# 特集 Lead-Free Brush Materials for Starter Motors*


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This paper reports the development of a lead-free brush material for high-load starter motors. These brushes can be used in much more extreme conditions --- at a PV-value (the product of the brush contact pressure and sliding velocity) approximately three times that of conventional starter motor brushes, and double the electrical current density. The major technical requirement for this development was the ability to reduce the electrical wear in brushes caused by commutation sparking. We developed a brush material that reduces electrical wear by adding a phosphorous compound. Because the phosphorous compound can improve both the lubricity at high-temperatures and the contact stability of the brushes, the developed brush reduces commutation sparks. The life of the developed brush is about 1.5 times longer than that of conventional brushes containing lead.



**Key words:** Carbon brush, Starter, Lead, Wear, Tribology


## 1. INTRODUCTION

DC motors are indispensable to improve automotive functions. Recently, 100-150 motors are installed on luxury cars and this number is increasing year by year. More than 90% of the automotive motors are brushed DC electric motors. Advantages of brushed DC motors are many: high energy-efficiency, high potential for minimization, good controllability of revolving speed, and so on. However, the most useful advantage is the low cost.  A brushless motor that has the same performance as a conventional brushed motor is more than twice the cost of the brushed motor. It is predicted that the high rate of the number of brushed motors in automotive motors is maintained at least more than several years because the cost competitiveness is one of the most important factors in the automotive industry. In these circumstances, it is considered that the importance of the technology development for life improvement, high efficiency, and high power of motors is increasing year by year.

Lead has traditionally been added to brushes for electric motors, but after being listed as a regulated substance under European environmental law, it must be eliminated from motors installed on vehicles registered from January 2005 when the law takes effect. In response to this requirement, DENSO CORPORATION has since March 2003 used lead-free brushes in all motors intended for all new vehicles, not only those for Europe. The function of brushes is to pass an electrical current to the revolving commutator found in electrical motors. Because the brushes slide against the commutator, brushes wear little by little, whenever the motor starts. And when the brush wears to its limit, the motor will not start. The life of a brush is generally the shortest in all motor parts. Therefore, brush material is key for motor life. Since adding lead to brushes was originally done to reduce brush wear, finding an alternative engineering solution to enable nonleaded brushes has been an important issue. We have used zinc and silver in place of lead as a solution to this issue.[1)2)]

However, some brushes for the starter used under high-load conditions, brush wear increased above the level of lead added brush simply by adding the above-mentioned zinc and silver, and required another material to be developed. This paper reports the development of a lead-free brush material for a high-load starter.[3)]

## 2. PECULIARITIES OF HIGH-LOAD STARTER BRUSHES

**Figures 1**, **2**, and **3** show automotive motors provided by DENSO group and their installed positions in a vehicle, brush use conditions, and structure of brushes and a commutator of a high-load starter, respectively. *PV*-value in **Fig. 2** is the product of the brush contact pressure (*P*) and the sliding velocity (*V*). The higher the *PV*-value, the higher the mechanical load. On the other hand, the higher the

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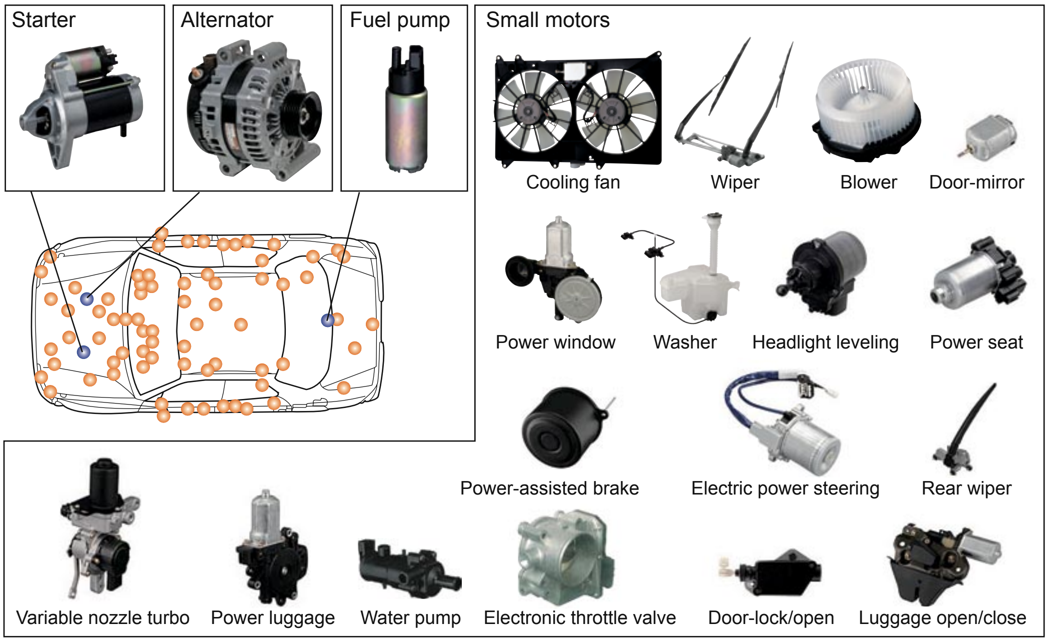



Fig. 1 Automotive motors and their installed positions

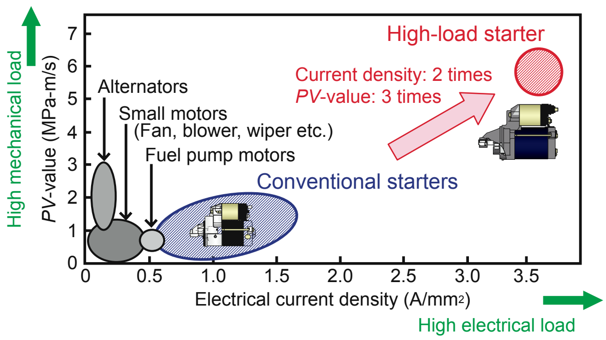



Fig. 2 Brush use conditions

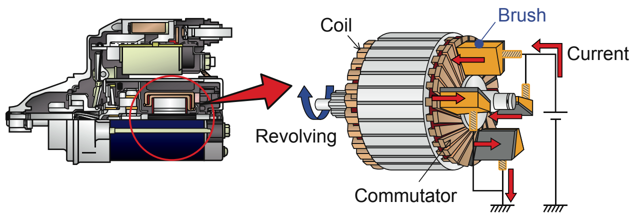



Fig. 3 Brushes and a commutator of a high-load starter

electrical current density, the higher the electrical load. In general, brush wear increase (motor life decrease) is caused by the high *PV*-value and the high electrical current density. The brushes of the high-load starter are used in much more extreme conditions – at the *PV*-value approximately three times that of conventional starter brushes, and double the electrical current density.

## 3. TECHNICAL REQUIREMENTS

**Figure 4** shows the brush structure of the high-load starter. **Table 1** describes the specifications of brush A (lead added) and brush B (non-leaded, Zn & Ag added). The material of the commutator is copper. As shown in **Fig. 4**, brushes for a high-load starter are two-layer brushes consisting of a low-resistance layer (a material containing much copper) and a high-resistance layer (a material containing less copper). A two-layer brush can improve the motor life without loss of motor efficiency and power because it reduces commutation sparks through the effect of the resistance-commutation by means of adding a high-resistance layer at the rear end and it keeps contact resistance low by a low-resistance layer of the front end.[4)-6)]

**Figure 5** shows the brush wear rate (brush wear length per sliding distance) of brush A and brush B in a starter start-stop-endurance test. The procedure of the starter start-stop-endurance test is as follows. First, The high-load starter was assembled with test brushes.[7)] Next, the assembled starter was installed in an engine. Then, the starter was operated at more than 2000 to 10000 times. After that, tested brushes were removed from the starter and each length was measured by micrometer. The brush wear length was the difference between initial and tested brush length. **Figure 5** indicates the largest value in the four brushes used in one test. As shown in **Fig. 5**, the brush wear rate of brush B was

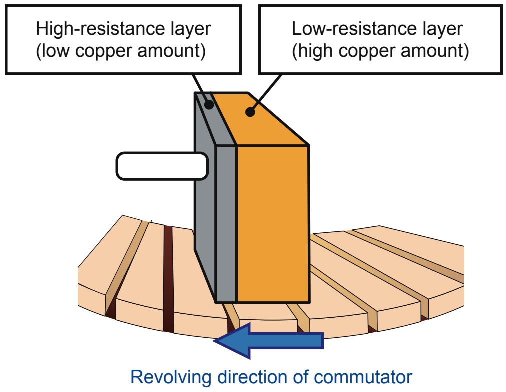



Fig. 4 Structure of two-layer brush

Table 1 Specifications of brush

| | Items | Brush A | | Brush B | |
|---|---|---|---|---|---|
| | | Low-resistance layer | High-resistance layer | Low-resistance layer | High-resistance layer |
| Chemical composition | Cu, wt% | 60 | 25 | 60 | 25 |
| | C, wt% | Rest | Rest | Rest | Rest |
| | $MoS_2$, wt% | 4 | | 4 | |
| | Pb, wt% | 3 | | 0 | |
| | Zn, wt% | 0 | | 3 | |
| | Ag, wt% | 0 | | 1 | |
| Physical property | Resistivity, $\mu$Ohm-m | 30 | 1500 | 30 | 1500 |
| | Apparent density | 4.0 | 2.4 | 3.8 | 2.5 |
| | Hardness (HsC) | 22 | 26 | 21 | 26 |
| | Bending strength, MPa | 34 | 25 | 30 | 21 |

about 1.4 times that of brush A. It is necessary to reduce the brush wear because the increase of brush wear causes motor life to decrease.

Brushes wear in a combination of two-modes of wear; electrical wear due to commutation sparks of the motor and mechanical wear attributable to sliding.[4)8)] Approaches to developing technology for reducing brush wear depend on the dominant wear mode (mechanical wear or spark-affected wear).[9)10)] To identify the dominant wear mode of the two brush materials for starters, we conducted brush-copper plate sliding tests simulating a situation in which commutation sparks did not occur and compared the mechanical wear of brush A and B. **Figure 6**, **Table 2** and **Fig. 7** show this test apparatus, conditions and results, respectively. Brushes were fixed by brush-holders and loaded by springs. Brushes, brush-holders and springs were the same parts as a high-load starter. The brush wear rate was measured in the same way

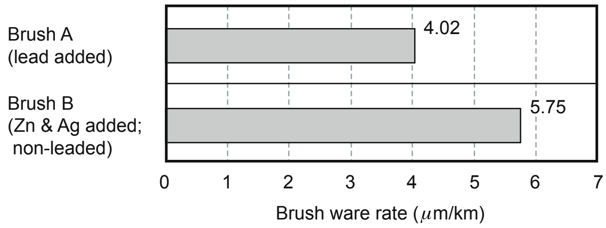



Fig. 5 Brush wear rate in starter start-stop-endurance test

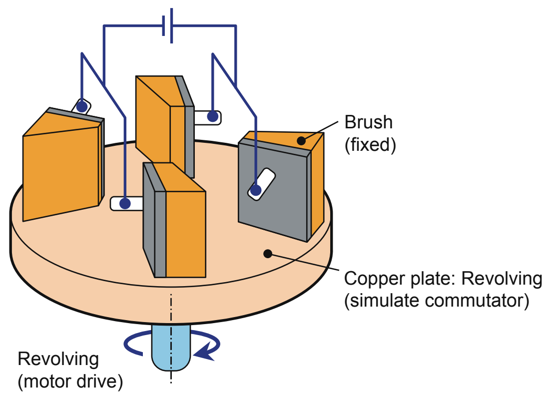



Fig. 6 Brush-copper plate sliding test apparatus

Table 2 Conditions of brush-copper plate sliding test

| | |
|---|---|
| Sliding speed, m/s<br>(Rotation speed of simulated commutator, $min^{-1}$) | 6.0<br>(2860) |
| Brush contact pressure, MPa | 0.37 |
| Electrical current density, A/$mm^2$ | 0.20 |
| Brush sliding radius (center), mm | 40 |
| Testing time, h | 20 |

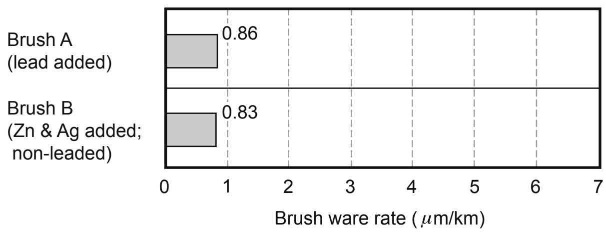



Fig. 7 Brush wear rates in sliding test

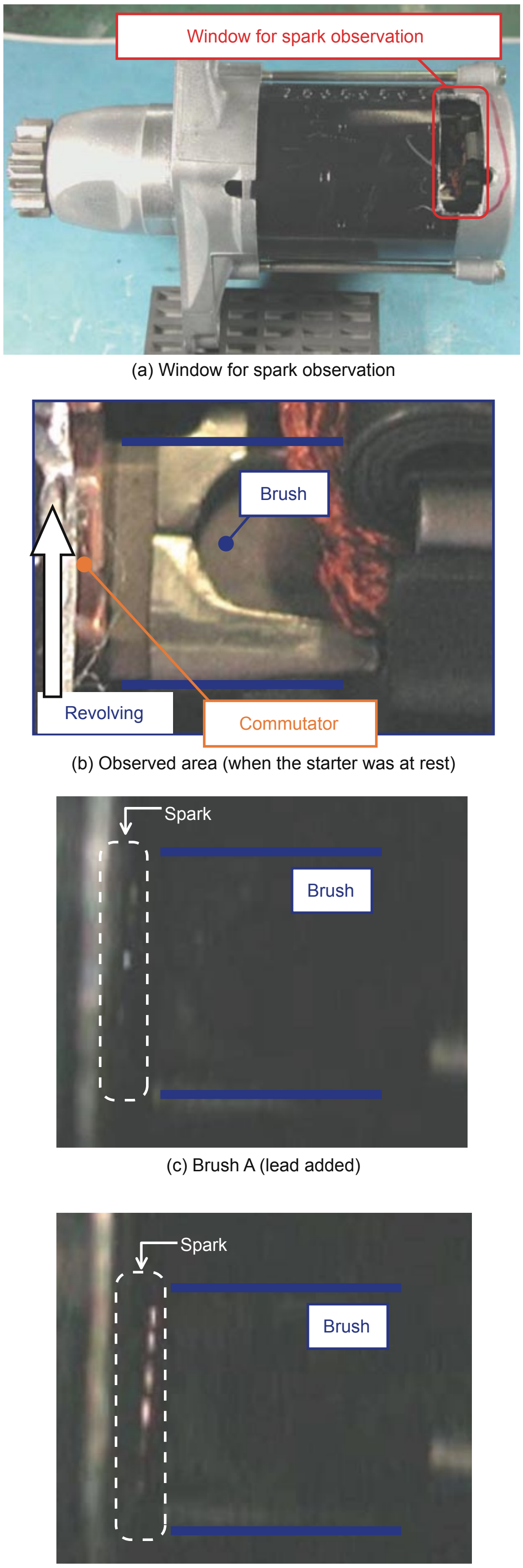
as the starter start-stop-endurance test.

As shown in **Fig. 7**, there was no significant difference in the brush wear rate between brushes A and B, and the brush wear rate of each brush in **Fig. 7** was less than 1/5 of the level shown in **Fig. 5**. Judging from these facts, it is presumed that the difference of brush wear rate between brush A and B in the starter start-stop-endurance tests was caused by a difference in the amount of sparks. Therefore, we observed sparks in the starter start-stop-endurance tests and investigated the sliding surfaces of brushes and commutators after the tests. **Figure 8** shows sparks observed in the starter start-stop-endurance tests. Sparks were observed from a window made on the cover-end as shown in **Fig. 8 (a)**. **Figure 9** shows photo image of an unused commutator. **Figures 10** and **11** show photo image of the commutator sliding surfaces after the tests. **Figure 12** shows SEM images of the rear end of the brush sliding surfaces after the tests.

**Figure 8** indicates that brush B produced a larger spark than brush A. Brush B produced a spark number of 6 to 7 by the method that is defined for quantifying the amount of spark by the Japanese electromechanical committee.[11] On the other hand, brush A produced a spark number of 3 to 4. It is generally stated that a harmful spark is a spark number more than 4 in practical use.[4)11)] The spark number of brush B surpassed that harmful spark level.

As shown in **Figs. 9**, **10** and **11**, the sliding surface of commutator sliding against brush B was damaged much more than that of brush A and there were island-shaped black adhesion-objects in places on it. It was considered that each adhesion-object was a mass of wear-particles of brush that was caused as follows. First, large sparks damaged the sliding surface of the commutator and its surface roughness became larger. Then, the brush wear amount increased excessively because of sliding on the roughened commutator surface. A damaged and roughened commutator sliding surface caused by large sparks is known as one of the major factors in brush wear increase.[4)12)13)] Furthermore, a damaged commutator sliding surface makes spark larger. Therefore, once a large spark occurs, the spark becomes progressively larger and larger. It was recognized that the commutator surface sliding against brush B in **Fig. 11** was typical of a sliding surface damaged by large sparks.

Commutation sparks usually occur at the rear end of a brush.[4)12)] As shown in **Fig. 12**, the rear end of brush B was damaged and was roughened by sparks much larger than that of brush A. In brush B, it was difficult to identify the copper powder, which is one of the ingredients of brush material, on the rear end of the sliding surface because most of the copper powders was damaged and was taken off from the surface. This phenomenon seen on brush B is a typical one that is caused when excessive sparks occur. In contrast, it was easy to identify the copper powders on the rear end of




(a) Window for spark observation

(b) Observed area (when the starter was at rest)

(c) Brush A (lead added)

(d) Brush B (non-leaded)

Fig. 8  Sparks in starter start-stop-endurance test

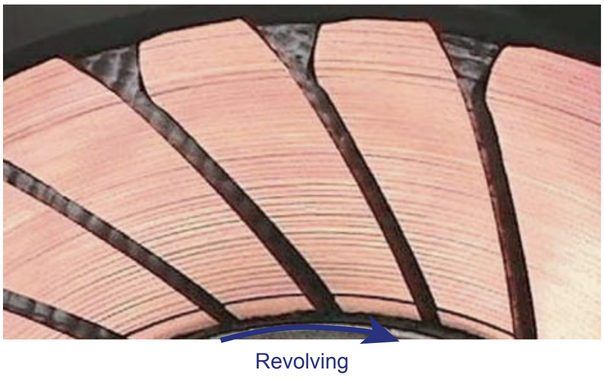



Fig. 9 Photo image of an unused commutator surface

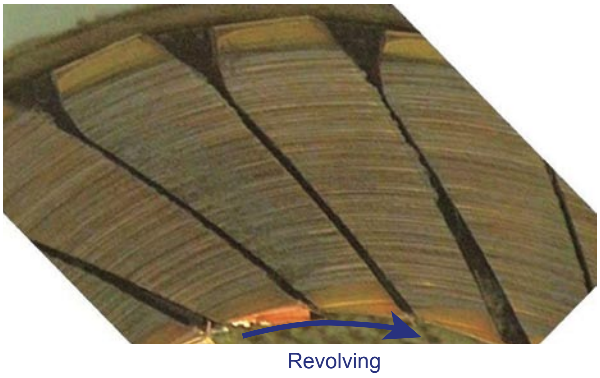



Fig. 10 Photo image of commutator sliding surface after starter start-stop endurance test with brush A

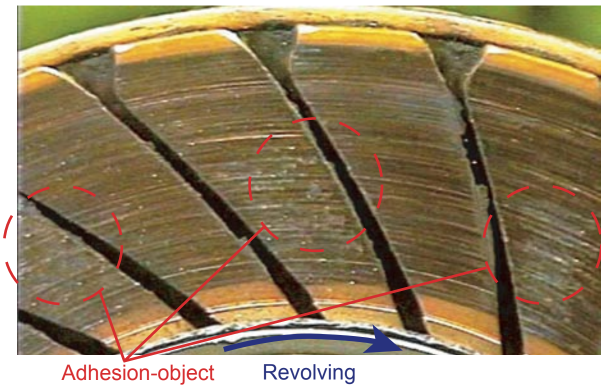



Fig. 11 Photo image of commutator sliding surface after starter start-stop endurance test with brush B

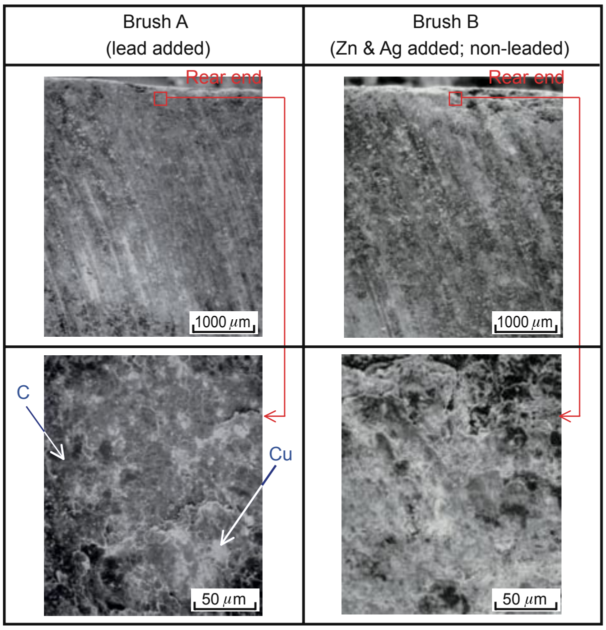



Fig. 12 SEM images of brush sliding surfaces after starter start-stop endurance test

brush A. And the minor damage was recognized on that of brush A.

From the above results, it was evident that electrical wear due to sparks was the dominant wear mode of the brushes and the large wear amount of brush B was caused by excessive sparks. Sparks must be reduced to reduce wear in brush B.

## 4. EXAMINING APPROACHES TO REDUCING COMMUTATION SPARKS AND SELECTING ADDITIVES

Good commutation is indispensable for the reduction of sparks, and two approaches are mainly available to improve commutation based on the theory of resistance-commutation. One is to increase the contact resistance between the brush and the commutator by increasing the electrical resistance of the brush material. The other is to improve contact stability between the brush and the commutator.[14)-16)] Only approaches that improving contact stability are discussed here with regard to brush B because the resistance of the high-resistance layer of brush B was already increased to the upper limit.

As an approach to increasing contact stability on the brush material, we considered adding a solid-lubricant to improve lubricity, and an extreme-pressure agent to reduce adhesion between the coppers contained in both the brush and the commutator materials. The extreme-pressure agent here is a lubricant that reduces both friction and wear by forming a film on the sliding surfaces and thus preventing direct contact between them under high contact pressure and sliding velocity, or the so-called extreme-pressure conditions.[16] It is exceedingly important for reducing wear to prevent direct contact between the same materials because the wear speed and the variation of the friction coefficient increase suddenly when the same materials slide directly over each other.[17][18] **Table 3** lists the solid lubricants we selected as candidate materials for the above mentioned purposes. A lubricant with excellent heat-resistance is considered effective for brushes for high-load starters because they tend to reach higher temperatures due to the high *PV*-value, high electrical current density and sparks as mentioned above. The temperature at the center of sparks is about 4,000 to 5,000 ˚C.[4] We selected lubricants with emphasis placed on heat-resistance. The lubricating property (in air) of solid-lubricants at high-temperature is generally affected by their thermal stability.[19][20] For example, a change in weight attributable to oxidation was observed with graphite at around 450 ˚C and with molybdenum disulfide at around 400 ˚C, and the friction coefficient increases accordingly.[19][21] For this reason, we measured the weight change rate of each lubricant listed in **Table 3** at the atmospheric temperature by thermogravimetry. **Figure 13** shows the results of this measurement. Note the polymer material was excluded from the candidate materials because its heat-resistance was obviously low. A phosphorous compound, the extreme-pressure agent, was the most stable and the lowest weight change rate up to 1000 ˚C. So we selected the phosphorous compound as our high heat-resistant lubricant.

Table 3  Solid lubricants selected

| | |
|---|---|
| Layer lattice structure | $MoS_2$, hBN |
| Polymeric material | PTFE |
| Extreme-pressure agent | Phosphorous compound |

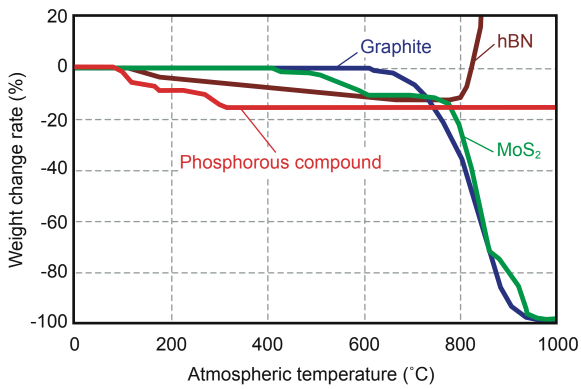



Fig. 13  Atmospheric temperature and weight change rates of solid lubricants (in air)

## 5. EFFECT OF ADDING THE PHOSPHOROUS COMPOUND

To confirm the sliding characteristics of the phosphorous compound containing brush material under high-temperature, we made brush materials which contained the phosphorous compound or another substance, and conducted collar-plate friction and wear tests in a high-temperature atmosphere. **Figure 14** illustrates the test apparatus, **Table 4** describes the test conditions, and **Fig. 15** shows the test results for the friction coefficient: $\mu$, $\Delta\mu$ (the variation in $\mu$), and the wear amount of the plate (brush material) after the test. Specimens were heated using the high-frequency induction heating method.[22] Each friction coefficient was calculated from the friction force caused on the collar measured by a strain gauge.[22] The wear amount of the plate is the volume of the ring-shaped wear trace measured by a shape-measuring instrument.

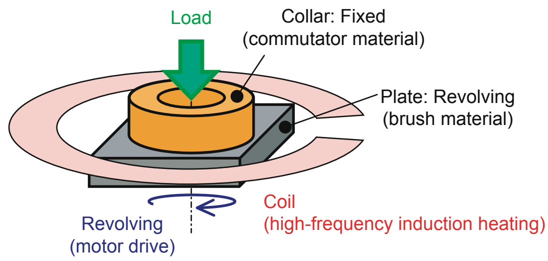



Fig. 14  Collar-plate friction and wear test apparatus

Table 4  Collar-plate frictions and wear test conditions

| | |
|---|---|
| Sliding speed, m/s | 0.75 |
| Contact pressure, MPa | 0.34 |
| Outside diameter of collar, mm | 25 |
| Inside diameter of collar, mm | 18 |
| Plate temperature, ˚C | 200 |
| Testing time, h | 1.0 |
| Outside diameter of collar, mm | 25 |
| Inside diameter of collar, mm | 18 |

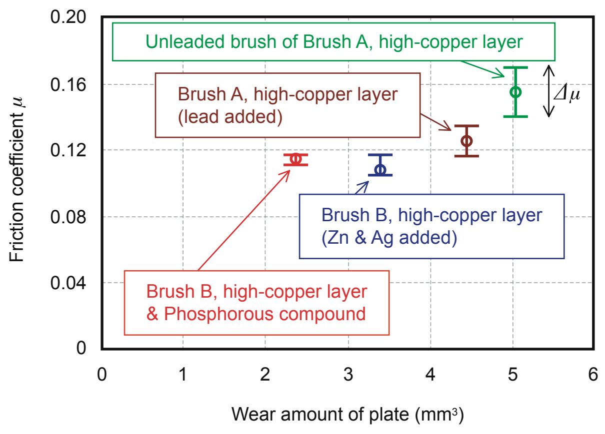



Fig. 15 Results of collar-plate friction and wear test

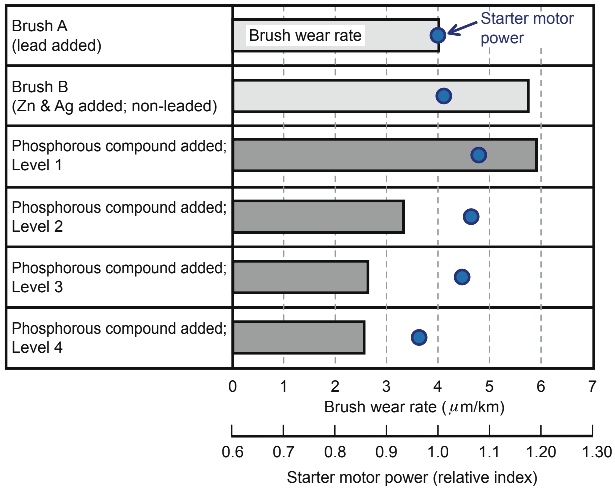



Fig. 16 Amounts of phosphorous compound and brush wear rates in starter motor start-stop endurance test/starter motor power

As shown in **Fig. 15**, the phosphorous compound-containing brush material was lower than the lead-added brush material in $\mu$, $\Delta\mu$, and wear amount. This result proves that the phosphorous compound can improve lubricity at high-temperature.

## 6. OPTIMIZING THE AMOUNT OF PHOSPHOROUS COMPOUND

To understand the influence of the amount of phosphorous compound in the high-load starter brush material, the relationships between the amounts of phosphorous compound, the brush wear rates ($\mu$m/km) and the starter powers were evaluated. Four brush materials with different amount of phosphorous compound were made based on the chemical composition of brush B shown in **Table 1**, to conduct starter start-stop-endurance tests. **Figure 16** shows the brush wear rates of those materials after the tests and the starter initial powers. Starter powers are indicated in a relative index calculated by considering the power of brush A (lead-containing) as one.

The higher the amount of phosphorous compound (higher the level number), the lower the brush wear rate as shown in **Fig. 16**. It is thought that increasing the amount of phosphorous compound increased the amount of phosphorous compound transferred to the sliding surfaces, and the transferred film improved lubricity. Level 2 and over materials surpassed lead-containing brushes in low-brush wear rate.

On the other hand, the higher the amount of phosphorous compound, the lower the starter power. It is thought that increasing the amount of phosphorous compound increased the contact electrical resistance between the brush and the commutator and decreased the starter power because phosphorous compound is a kind of insulating material. Level 4 material was inferior in starter power to a lead-containing brush.

According to the above results, Level 3 was selected as the optimum amount of phosphorous compound in a high-load starter brush (this brush is hereinafter referred to as the developed brush). The life of the developed brush was approximately 1.5 times longer than that of a lead-containing brush.

## 7. VERIFYING AND DISCUSSING THE EFFECT OF IMPROVEMENT AGAINST TECHNICAL REQUIREMENT

### 7.1 Effect of spark reduction

**Figure 17** shows a spark of the developed brush generated in the starter start-stop-endurance test. **Figure 18** shows photo images of the brush and commutator sliding surfaces after the tests. **Figure 19** shows SEM images of the brush sliding surfaces after the tests. Conditions of the test and observations were the same as mentioned in Section 3.

The developed brush produced a spark number of 2 to 3. By adding phosphorous compound, sparks from the developed brush were reduced to or below the level of sparks from a lead-containing brush shown in **Fig. 8 (c)**. As shown in **Fig. 18** and **Fig. 19**, the sliding surfaces of the developed brush and the commutator had the same or a better condition than those of the lead containing brush shown in **Fig. 10** and **Fig. 12**. Sliding surfaces damaged by large sparks were not recognized as follows. The large

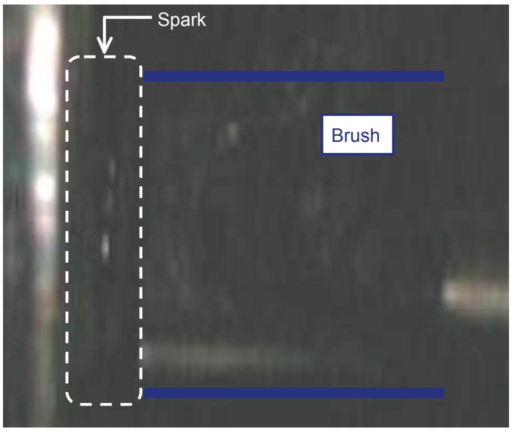



Fig. 17 Spark of developed brush in starter start-stop-endurance test

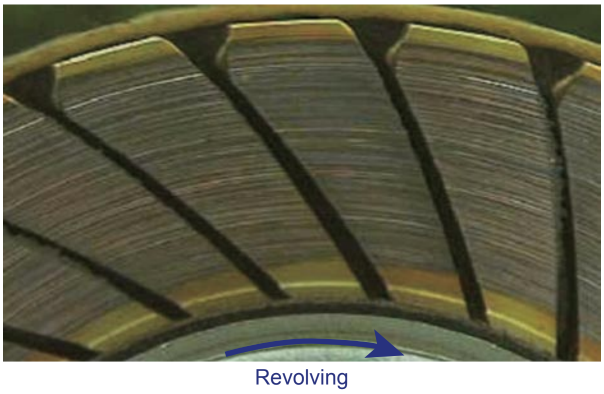



Fig. 18 Photo image of the commutator sliding surface after starter motor start-stop endurance test with developed brush

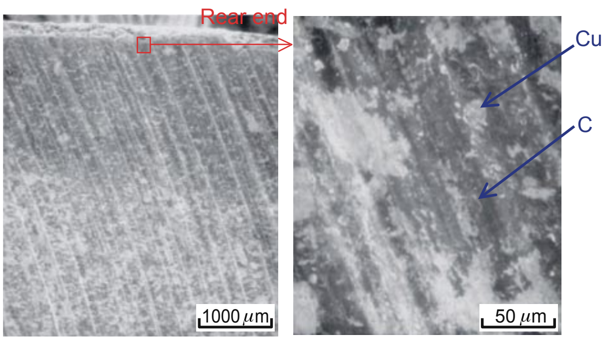



Fig. 19 SEM images of brush sliding surfaces after starter motor start-stop endurance test

roughness and the island-shaped black adhesion-objects on the sliding surface of the commutator shown in brush B (**Fig. 11**) were not observed on that of the developed brush. And it was easy to identify the copper powder on the rear end of the developed brush shown in **Fig. 19**. From the above results, the effect of reducing sparks in the developed brush was verified.

### 7.2 Discussion about the lubrication-film on the sliding surface

To understand how the phosphorous compound added to the brush existed in the lubrication-film formed on the sliding surface, the components and their state at various depths of the lubrication-film formed on the commutator surface after the starter start-stop-endurance test as shown in **Fig. 18** was analyzed. Auger electron spectroscopy (AES) was used for component analysis and X-ray photoelectron spectroscopy (XPS) was used for state analysis. $Ar^+$ beam was used for sputtering the lubrication-film in the depth-direction. The lubrication-film was analyzed approximately every 5 nm in the depth-direction and it was continued up to approximately 500 nm by AES, approximately 40 nm by XPS. **Figure 20** and **Fig. 21** show the results of the AES and XPS, respectively. In **Fig. 20**, the point of 0 nm in depth is the outermost surface of the lubrication-film.

As shown in **Fig. 20**, the thickness of the lubrication-film formed on the sliding surface of the commutator was approximately 33 nm, and it consists mainly of carbon and copper. The concentration becomes lower in the deeper part of the film. On the other hand, concentrations of Mo, S, X (an element of phosphorous compound), P and O, the constituent elements of $MoS_2$ and phosphorous compound, were highest in the interface between the lubrication-film and the outermost surface of the commutator. As shown above, it was found that components of solid-lubricants were distributed in different concentrations at various depths in the film.

In **Fig. 21**, each line indicates the result of the XPS in a depth of the film and the upper level lines signify the results in deeper parts of the film. As shown in **Fig. 21 (a)**. Both $MoS_2$-peak and the metallic-molybdenum-peaks were observed in the film. The intensities of $MoS_2$-peak and the metallic-molybdenum-peaks became larger in the deeper part of the film and the intensity of metallic-molybdenum-peaks was several times larger than that of $MoS_2$ in every depth. Therefore, it was considered that the amount of $MoS_2$ that had a lubrication-effect existed only a little in the film. It is presumed that lubricity given by $MoS_2$ transferred from the brush was deemed to be lower because most of $MoS_2$ changed into the metallic state in the film. On the other hand,

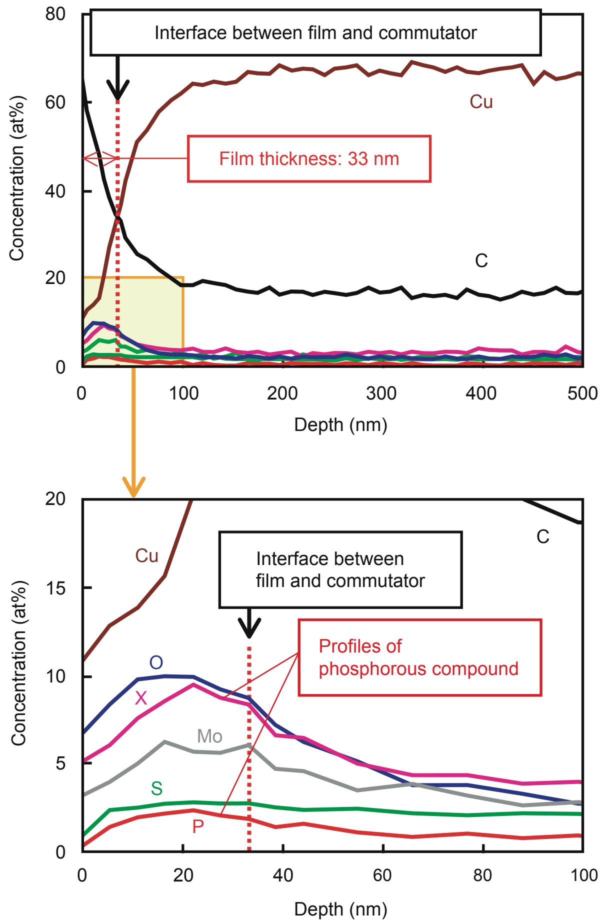



Fig. 20  Results of AES of commutator sliding surface in depth-wise direction

it seemed that phosphorous compound maintained its state because almost no change was observed in the condition of the phosphorous compound in the deeper part of the film as shown in **Fig. 21 (b)**.

From the above discussion, it is understood that phosphorous compound existed in the lubrication-film, especially in the interface between the film and the outermost surface of the commutator, and improved the lubrication condition between the brush and the commutator.

## 8. CONCLUSION

(1) Wear in brushes for high-load starters was reduced by adding phosphorous compound, a heat-resistant extreme-pressure agent, in order to reduce commutation sparks through the improvement of contact stability at high-temperature.

(2) We established a technology for lead-free brushes for high-load starters, and developed a long-life lead-free brush material that serves approximately 1.5 times longer than conventional lead-containing brushes.

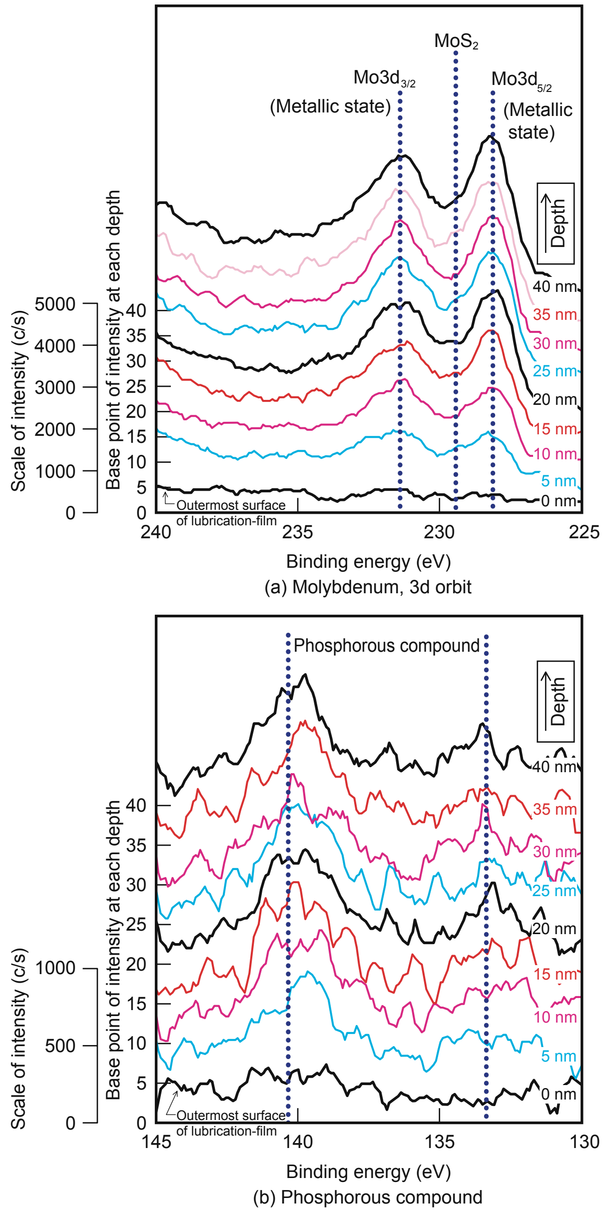



Fig. 21  Results of XPS of commutator sliding surface in depth-wise direction

The developed technology through this study provides lead-free brush as well as brush life improvement. Brush life of conventional starters can also be improved by using this lead-free technology, not only high-load starters. So this technology has been adopted for new model starters released after this study. We will work toward development of materials and the engineering for both environmental friendly and competitive technology.

## REFERENCES


1) R. Honbo, K. Sawa, H. Wakabayashi, Y. Murakami, N. Inayoshi, K. Inukai, T. Shimoyama, N. Morita, “Development of the lead-free carbon brush material for starters,” IEICE Trans. Electron., vol. E88-C, no.8, pp. 1675-1681, August 2005.
2) R. Honbo, H. Wakabayashi, Y. Murakami, N. Inayoshi, K. Inukai, T. Shimoyama, N. Morita, “The development of the lead free carbon brush for starters,” SAE Trans., vol. 114-5, pp. 268-272, March 2006.
3) R. Honbo, K. Sawa, H. Wakabayashi, Y. Murakami, N. Inayoshi, K. Inukai, T. Shimoyama, N. Morita, “Development of the lead-free brush material for the high-load starter,” IEICE Trans. Electron., vol. E90-C, no.8, pp. 1634-1642, August 2007.
4) The Carbon Society of Japan, Brushes for motors and their use, in Japanese, Nikkan Kogyo Shimbun Ltd., Tokyo, 1976.
5) T. Matsuda, Y. Suzuki, N. Sasanami, “Commutating capability of dual-grade split brush,” in Japanese, Tanso, no.151, pp. 2-7, 1992.
6) Y. Suzuki, N. Sasanami, T. Matsuda, M. Yamaguchi, “Commutating capability of two-grade double-layer brush,” in Japanese, Tanso, no.151, pp. 13-19, 1992.
7) K. Mitani, Electrical components for engines, in Japanese, Sankaido, Tokyo, 1996.
8) K. Sawa, The basis of commutation arc phenomena and brush/commutator wear, in Japanese, Industry and science systems, 2003.
9) Y.Murakami, K.Takeuchi, T. Matsuda, T. Hotta, “Development of a Long-life Carbon Brush Material for Fuel Injection Pumps” in Japanese, the Collection of Drafts for the Spring Tribology Conference, pp. 35-36, 2000.
10) M. Yamaguchi, “Carbon brush; it’s friction and wear, ” in Japanese, Lubrication vol.26 no.5, pp. 351-354, 1981.
11) The japanese electrotechnical committee, JEC-2120 Direct current machines, in Japanese, Denkishoin, 2001.
12) R.Holm, Electric contacts, 4th Edition, Springer-Verlag New York Inc., 1967.
13) N. Yamashita, Commutator damages and prevention measures, in japanese, Industry and science systems, 2003.
14) T. Takemasa, Performance and directions of electric brushes, in Japanese, Tokyo denki university press, 1958.
15) T. Ichiki, Theory and practice of carbon brushes, in Japanese, CORONA Publishing, 1978.
16) K. Nagakura, M. Yamada, K. Sawa, “A study on sliding behavior under commutation phenomenon in gasoline,” in Japanese, IEE Technical report, RM-97-1, pp. 1-6, 1997.
17) Y. Yamamoto and S. Kaneta, Tribology, in Japanese, Rikogakusha Publishing, Tokyo, 1998.
18) J. Okamoto, K. Nakayama, M. Sato, An introduction to tribology, in Japanese, Saiwaishobo, Tokyo, 1990.
19) Y. Tsuya, Solid-Lubrication Handbook, in Japanese, Saiwai Shobo, Tokyo, 1978.
20) H.E.Sliney, “Solid libricant materials for high temperatures - a review,” Tribology international, vol.15, no.5, pp. 303-315, 1982.
21) Y. Miyakawa, M. Nishimura, W. Abe, “Study on lead monoxide as solid lubricant for high temperatures (1),” in Japanese, Lubrication, vol.15, no.7, pp. 391-406, 1970.
22) Y. Shimura, “Technical note for tribology tests of materials at high temperatures,” in Japanese, Tribologist, vol.37, no.9, pp. 772-775, 1992.

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