# IMPROVEMENT IN TOOTH SURFACE STRENGTH OF CARBURIZED TRANSMISSION GEARS BY FINE PARTICLE BOMBARDING PROCESS

Masatoshi Yoshizaki
Hino Motors, Ltd., 3-1-1, Hino-dai, Hino-Shi, Tokyo, 191-8660, Japan

*Gear surface fatigue endurance tests were carried out using gears treated with the fine particle bombarding process (denoted hereafter as FPB) under three different peening conditions. Shot peened gears by a conventional impeller-type machine were used as comparison. The results showed that FPB increased the tooth surface strength (pitting resistance) by 1.21 to 1.28 times in Hertzian stress compared to the conventional impeller-type shot peening. Next, the influence of FPB on the tooth surface properties such as residual stress, hardness, roughness, surface texture, etc. were examined. After obtaining the results, the following factors of FPB that influenced tooth surface strength increase were discussed: (a) high residual compressive stress produced below the surface, (b) greatly increased hardness below the surface, (c) excellent conformability of the tooth surface, (d) micro hollows on the tooth surface generated after running. The author pointed out that the latter two were unique factors caused by FPB and contributed much to the improvement of tooth surface strength.*

**Key Words** Fine Particle Bombarding, Gear, Pitting, Spalling, Residual Stress.

## 1. INTRODUCTION

Power transmission gears have been required to increase their load carrying capacity in order to respond to higher power engines, while at the same time reduce in component weight and size. Recently, it has been an important issue to increase the tooth surface strength (pitting resistance) of the gears in developing a new vehicle-transmission with high reliability, because that often determines the gear life.

Shot peening has long been widely used as an economical and effective method for improving the fatigue strength of mechanical components such as transmission gears and suspension springs in the automotive industry. In recent years "hard" shot peening, defined as a higher intensity peening using harder shot media with a higher shot velocity (e.g. Hatano, 1992), has been applied to the components. The hard shot-peening further increases the compressive stress below the worked surface over that produced by conventional shot-peening. Townsend (1992) reported that the 10-percent surface fatigue life of the hard shot-peening gears was 2.15 times that of the conventional shot-peening gears. The author (Yoshizaki, 2000) also reported that hard shot-peening was effective to increase tooth surface strength; however, it was shown in the same report (Yoshizaki, 2000) that hard shot-peening under certain conditions using conventional size of shot particles such as those with a diameter of 0.6 to 0.8 mm decreased the tooth surface strength compared to conventional shot-peening. Even if a higher intensity peening is applied, there is a limit to the effect of the "shot peening" on the tooth surface strength increase.

Fine particle bombarding (denoted as FPB) is a surface modification process that takes fine (20 to 200 μm) and hard (Hv 750 to 1000) particles and impacts them on the metal surface at a high speed (more than 100 m/s), which in principle similar to shot peening. FPB has been already applied in Japan to extend lifetimes of dies and metal cutting tools, and to reduce friction on contact surfaces (e.g. Kagaya, 2002). Recently the application of FPB has become broader because of its superior effects (Ishiwata, 2005); however, its influence on the tooth surface strength of gears has not been clarified. The purpose of this study is to determine quantitatively the effect of FPB on the tooth surface strength of carburized gears, and to clarify the factors of FPB that influence tooth surface strength.

## 2. EXPERIMENTAL

### 2.1 Test Gears

The specifications of the test gears are given in Table 1. Tip relief and crowning were properly applied to the tooth flank to obtain appropriate tooth surface contact. Each test gear was finished equally and with high accuracy by grinding in order to exclude the influence of tooth flank deviation on the tooth surface strength (Yoshizaki, 2001). The abnormal surface layers (Yoshizaki, 1999) generated by the gas carburizing process on the tooth surfaces were removed by grinding.

Table 1 Dimensions of test gears

| | Driver | Driven |
|---|---|---|
| Normal module (mm) | 3.5 | |
| Normal pressure angle (deg.) | 22.5 | |
| Number of teeth | 34 | 31 |
| Helix angle (deg.) | 23 | |
| Addendum modification coefficient | −0.0174 | −0.1595 |
| Center distance (mm) | 123 | |
| Face width (mm) | 50 | 27 |
| Tooth surface finishing | Grinding after carburizing | |
| Material | SCM420H (JIS) | |
| Heat treatment | Gas carburizing | |
| Surface hardness before peening (at a depth of 0.1 mm, Hv) | 793 – 808 | |
| Effective case depth (mm) | 1.1 – 1.2 | |
| Accuracy | Grade 3 –4 (ISO) | |

### 2.2 Conditions of the Fine Particle Bombarding Process

Three different conditions of FPB, as shown in Table 2, were used in this study. The arc heights of FPB-a, FPB-b and FPB-c were different, which were obtained by changing the diameter of the particles and the air pressure of the injection. Conventional impeller-type shot-peening（denoted hereafter as SHP-n）was also used for comparison with FPB. The conditions of the SHP-n were an arc height of 0.35 mmA, a shot diameter of 0.8 mm, a shot hardness of Hv 560, and a coverage of 200 %. The peening intensity of the SHP-n is lower than that of the hard shot-peening mentioned above, which has long been widely used for transmission gears as a method for improving bending fatigue strength. Both the driver and the driven gears were treated under the same peening conditions after finish grinding.

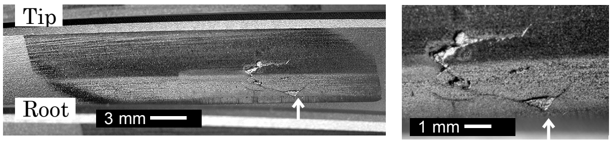
Table 2 Conditions of fine particle bombarding process

| Code | Shot particle | | | Peening condition | | |
|---|---|---|---|---|---|---|
| | Diameter | Material | Hardness | Arc Height | Coverage | Air press. |
| FPB a | 80-130 μm | SKH (JIS) | Hv 750-800 | 0.41 mmN | 200 % | 0.4-0.6 MPa |
| FPB b | | | | 0.33 mmN | | |
| FPB c | | | | 0.24 mmN | | |

### 2.3 Test Condition and Procedure

The test apparatus used in this study was a power-circulating type gear testing machine. A gear wheel was installed as the driver, and the tests were made at a rotational speed of 1500 rpm for the pinion. The lubricating oil was a mineral gear oil（80W-90, GL 5）that is used for truck transmissions. The oil was supplied to the engaging side of the test gear pair at a rate of 1.2 l/min, and the temperature of oil supplied was controlled at 90 ± 2 °C.

FPB c Magnified view



$P_H$ = 1.96 GPa, $N_f$ = 14.7×10$^6$

Fig. 1 Typical failed tooth surface in the test.

The test gears were first run-in, which was done according to a step-up loading procedure（Haizuka and Naruse, 1999）in which the load was increased every 2.0×10$^4$ cycles from a low load up to the test load for each test. The test gears were then run until failure such as pitting or spalling occurred on the tooth surfaces. In running under the test load, observations of the test gear teeth were conducted at certain time intervals. In the tests of this study, the tooth surface strength was determined by the damaged area of the tooth surface and vibration level of the test gear box. The criterion of the damaged area was 2 percent of area damaged for the total area of meshing teeth, or 4 percent of area damaged on any one tooth（Yoshizaki, 2001）. A vibration detection transducer located on the gearbox automatically stopped the testing machine if any tooth damage rapidly grew.

## 3. RESULTS OF THE EXPERIMENT

Gear surface fatigue endurance tests were carried out using gears treated with FPB and SHP-n. Figure 1 shows photographs of the typical failed tooth surface in the test. The surface fatigue damage that occurred in the tests were considered to be caused by a crack initiated on the surface. It is because arrowhead cracks and pits appeared on the tooth surfaces in the running as shown in Fig. 1, which is a typical feature of surface initiated failures（Murakami, 1996）.

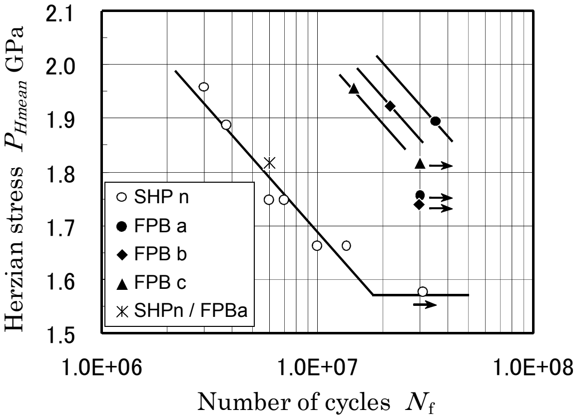


Fig. 2 Experimental results of tooth surface strength. "SHPn / FPBa" denotes that the test was made using the SHP-n gear as the driver and the FPB-a gear as the driven.

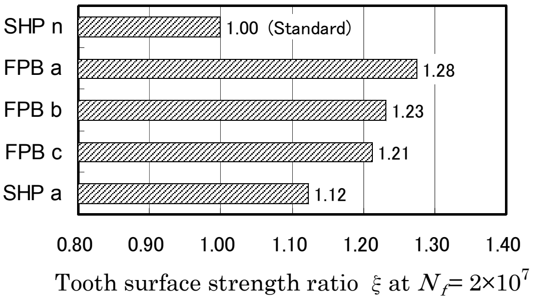


Fig. 3 Comparison of tooth surface strength $P_H$ at a number of cycles $N_f$ of 2×10$^7$.
Data expressed by SHP-a is quoted from refe. (11) as a typical example of hard shot- peening.

The results of the tooth surface strength experiment are represented in Fig. 2. The figure shows the relation between the Hertzian stress $P_H$ at the working pitch point and the number $N_f$ of cycles to failure. The values $N_f$ are measured for the driven gear. The plots with arrows in the figure indicate that no failure occurred on the tooth surface, and thus the running was terminated. Figure 3 shows the effect of FPB on the tooth surface strength compared to that of SHP-n. The tooth surface strength ratio ξ in Fig. 3 is a relative value of the tooth surface strength expressed by Hertzian stress $P_H$ at a number $N_f$ of 2.0×10$^7$ cycles, which is based upon the tooth surface strength of the SHP-n gears at a number $N_f$ of $2.0\times10^7$ cycles (=1.57 GPa). The value $\xi$ of the SHP-n gears is invariably defined as 1.00. The data on SHP-a is quoted from the reference (11) as a typical example of the hard shot-peened gears. The SHP-a was performed by an air-pressure nozzle type machine, and the conditions were an air pressure of 0.54 MPa, a shot diameter of 0.6 mm, and a shot hardness of Hv 700. The ratio $\xi$ of the SHP-a gears is quoted as a relative value based upon the tooth surface strength of "SHP-d" gears described in the reference (11) since the intensity of the SHP-d is approximately equal to that of the SHP-n in this study. It is clear that the tooth surface strength of the FPB gears were much higher than that of the SHP-n gears. The tooth surface strength ratio $\xi$ of the FPB gears were 1.21 to 1.28. The hard shot-peening (SHP-a) was also effective to increase the tooth surface strength compared to the SHP-n; however, $\xi$ of the FPB gears were higher than that of the hard shot-peened gears.

On the other hand, it is also shown in Fig. 2 that no effect of FPB on the tooth surface strength increase can be obtained when only one side of a gear pair is treated with FPB. The plot denoted as "SHPn / FPBa" in Fig. 2 expresses the test result using a gear pair: the SHP-n gear as the driver and the FPB-a gear as the driven. In this test, fatigue damage of the tooth surface occurred on the SHP-n gear. FPB should be performed on both gears of a pair in order to improve the tooth surface strength.

## 4. EFFECT OF FINE PARTICLE BOMBARDING ON TOOTH SURFACE PROPERTIES

### 4.1 Residual Stress

The residual stress distributions below the tooth surface of the untested gears are shown in Fig. 4, where the data on SHP-a are quoted from the reference (11) as an example of a hard shot-peened gear. The measurements were made by the X-ray diffraction method at the working pitch point in the tooth profile direction. In measuring the stress distribution, an electro-chemical polishing was applied and the measurement was repeated at each depth. It is shown in Fig. 4 that the SHP-a produced higher residual compressive stress below the surface than the SHP-n. On the other hand, FPB further increased the residual compressive stress over that produced by the SHP-a. The maximum value of the residual compressive stress $\sigma_{Rmax}$ produced by FPB were -1800 to -2080 MPa at a depth d of approximately 10 μm below the surface. The higher the arc height of FPB, the higher the $\sigma_{Rmax}$ generated. However, the residual compressive stresses produced by FPB were limited in the shallow region from the surface to a depth d of approximately 35 to 60 μm.

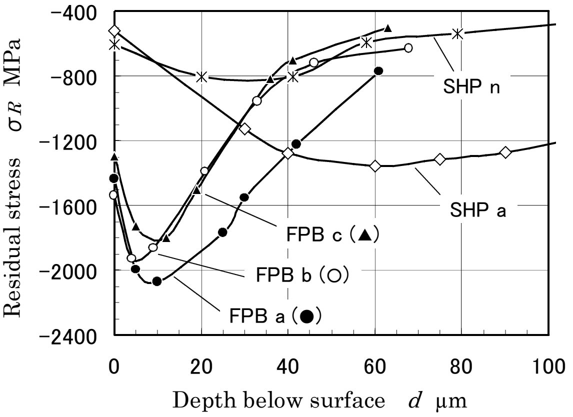


Fig. 4 Residual stress distribution of tooth surface. Data expressed by SHP-a is quoted from refe. (11) as a typical example of hard shot-peening.

### 4.2 Hardness

Figure 5 shows the hardness distributions below the tooth surface of the test gears. The hardness was measured at the working pitch point of the untested gears by using a micro-Vickers hardness tester. The hardness was obviously increased by FPB in the region

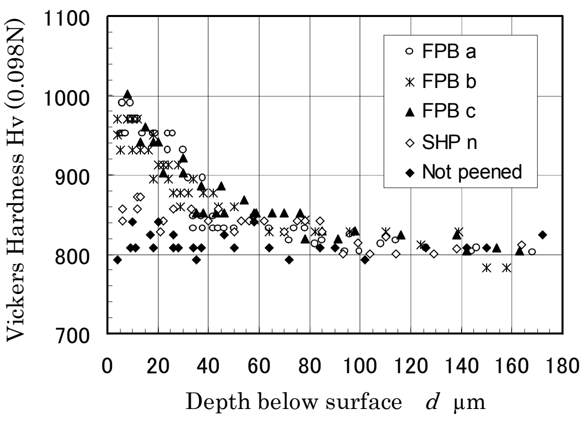


Fig. 5 Hardness distribution of tooth surface.

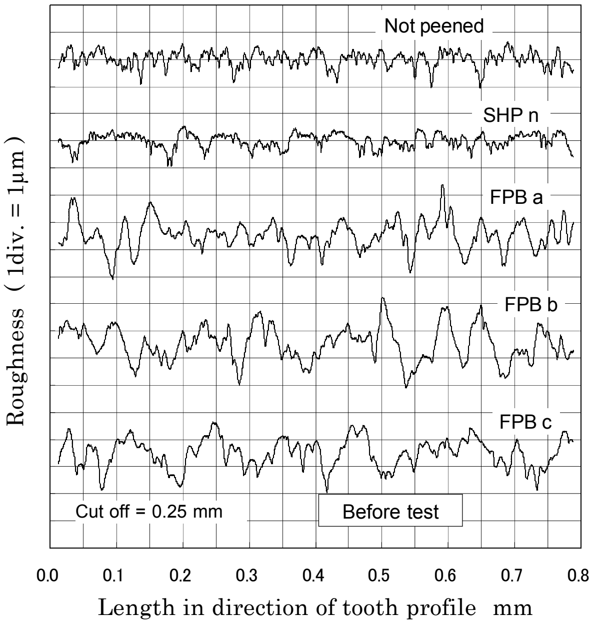


Fig. 6 Tooth surface roughness before test.

from the surface to a depth d of approximately 80 µm. Among the three conditions of FPB, there were no clear differences in the effect of FPB on the hardness increase. SHP-n also increased the hardness near the surface; however, FPB was more effective. By quoting the measured hardness of the tooth surface of the SHP-a gear（hard shot-peened gear）from the reference（11）, the hardness near the tooth surface of the FPB gears were almost the same as that of the hard shot-peened gear, or their differences were small within the range of a depth d of 25 to 100 µm.

### 4.3 Tooth Surface Roughness

Examples of the measured tooth surface roughness before the tests are shown in Fig. 6. The measurements were done along the tooth profile of the gears at a cut-off length of 0.25 mm. The tooth surface roughness, expressed in the maximum peek-to-valley height of the surface profile（Rz, JIS B0601-2001）, was 1.8 µm for the not-peened gear, 1.6 µm for the SHP-n gear, and 2.3 to 2.8 µm for the FPB gears. SHP-n made the peak of the roughness profile slightly flat, in contrast FPB increased the tooth surface roughness. It is seen in the roughness profile performed by FPB that the undulation with a repetition period of approximately 40-80 µm and the microscopic roughness with a fine pitch in approximately 10 µm overlapped.

### 4.4 Tooth Surface Roughness after Running-in

Figure 7 shows the tooth surface roughness of the test gears after the running-in. The tooth surfaces of the FPB gears were smoothed in a short period of running despite the fact that FPB made tooth surfaces rough as shown in Fig. 6. On the other hand, only a small change was seen in the surface roughness of the SHP-n gear tooth measured before and after the running-in. Although tooth surface roughness generally decreases in running, the rate of change in roughness varies with the circumstances. The characteristic of the contact surfaces that are smoothed in an early stage of the running by appropriate wear-in is called good "conformability", which depends on the surface conditions such as the texture and the hardness, the lubricating conditions, the running conditions, etc. It was found that the tooth surfaces treated with FPB had superior conformability compared to that of SHP-n.

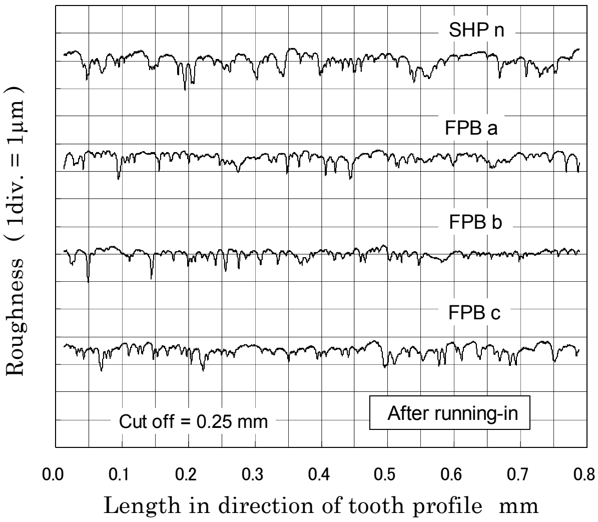


Fig. 7 Tooth surface roughness after running-in.

### 4.5 Tooth Surface Texture

Figure 8 shows the scanning electron micrographs of the tooth surfaces before the tests. The observations were done for a not-peened gear and the peened gears. Grinding marks were seen on the tooth surface of the not-peened gear. The tooth surface of the SHP-n gear was deformed by the collision of the shot particles though the grinding marks clearly remained. On the tooth surfaces of the FPB gears, the grinding marks had completely disappeared and uniform non-directional surfaces with dents and a microscopic scaly texture were formed.

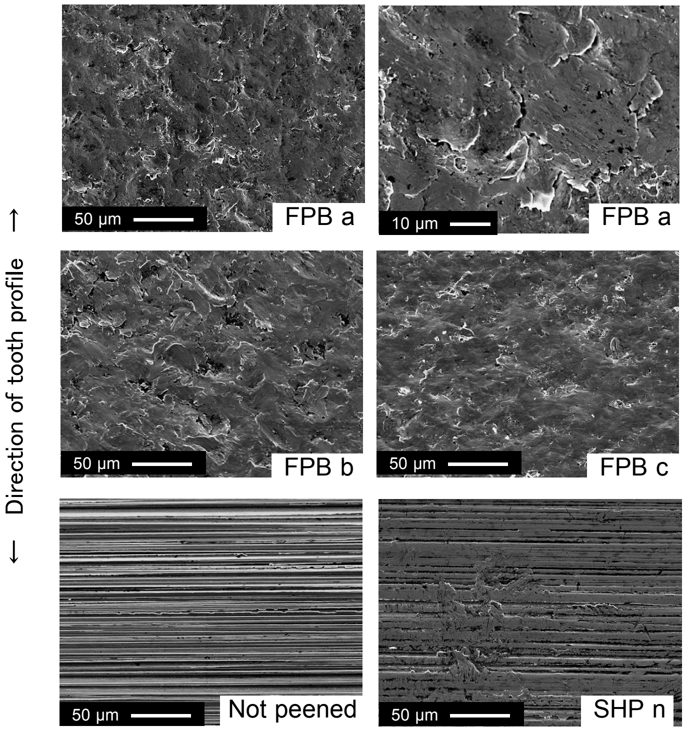


Fig. 8 Observation of tooth surfaces by SEM.

### 4.6 Observation of Tooth Surface after Running

Morphological changes of tooth surfaces after running were observed by using an SEM. Figures 9-1 and 9-2 show the photomicrographs of the tooth surfaces of the FPB-a gear and the SHP-n gear, respectively. Photo-A shows the observation of the surface in an early stage of the running-in, Photo-B shows that after the running-in, and Photo-C depicts the gears after running of a number $N_f$ of $3\times10^7$ cycles. The observations were done near the working pitch point of the gears. In each photograph, the vertical direction corresponds to the tooth profile direction, and the upper side is the tooth tip.

It is seen in Fig. 9-1-A, for the FPB gear, that micro cracks appeared on the locally flat parts formed by an initial wearing of convex parts on the surface. After the running-in (Fig. 9-1-B), the cracks slightly developed and partially peeled off to generate micro hollows. After the running of a number $N_f$ of $3\times10^7$ cycles at a Hertzian stress $P_H$ of 1.75 GPa (Fig. 9-1-C), the micro hollows with a size of 10 to 20 μm appeared uniformly on the whole surface. The depth of the micro hollows were 0.2 to 0.8 μm as seen from the measurement result shown in Fig. 10.

On the other hand, it is seen in Fig. 9-2-A and 9-2-B, for the SHP-n gear, that micro cracks appeared on the worn parts along the grinding marks and the cracks peeled off in the form of a chain. After the running of a number $N_f$ of $3\times10^7$ cycles at a Hertzian stress $P_H$ of 1.57 GPa (Fig. 9-1-C), a lot of pits occurred along the grinding marks and showed signs of connecting to grow larger.

From the observations above, it was found that the micro hollows with a size of 10 to 20 μm and a depth of 0.2 to 0.8 μm were generated uniformly on the tooth surface of FPB gears after running. The initial dents, so called "dimples", formed on the tooth surface by FPB wore out in running.

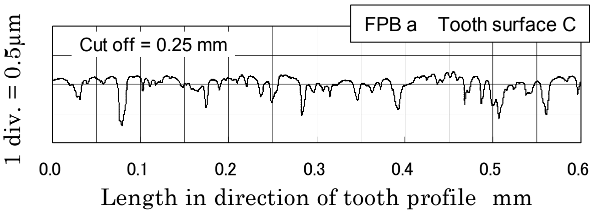


Fig. 10　Roughness of the tooth surface C processed by FPB-a shown in Fig. 9.

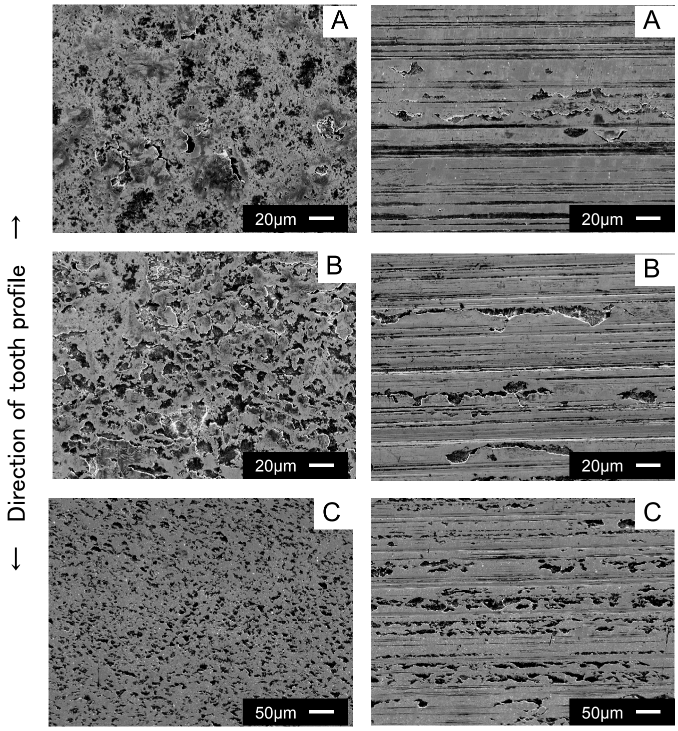


Fig. 9-1　FPB a

Fig. 9-2　SHP n

Fig. 9　Observation of tooth surfaces during tests.
A : Early stage of running-in
B : After running in
C : After running $N_f \fallingdotseq 3\times10^7$

## 5. DISCUSSIONS

From the experiment results described above, the characteristic features of the tooth surface performed by FPB are summarized as follows:

- Very high residual compressive stress was produced below the surface.
- The hardness below the surface was greatly increased.
- The conformability of the tooth surface was excellent.
- Machine tool marks completely disappeared and uniform non-directional surfaces with microscopic scaly texture were formed.
- Micro-hollows were generated on the tooth surface after running.

The effects of these characteristic features on the tooth surface strength increase are discussed in this chapter.

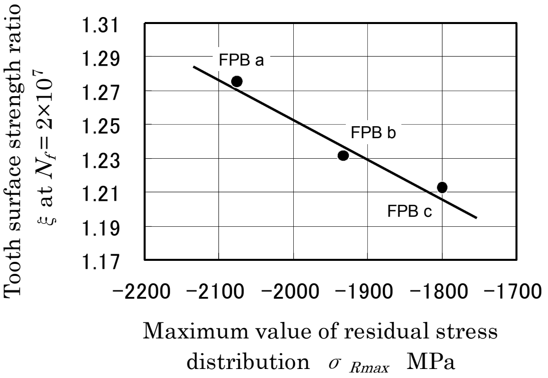


Fig.11　Relation between tooth surface strength ratio and maximum value of residual stress distribution for FPB gears.

### 5.1 Effect of Residual Compressive Stress and Hardness

It has been reported that both compressive stress and high hardness are beneficial in increasing resistance to fatigue failures because crack growth is slowed significantly in a compressive and/or hardened layer (e.g. Suzuki, 1999). Figure 11 shows the relation between the tooth surface strength ratio $\xi$ and the maximum values of the residual compressive stress below the surface $\sigma_{Rmax}$ for the FPB gears. Within the limits of this experiment, the higher the $\sigma_{Rmax}$ produced, the higher the $\xi$ obtained. It is obvious that the high residual compressive stress produced by FPB contributed to the improvement in tooth surface strength.

The hardness below the tooth surfaces were greatly increased by FPB compared to SHP-n as shown in Fig. 5. It was clear that the hardness increase was one of the factors due to FPB that improved the tooth surface strength. However, the contribution rate of the hardness increase by FPB on improving the tooth surface strength was obscure since clear differences in hardness were not apparent among the three conditions of the FPB gears.

### 5.2 Effect of Conformability of Tooth Surface

Figure 12 shows the relation between the tooth surface strength ratio $\xi$ and the tooth surface roughness ratio Rza/Rzb. The data indicated by SHP a - SHP d are quoted from the reference (11) as examples of conventional shot-peened gears. Although the definition of $\xi$ is shown in chapter 3, $\xi$ of SHP-a, SHP-b, SHP-c gears in Fig. 12 are expressed in values relative to the tooth surface strength of the SHP-d gears because the intensity of SHP-d is approximately equal to that of SHP-n. The value $\xi$ of the SHP-d gears, as well as the SHP-n gears, is 1.00. The tooth surface roughness ratio Rza/Rzb was defined to represent quantitatively the conformability of the tooth surface. Rzb and Rza were the maximum peek-to-valley height (Rz, JIS B0601-2001) of the tooth surface profile before and after the running-in, respectively.

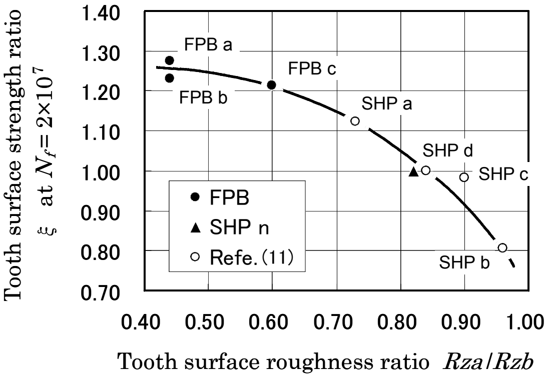


Fig.12 Relation between tooth surface strength ratio and tooth surface roughness ratio.
*Rzb* : Maximum height before running-in
*Rza* : Maximum height after running-in
Data indicated by SHP a - SHP d are quoted from refe. (11).

An adequate correlation was observed between $\xi$ and Rza/Rzb in Fig 12. The tooth surface strength was improved when the tooth surface roughness ratio was lower, namely, when the conformability of the tooth surface was better. Even if the tooth surface is rough before running, high tooth surface strength can be obtained when the tooth surfaces are smoothed in an early stage of running (e.g. Mizutani, 2005). The excellent conformability of the tooth surface treated with FPB contributed much to the improvement in the tooth surface strength.

### 5.3 Tooth Surface Texture and Conformability

The reason why the tooth surface of the FPB gear had excellent conformability is considered as follows: It was observed on the FPB gear surface that the uniform non-directional surfaces with microscopic scaly texture were formed as shown in Fig. 8. Those microscopic "scales" slightly shaved off the tooth surface to promote appropriate wear. In the process of the "shaving", the high residual compressive stress produced near the surface prevented further growth of micro-cracks initiated on the surface. Both the microscopic scaly texture and the high residual compressive stress were activated to improve the conformability of the tooth surface.

### 5.4 Effect of Micro-Hollows Generated After Running

Recently, studies on the relationship between the micro-texture of contacting surfaces and tribological properties have been reported. Etsion, et al. (2002) presented the effectiveness of micro-dimples, produced by laser surface texturing, to reduce the friction of reciprocating automotive components.

As mentioned above, the micro-hollows with a size of 10 to 20 μm and a depth of 0.2 to 0.8 μm were generated on the tooth surface of the FPB gears after running. The author considers that the micro-hollows acted as micro oil-pools and were beneficial in forming oil film on the tooth surface, which contributed to the improvement in the tooth surface strength. It is anticipated that the effect of the micro-hollows on the tooth surface strength increase is more remarkable when lower-viscosity oil, which has recently been used for a vehicle transmission in order to decrease the churning loss of the oil and improve fuel consumption, is used. However, additional experimental measurements are necessary to verify the effect of the micro-hollows, which calls for further research.

### 5.5 Improvement in Tooth Surface Strength by FPB

Generally, there are three essential measures in order to improve tooth surface strength of gears:

(1) To increase the mechanical strength of the tooth surface
(2) To reduce the Hertzian stress applied on the tooth surface
(3) To improve the oil film forming on the tooth surface

On the other hand, the following properties of the FPB gear tooth that influence tooth surface strength increase became clear after examining the experimental results:

(a) High residual compressive stress produced below the surface
(b) Greatly increased hardness below the surface
(c) Excellent conformability of the surface
(d) Micro-hollows on the surface generated after running

The effects of (a), (b), (c) and (d) on the above three essential measures are summarized as follows: First, (a) and (b) are effective in preventing the initiation of micro-cracks on the tooth surface and also in slowing the growth of the cracks, which contributes to (1). Next, the peak of the surface roughness become flat and smooth in the early stage of running since the tooth surfaces have excellent conformability (c), which is beneficial in increasing the specific film thickness and forming oil film on the tooth surface (Matsumoto, 1975). At the same time, the actual contact area on the tooth surface is increased, therefore the local tooth bearing are developed. That is to say, (c) contributes to both (3) and (2). Furthermore, the micro-hollows on the tooth surface (d) contributes to (3) as it promotes the formation of the micro oil-pools. Among the four effects, (c) and (d) are the unique factors caused by FPB, and are not observed in conventional shot-peened gears. Therefore, these factors are considered to contribute much to the improvement in tooth surface strength. However, it is difficult to clarify the contribution rate of the effects of (a), (b), (c) and (d) to the tooth surface increase because of the interaction of these effects.

The above factors are all beneficial in increasing resistance to surface initiated failures. In order to obtain further improvement in the tooth surface strength, some devised measures against internal initiated failures are required.

## 6. CONCLUSIONS

The results obtained in this study are summarized as follows:

1. FPB increases the tooth surface strength (pitting resistance) by 1.21 to 1.28 times in Hertzian stress compared to the conventional impeller-type shot-peening. Furthermore, the effect of FPB is higher than that of properly controlled hard shot-peening.
2. Although FPB makes tooth surfaces rough, the surfaces become smooth in a short period of running. That is to say, the tooth surfaces treated with FPB have excellent conformability.
3. Micro-hollows with a size of 10 to 20 μm and a depth of 0.2 to 0.8 μm are generated uniformly on the tooth surface of the FPB gears after running. The initial dents, so called "dimples", formed on the tooth surface by FPB wear out in running.
4. The following factors due to FPB that influence tooth surface strength increase are discussed: (a) high residual compressive stress produced below the surface, (b) greatly increased hardness below the surface, (c) excellent conformability of the tooth surface, (d) micro-hollows on the tooth surface generated after running. Among the four effects, (c) and (d) are unique factors caused by FPB, and contribute much to the improvement in the tooth surface strength.
5. No effect of FPB on the tooth surface strength increase can be expected when only one side of a gear pair is treated with FPB. FPB should be performed on both gears of a pair.

## ACKNOWLEDGMENT

The author would like to express his appreciation to Mr. Masato Ishiwata of Fuji Manufacturing Co., Ltd. for his advice on setting the FPB conditions and for performing FPB on the test gears. The author also wishes to thank Mr. Masaru Komiya of Hino Motors, Ltd. for his help in conducting the tests in this study.

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