell located on the counterbody. The friction coefficients are then obtained by dividing the measured forces by the applied load.

The sliding speed ranged from 0.01 to 1.00 m/s. First, the sliding speed was increased gradually at intervals of 600 s from 0.01 to 1.00 m/s. Then, the sliding speed was decreased from 1.00 to 0.01 m/s. The results obtained over three measurements were then averaged. The oil (SHOWA SHELL SEKIYU K. K., SAE 20) was applied to the sliding surface before the test.

3. RESULTS AND DISCUSSION

3.1 Surface texture

Fig. 2 shows a SEM image of the Nylon/PAI composite coating. A number of dimples were observed on the surface of the coating. The dimple spacing was random, and there was also an area where the dimple spacing was narrow. Although there was variation in the size of the dimples, it generally corresponded to the grain diameters of the nylon particles. It was also found that the depths of the dimples were about 10% of the nylon grain diameters based on an examination of the AFM measurements. It is presumed that the dimple formation occurs due to the difference of the thermal characteristics between the PAI (thermosetting resin) and the nylon (thermoplastic resin).

Table 1 lists the detailed test conditions.

<table>
<thead>
<tr>
<th>Test disk (revolving)</th>
<th>Load (N)</th>
<th>Sliding speed (m/s)</th>
<th>Rotational radius (mm)</th>
<th>Lubricant</th>
<th>Oil tilter (μℓ)</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball (stationary)</td>
<td>5</td>
<td>0.01–1.00</td>
<td>17–20</td>
<td>SAE 20</td>
<td>5</td>
<td>R.T.</td>
</tr>
</tbody>
</table>

Table 1. Tribometer test conditions

![Fig. 2. SEM image of the Ny5/PAI composite coating.](image-url)
Fig. 3 shows the relationship between the additive amount of nylon particles and the area ratio of dimples obtained from SEM image analysis. When the additive amount of nylon particles was 4.7 vol. % or less, the additive amount and the area ratio had a proportional relationship. However, when the additive amount of nylon particles was more than 4.7 vol. %, the area ratio increased at a lower rate than when it was 4.7 vol. % or less. In addition, when the additive amount of nylon particles was more than 4.7 vol. %, a concentration of dimples was observed in the SEM image. Therefore, it is thought that dimples are hard to distribute uniformly when the additive amount of nylon particles exceeds about 4.7 vol. %.

Fig. 4 shows the relationship between the additive amount of nylon particles and the surface roughness (Ra) of the Nylon/PAI composite coating. The additive amount of nylon particles and the Ra of the Nylon/PAI composite coating were in a proportional relationship. In addition, the Ny10/PAI composite coating has a rough surface compared with the Ny5/PAI composite coating.

3.2 Friction coefficient

Fig. 5 shows the sliding speed dependence on the friction coefficients of PAI-only and Nylon/PAI composite coatings under oil lubrication. The friction coefficient of the Ny5/PAI composite coating was lower than that of the PAI-only coating at all sliding speeds, as shown in Fig. 5(a). Except at a sliding speed of 0.01 m/s, the friction coefficient of the 16.7 vol. % Ny10/PAI composite coating was higher than that of the PAI-only coating at all speeds, as shown in Fig. 5(b). The friction coefficients of the PAI-only and Nylon/PAI composite coatings were smallest at a sliding speed of 0.05 or 0.10 m/s. At a sliding speed of 0.05 m/s or less, the friction coefficient of the PAI-only coating changed drastically.

Fig. 5. Friction coefficients of the (a) Ny5/PAI and (b) Ny10/PAI composite coatings as a function of sliding speed under oil lubrication.
although those of the Nylon/PAI composite coatings hardly increased. At a sliding speed of 0.01 m/s, the difference between the friction coefficients of the PAI-only and Nylon/PAI composite coatings was most apparent. When the sliding speed is low, it is supposed that the frequency of solid contact between the coating and the ball increases. Therefore, the cause of the lower friction coefficient for the Nylon/PAI composite coating than for the PAI-only coating at a sliding speed of 0.05 m/s or less is considered to be the dimples, which were observed during the measurement of the surface texture. It is supposed that the oil reserves in the dimples, resulting in improved oil retentivity.

Fig. 6 shows the relationship between the additive amount of nylon particles and the friction coefficient of the Nylon/PAI composite coating at a sliding speed of 0.01 m/s. The friction coefficient of the Nylon/PAI composite coating decreased with an increase in the additive amount of nylon particles until about 3 to 5 vol. %. However, the friction coefficient of the Nylon/PAI composite coating then gradually increased when the volume fraction of the nylon particles exceeded 3 to 5 vol. %. The lowest friction coefficient of the Nylon/PAI composite coatings was one-half that of the PAI-only coating. In addition, when the additive amount of nylon particles was 10 vol. % or less, there was almost no difference in the friction coefficients of the Ny5/PAI and Ny10/PAI composite coatings. However, when the additive amount of nylon particles was 16.7 vol. %, the friction coefficient of the Ny10/PAI composite coating became larger than that of the Ny5/PAI composite coating. From the examination of the surface texture of the Nylon/PAI composite coatings, it was estimated that the difference is dependent on the surface roughness. Therefore, it was found that there is an optimum amount of nylon particles for the PAI coating based on the friction behavior.

4. CONCLUSIONS
Dimples were formed on the surfaces of the Nylon/PAI composite coatings with sizes corresponding to the grain diameters of the nylon particles. From the result of the friction tests using the ball-on-disk tribometer, at low speeds (when solid contact between the coatings and the ball takes place frequently), the Nylon/PAI composite coating showed excellent tribological behavior. The dimples played an important role in maintaining the oil under mixed lubrication. The optimum amount of nylon particles was between 3 and 5 vol. %. The effect of the dimple size was small between the 5 and 10 μm grain diameters, and there was no difference in the friction coefficients at the actual sliding conditions.

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REFERENCE

Fig. 6. Friction coefficients of the Nylon/PAI composite coatings as a function of the additive amount of nylon particles at a sliding speed of 0.01 m/s.