

Development of Lead-free Bearing for High-speed, High-load Engine

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ABSTRACT

A lead-free bearing was developed for use in high-speed and high-load gasoline engines made by Honda.

The development method involved the application of a new resin coating material with optimized surface roughness and solid lubricant arrangement ratio to an existing aluminum alloy bearing surface, which realized a lead-free bearing.

The new resin coating bearings achieved performance (seizure resistance and fatigue resistance) equal to or better than that of the lead alloy plating bearings conventionally used in high-speed and high-load gasoline engines.

1. Introduction

To support recent increases in engine capacity and control of exhaust gases, and to enhance fuel economy, bearing unit loads are tending to rise, oil film thicknesses are becoming thinner, and bearing environments, typified by sliding velocity and unit load, are becoming more severe⁽¹⁾⁻⁽⁴⁾.

The connecting rod bearings of high-speed and high-load gasoline engines for automobiles normally use a three-layer copper alloy, and the overlay generally uses electroplated lead alloy plating material.

However, lead is an environmentally hazardous substance, and the End-of-Life Vehicles (ELV) directive is scheduled to take effect in Europe from July 2011, at which time it will no longer be possible to use lead alloy plating material. However, durability in high-speed and high-load gasoline engines with a sliding velocity of 20 m/s or more is an issue for existing lead-free bearings used in automobile engines. The concerns when changing to lead-free bearings are deformation due to fluctuating load, and a drop in running-in characteristics that indicates restoration with respect to melting and re-solidification during local heating. Lead-free technologies include methods such as lead substitution plating and sputtering⁽⁵⁾. However, liquid waste disposal is an issue for plating, and the high price of sputtering equipment gives rise to cost issues when applied to parts. For these reasons, a lead-free bearing capable of withstanding high-speed and high-load gasoline engine specifications was developed by

using a resin coating material with optimized surface roughness and solid lubricant arrangement ratio aimed at achieving seizure resistance equal to or better than that of lead alloy plating material. This paper reports the technologies involved.

2. Development Concept of Bearing for High-speed and High-load Gasoline Engine

Figure 1 shows the operating range of existing lead-free bearings. Honda mass-produces high-speed and high-load gasoline engines with a sliding velocity of 20 m/s

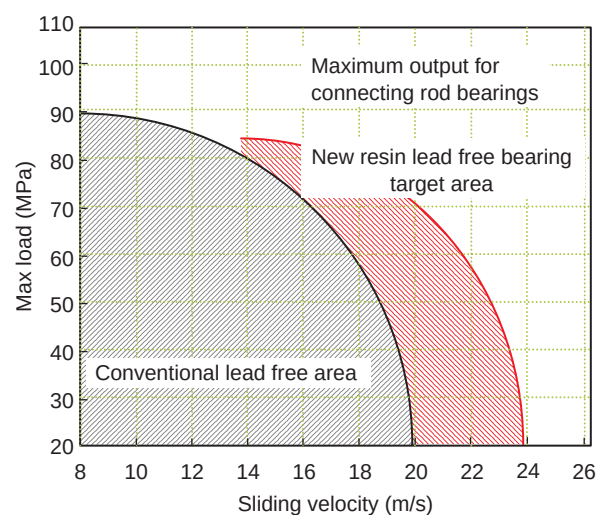
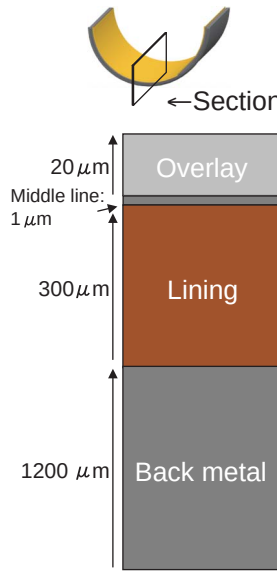


Fig. 1 Correlation of sliding velocity and max load

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Table 1 Bearing specification comparison



		Lead alloy plating	New coating material
Overlay	Material	Pb-4.5Sn-8.5In	MoS ₂ : 72 mass% ± 2 mass% + PAI
	Thickness	20 μm	5 ± 2 μm
	Surface form	–	(0,0,0) c axis arrangement
Middle line	Material	Ni plating (1 μm)	–
	Thickness	–	–
Lining	Material	Cu-3.5Sn-15Pb	Al-7Sn-3.7Si-1.5Cu
	Thickness	–	–
Back metal	Material	S20C	S20C
	Thickness	–	–

or more, and it is necessary for bearings used in this range to have the following characteristics:

- (1) Load resistance and seizure resistance
- (2) Running-in characteristics with respect to impact loads
- (3) Solid lubricity in case of oil film out

Table 1 shows the specifications of the newly developed resin coating bearing with respect to these necessary characteristics. The conventional lead alloy plating bearing specifications are also shown for comparison.

The new resin coating material combined a certain amount or more of polyamide-imide (PAI) to enhance the running-in characteristics of the aluminum alloy bearing surface, and molybdenum disulfide (MoS₂) to enhance solid lubricity. The coating thickness was set at 5 ± 2 μm. Load resistance focused on the surface roughness and MoS₂ crystal direction, and resin coating specifications that increased the load resistance were set as a development concept.

3. Technical Contents

3.1. Enhancement of Load Resistance and Seizure Resistance by Optimization of Surface Roughness

Bearing static load tests were performed using the bearing rig tester shown in Fig. 2 to verify the seizure resistance of the new resin coating material. This bearing rig tester can evaluate the seizure resistance and fatigue resistance of isolated bearings by rotating a test shaft to apply a fluctuating load. The effect of the resin coating material surface condition on seizure resistance was verified under the conditions shown in Table 2.

Attempting to prevent oil film out on the bearing surface is considered important for increasing load resistance, so the coating surface roughness was

Table 2 Seizure test conditions

Sliding velocity	20 m/s
Bearing dimension	φ48 mm
Oil temperature	80 °C
Oil pressure	0.1 MPa
Clearance	65 μm
Loaded	3 kN step-up

investigated. Figure 3 shows the results. Seizure resistance becomes lower as the surface roughness ($R_{z,IS}^{(6)}$) becomes rougher. This is thought to be because when momentary oil film out occurs due to impact load or other factors, and solid contact occurs between the bearing and the crankshaft, the convex portions of the coating, shown in the SEM surface observation results on the right side of Fig. 4 (the black dotted lines indicate the peaks), become hot due to local contact, leading to seizure. Figure 5 shows the convex form of the perpendicular section of the dotted line portions in Fig. 4. On the other hand, the seizure resistance target was met when the surface roughness is smooth, which confirmed the effects of smoothing.

Based on the results of the above bearing seizure rig

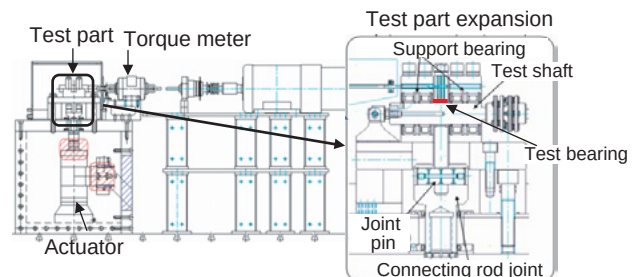


Fig. 2 Bearing rig tester

tests, the surface roughness after coating was set at Rz_{JIS} : 2.5 μm or less, which satisfies the target seizure unit load.

3.2. Enhancement of Load Resistance and Seizure Resistance by Optimization of Arrangement Ratio

When the a and b axes indicated by the Miller index of crystal direction are aligned with the bearing circumference direction as shown in Fig. 6, MoS_2 is known to possess cleavage characteristics in these directions. For this reason, the c axis direction, which is in the bearing center circle direction perpendicular to the a and b axes, is expected to have better load resistance. Therefore, the percentage of MoS_2 particles that are arranged in an orderly manner (arrangement ratio) was optimized with the aim of enhancing load resistance by aligning the c axis of the MoS_2 particles. Figure 7 shows the bearing static load rig test results, which indicate a positive correlation between the arrangement ratio and the seizing unit load. This is because MoS_2 has a layered

crystal structure with a hexagonal system, so the coupling between the sulfur in adjacent layers is weak, and when shearing force is applied, cleavage tends to easily occur in the a and b axis directions; that is to say, the bearing circumference direction. On the other hand, the coupling between the molybdenum and sulfur is strong, which gives the c axis (0,0, ℓ) surface better load resistance. It is thought, therefore, that the cleavage characteristics of MoS_2 particles arranged in an orderly manner will provide good solid lubricity. The coating conditions were set to level the squamous MoS_2 particles after coating application in order to arrange the MoS_2 particles, and the arrangement ratio was set at 80% or more.

Static load tests for isolated bearings were performed using the bearing rig tester at sliding velocities from 17.5 up to 25.0 m/s, and the seizure resistance was verified. Figure 8 shows the results compared with lead alloy

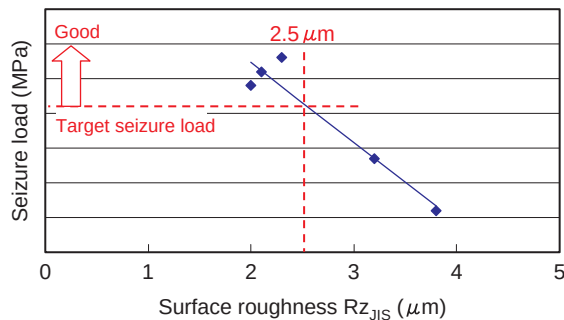


Fig. 3 Seizure resistance and surface roughness

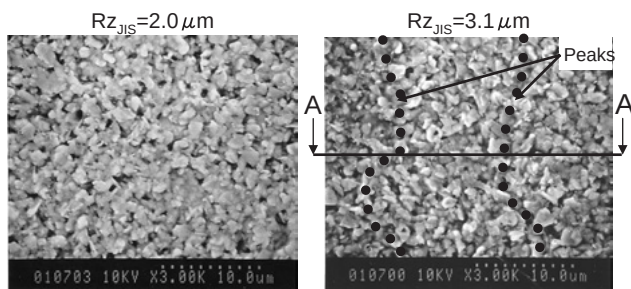


Fig. 4 SEM images of MoS_2 coating surface

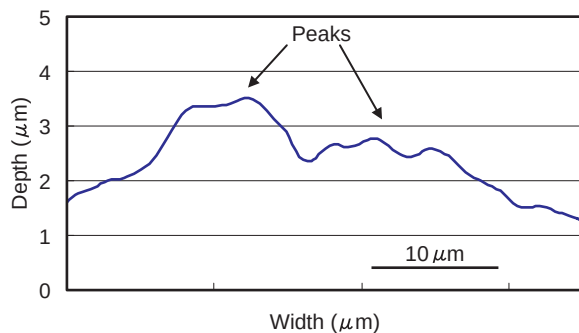


Fig. 5 A-A cross section

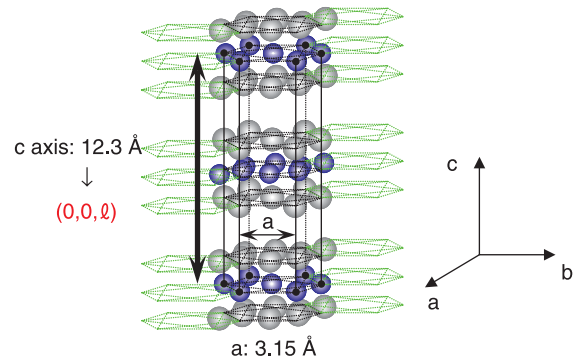


Fig. 6 MoS_2 crystal structure

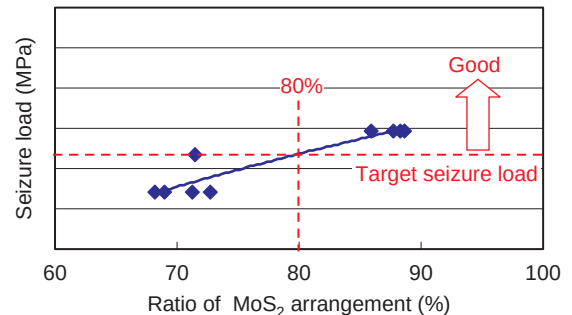


Fig. 7 Seizure resistance and MoS_2 arrangement ratio

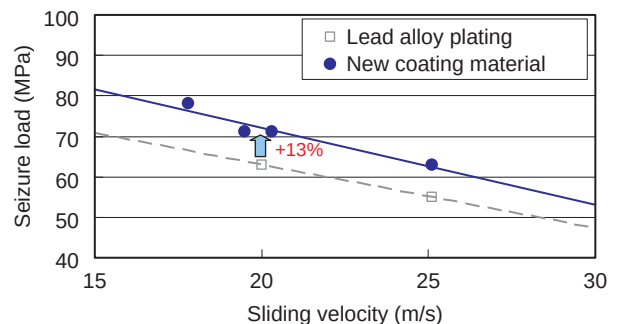


Fig. 8 Seizure resistance and sliding velocity

Table 3 Fatigue test conditions

Sliding velocity	23.3 m/s
Bearing dimension	$\phi 48$ mm
Oil temperature	100 °C
Oil flow-rate	1 L/min
Clearance	75 μ m
Loaded	100 MPa $\times$ 300 Hz sine wave

plating material. The new resin coating material obtained seizure resistance equal to or better than that of the lead alloy plating material over the entire range from low to high sliding velocities. In particular, setting a MoS₂ particle arrangement ratio of 80% or more is thought to have effectively increased the load resistance.

In addition, the bearing fatigue characteristics were tested using the bearing rig tester, under the conditions shown in Table 3. The results were compared up to a repeat count of 1×10^7 times, and showed that fatigue resistance equal to or greater than that of lead alloy plating bearings was obtained. In particular, smoothing of the surface roughness is thought to have suppressed the striking that involves solid contact between the crankshaft and the bearing, which meant that oil film out does not easily occur, so there was less heat generation due to local solid contact.

3.3. Running-in Characteristics with respect to Impact Loads

To secure running-in without seizing when an impact load is applied to the bearing overlay at a high sliding

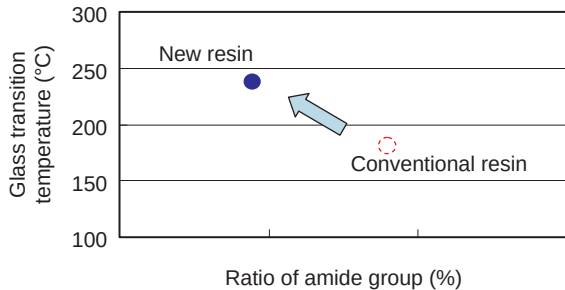


Fig. 9 Correlation of amide ratio and glass transition

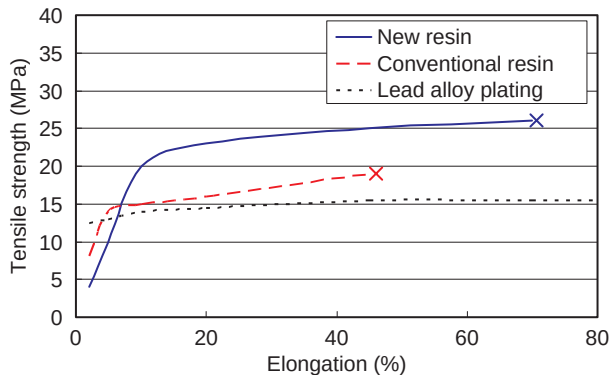


Fig. 10 Correlation of elongation and strength at 200 °C

velocity, the overlay should possess sufficient heat resistance and modification ability, the latter of which is an index for elongation and strength, to a level close to those of lead.

Figure 9 shows the relationship between the ratio of amide group and the glass transition temperature in the resin materials. Heat resistance is thought to be an issue for resin with a high ratio of amide group, as reported at JSAE⁽⁷⁾, resin (PAI) with a low ratio of amide group was selected that has a heat resistance temperature near that of lead (lead melting point: 327°C). Next, Fig. 10 shows the relationship between the resin elongation and strength at 200°C. While the highly heat resistant resin mentioned above has elongation that is half or less than that of lead, the modified PAI is known to have elongation equivalent to that of lead.

3.4. Solid Lubricity in case of Oil Film Out

With respect to solid lubricity, the compatibility of three different solid lubricants was confirmed in order to guarantee tribological properties in case of oil film out. Stick slip tests were performed as shown in Fig. 11. As shown in Fig. 12, the wear of the opposing material after the test was low in the case of MoS₂, which has cleavage characteristics. In addition, as reported at JSAE⁽⁷⁾, the combination amount was set based on measurements of the wear experienced by the MoS₂-coated test specimen and the steel ball. The test results in Fig. 13 show that steel ball wear was low at a MoS₂ combination amount

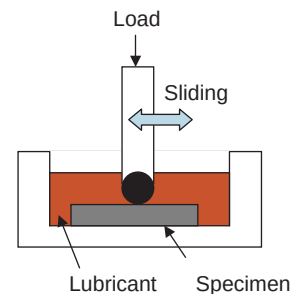


Fig. 11 Stick-slip tester

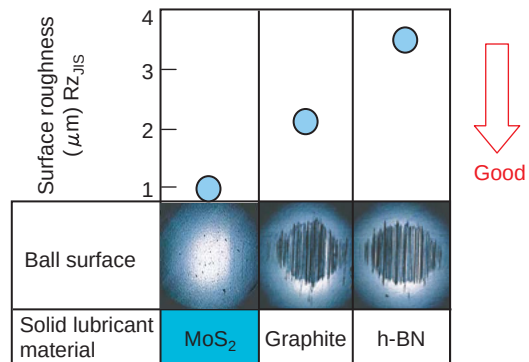
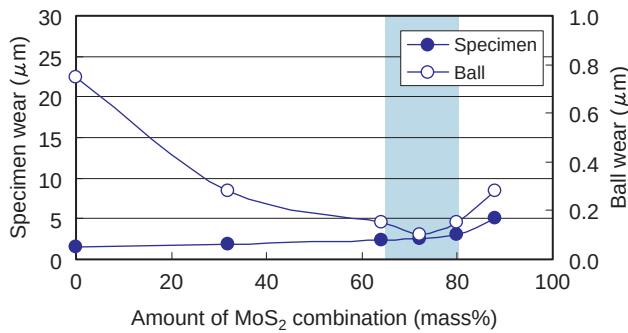


Fig. 12 Correlation of solid lubricant material and surface roughness

Fig. 13 Correlation of MoS₂ combination and wear

of 72 mass%. Therefore, the combination ratio of MoS₂, the solid lubricant to be combined into the resin coating, was set at 72 mass%.

4. Confirmation of Bearing Durability

4.1. Verification of Seizure Resistance after Coating Abrasion

Seizure resistance was confirmed under the assumption that the new coating material on the overlay had abraded. The relationship with the lining exposure rate after coating abrasion was confirmed under the conditions given in Table 2. Figure 14 shows that the new resin coating bearings have seizure resistance equal to or better than that of lead alloy plating bearings. This is thought to be affected by the presence of an adhesive layer between the overlay and the lining. Lead alloy plating bearings have a 1 μm nickel plating layer to help prevent counter diffusion between the tin in the overlay and that in the

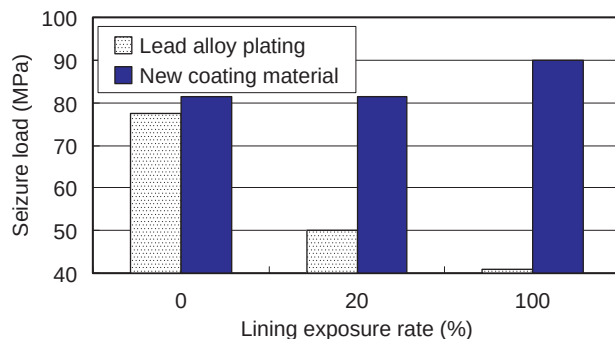


Fig. 14 Seizure resistance of lining exposure rate

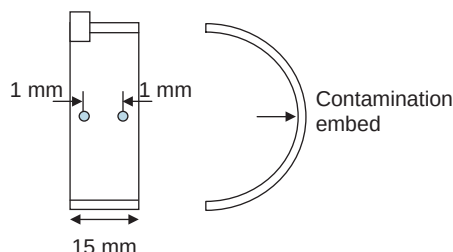


Fig. 15 Contamination trap position

Table 4 Contamination toughness test conditions

Sliding velocity	20 m/s
Bearing dimension	φ48 mm
Oil temperature	140 °C
Oil pressure	1.0 MPa
Clearance	60 μm
Loaded	3 kN step-up

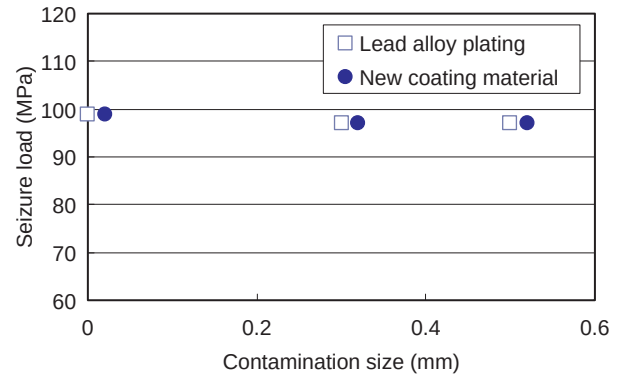


Fig. 16 Seizure resistance and contamination size

lining, and to increase the plating adhesion. This nickel plating layer has low tribological properties, and the seizure resistance decreases when it is exposed. The new resin coating material does not have an intermediate layer between the overlay and the lining, enabling use of an aluminum alloy lining that maintains the tribological properties even when the coating abrades.

4.2. Verification of Seizure Resistance with respect to Contaminant

Seizure resistance was confirmed with respect to contaminant inside the engine. Table 4 shows the conditions tested using the bearing rig tester. Contaminant is thought to affect bearing performance when it becomes embedded in the sliding surface, so seizing tests were performed by embedding contaminant directly onto the sliding surface as shown in Fig. 15.

Actual chips occurring during crankshaft machining were gathered as contaminant, and were sorted by length in the longitudinal direction. The results showed that seizure resistance was the same as that of lead alloy plating material up to a contaminant size of 0.5 mm (Fig. 16). This is because the elongation properties, surface roughness and MoS₂ particle arrangement ratio of the binder resin were enhanced, so the running-in characteristics, including solid lubricity, were equivalent to those of lead alloy plating bearings.

5. Confirmation of Compatibility in an Actual Engine

A 3.7-liter V6 engine was used to verify the compatibility of the newly developed resin coating

Table 5 Engine test conditions

Engine	3.7L V6 gasoline	
No.	(1)	(2)
Rotations	6200 rpm*WOT	6800 rpm*WOT

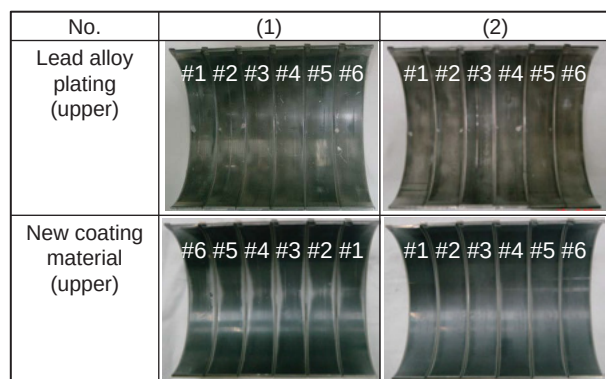


Fig. 17 Appearance of bearings after engine test

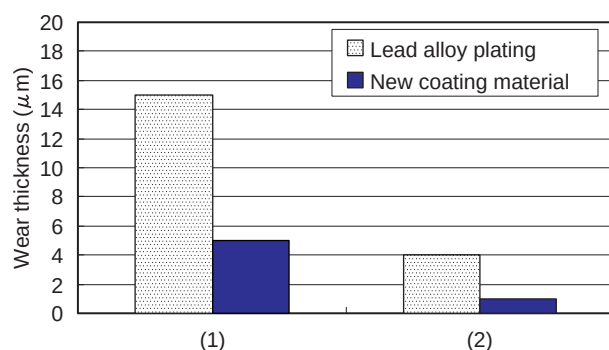


Fig. 18 Wear of durability test

bearings in an actual engine. Durability tests were performed, and the connecting rod bearings are used for verification. Table 5 shows the test conditions at wide open throttle (WOT).

Figure 17 shows the appearance of the bearings after the test. The sliding surfaces of the bearings were in good condition, and there was no seizing or fatigue cracking in any of the tests. In addition, Fig. 18 shows the bearing wear (damage) amount. The results showed wear of 4 to 5 μm under condition (1), and 1 to 2 μm under condition (2), indicating a wear resistance better than that of lead alloy plating bearings.

6. Conclusion

- (1) The surface roughness and MoS_2 particle arrangement ratio of a new resin coating material were optimized to increase the load resistance and seizure resistance. The surface roughness was set at $Rz_{\text{JIS}} = 2.5 \mu\text{m}$ or less, and the MoS_2 arrangement ratio was set at 80% or more.
- (2) The seizure resistance of the new resin coating bearings

with respect to contaminant was verified, and found to be the same as that of lead alloy plating material up to a contaminant size of 0.5 mm (maximum length).

- (3) Durability tests were performed for the new resin coating bearings in an actual engine. Seizing and fatigue cracking did not occur, and results equal to or better than those of conventional lead alloy plating bearings were obtained.

New resin coating lead-free bearings were developed that have performance equal to or better than that of lead alloy plating bearings for high-speed and high-load gasoline engines. These new bearings were applied to the connecting rods of the 2008 model year ACURA RL.

References

- (1) Mihara, K., Schubert, W., Deicke, K., Reinicke, R., Damm, K.: Development of Lead Free Sputter Bearings for Highly Loaded Engines, 2008 JSAE Annual Congress Proceedings, No. 148-08, p. 15-18 (2008)
- (2) Machida, K., Takahashi, S., Ueshima, H., Fujiki, K.: Proposal of New Bearing Simulation Rig Tester for High Efficiency Engine Bearing Development, Honda R&D Technical Review, Vol. 18, No. 2, p. 131-139
- (3) Kanayama, H., Kawakami, S., Gouhara, C., Fuwa, Y., Michioka, H.: Development of new Engine Bearings with Overlay Consisting of Solid Lubricants, 1997 JSAE Annual Congress Proceedings, No. 976, p. 141-144 (1997)
- (4) Goto, Y., Tomikawa, T., Suga, S.: Development of Pb Alloy overlay for High Rotation Engines, 2001 JSAE Annual Congress Proceedings, No. 66-01, p. 9-12 (2001)
- (5) Kamiya, S., Tomikawa, T., Goto, Y., Honda, F.: Friction Characteristics of Ag-Sn Alloy Layer Prepared by RF Sputtering, JOURNAL OF JAPANESE SOCIETY OF TRIBOLOGISTS, Vol. 45, No. 2, p. 158-155 (2000)
- (6) Japanese Standards Association: JIS Handbook, Mechanical Instrumentation, 46, p. 636 (2007)
- (7) Kabeya, Y., Kawagoe, K., Fuwa, Y., Saito, Y.: Development of high speed and high load engine bearings with Solid Lubricant Overlay, 2006 JSAE Annual Congress Proceedings, No. 9-06, p. 1-4 (2006)

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