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Thin Film Sensors for Measuring Oil Film Condition in Machine Sliding Surfaces

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***Abstract*— In order to reduce CO2 emissions and fuel consumption, the reduction of mechanical friction loss is very important technologies. To reduce such friction loss, understanding the lubrication conditions of engine sliding surfaces are very important. In order to investigate their conditions and to validate the CAE (Computer aided engineering), the author has developed a thin-film pressure, strain, temperature and also thin-film gap sensor and measured the distributions of oil-film condition in sliding surface in machinery main bearings, piston skirts, pin-bosses and gear tooth surfaces. In this paper, the structure and form of thin-film sensor especially for piston skirts, plain bearings were discussed and provided a measurement example.**

***Keywords*— Thin-film, oil film thickness, Oil film pressure, Thermal sensitivity, Gauge factor**

I. Introduction

Internal combustion engines have been required for further improvement of thermal efficiency, i.e. reduction of fuel consumption. While downsizing turbo engines are often mentioned as the trend in recent years, cylinder pressure has been increasing and engines are becoming compact and light weight. Because of this, the engine components have become narrower and thinner-walled, and local lubrication performance in sliding parts is continuously increasing due to high pressure and partial contact. Appropriate calculation conditions and also the verification of the calculation results by the precise measuring method have been required. However, calculated results in sliding surface with deformation in engine operating condition have not yet been confirmed experimentally. The optimization of the multi-layer form a film of the sensor shape and sensor film was performed in order to reduce the temperature sensitivity and the strain sensitivity is a measurement error of the oil film pressure.

II. Oil film pressure sensor

A. Measurement Principle

Cu-Mn-Ni alloy was used as the pressure sensing material, and electrical resistance of this alloy changes according to the changes in pressure. Oil-film pressure was measured after converting this change in resistance into change in voltage using Wheatstone bridge circuit (refer to Fig.1). For resistance R1 through R3 of each side except sensors, variable resistors were used and adjusted the resistance value of each side according to the resistance value of individual thin-film sensor. This voltage output was recorded by data logger through strain amplifier.

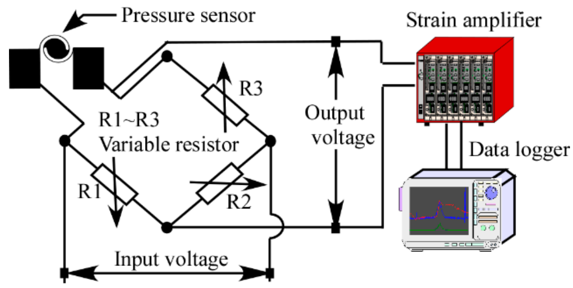


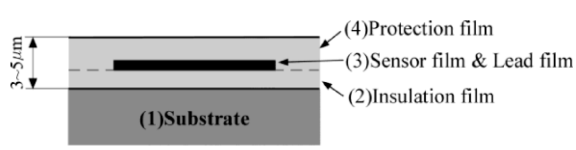
Fig.1 Measurement circuit (Wheatstone bridge)

B. Structure

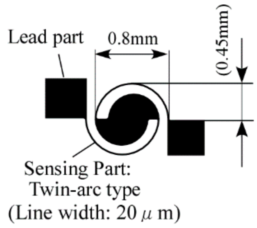
The sensing part of the thin-film pressure sensor employed in this research is a thin-film resistor directly deposited physical vapor deposition in the area intended for measurements. The sensor does not require mounting holes or oil-leading holes for use in measurement, and its shape when mounted can follow the curvature of sliding parts. It is therefore a sensor that has an extremely minimal effect on the measurement target, and it does not change it shape, reduce its stiffness or increase its mass.

Fig.2 (a) shows the film structure of a sensor. On the sliding surface of substrate, thin-film sensor having total film thickness 3~5μm was sputtered and it comprised of insulation film (Al_2O_3) for maintaining insulation between the substrate and the sensor, sensing and lead part film (Cu-Mn-Ni alloy) that detects oil film pressure and has a role which takes out the signal outside respectively. Protection film (Al_2O_3) that maintains insulation of the sensor film and protects the sensor film from the contact of counter parts object.

Fig.2 (b) shows the configuration of thin-film pressure sensor. Pressure sensing part which has been used conventionally in our research comprised two semicircular arcs of φ0.8mm, line width 20μm and two semicircles in the center. This is one configuration of realizing minimum strain sensitivity (gauge factor) of thin-film pressure sensor.



(a) Structure of sensor.



(b) Twin arc

Fig.2 Structure of thin-film sensor

C. Sensor material

In order to find the best alloy composition for the pressure sensor, we varied the composition of the Cu-Mn-Ni alloy(1)~(5) as given in TABLE I and measured the pressure sensitivity and temperature sensitivity. No.(6) is a Ni-Cr alloy, which will be referred to in later sections.

TABLE I

SENSOR ALLOYS FOR THIN-FILM PRESSURE SENSOR

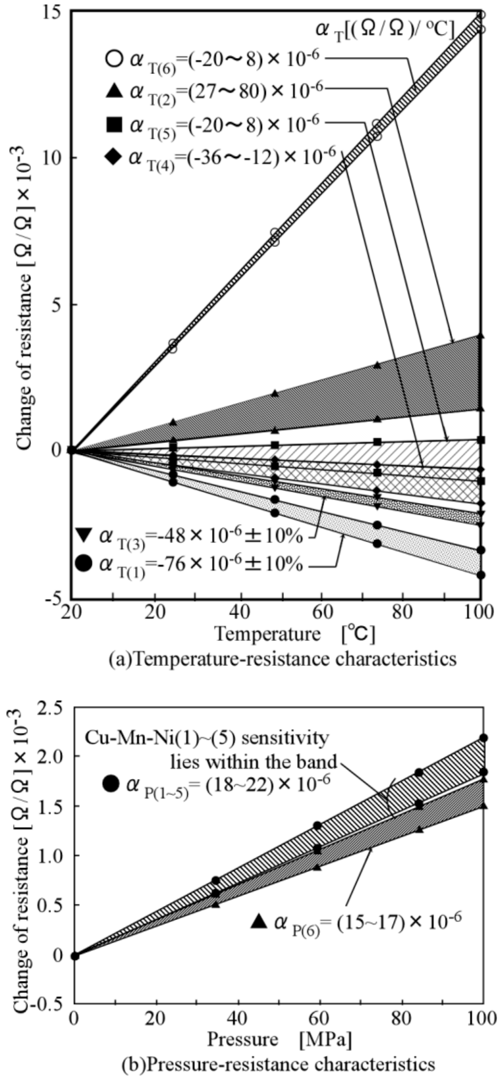
Sensor Alloy	Alloy composition [wt%]
(1)Cu-Mn-Ni(I) (2)Cu-Mn-Ni(II) (3)Cu-Mn-Ni(III) (4)Cu-Mn-Ni(IV) (5)Cu-Mn-Ni(V)	(8～15) Mn, (2～4) Ni, Rest Cu
(6)Ni-Cr Alloy	(80 ～90) Ni, Rest Cr

D. Reduction of temperature sensitivity

Fig.3(a) shows the temperature sensitivity for the various compositions in TABLE I. The composition (2) showed positive sensitivity $\alpha_{T(2)}$ =(27~80)×10^{-6} [(Ω/Ω)/ºC], while the composition (1), (3) and (4) showed negative one. The composition(5) showed both positive and negative sensitivity, $\alpha_{T(5)}$ =(-20~8)×10^{-6}[(Ω/Ω)/ºC]. Among the Cu-Mn-Ni alloys tested, this composition(5) gave the smallest temperature sensitivity including the sensitivity of $\alpha_{T(5)}$ =0.

E. Pressure sensitivity

As shown in Fig.3(b), the pressure sensitivities of the Cu-Mn-Ni alloys fell in the range (18~22)×10^{-6} [(Ω/Ω)/MPa], regardless of the composition. From the temperature sensitivity and pressure sensitivity values shown in Fig.2, the error in measured pressure for temperature difference by 1°C is calculated and depicted in Fig.3(c). In the temperature range 50~100°C, the alloy(5) had the smallest value, (-1.1~0.4)[MPa/°C]. Therefore, for measuring pressure under temperature change, this alloy is most suitable.



(c)Pressure measurement error against unit temperature difference

Fig.3 Characteristics of materials for thin-film pressure sensor

F. Strain gauge sensitivity

Fig.4 shows the transverse sensitivity ratio tester of strain gauge for examining the twin arc type gauge factor (Kc). The legs of this tester applying a force F from the direction shown in Fig.4 was distorted 1000με in the width direction (Fig.4, y direction) of this tester. In this case, this tester in the longitudinal direction (Fig.4, x direction) was distorted (5 ~ 2) με. Each direction of twin arc-type thin-film pressure sensors were mounted to the orthogonal to the upper surface of the beam portion of the length 20mm in this tester. As the monitor of the strain amount in the x-direction and y-direction, commercially available two-axis strain gauge was mounted in the beam portion.

As shown in TABLE II, gauge factor in the longitudinal direction strain sensitivity Kl and lateral direction strain sensitivity Kw was the same value. The TABLE II showed the strain gauge sensitivities of the Cu-Mn-Ni alloys (Kl=Kw=Kc=-0.25 ～ -0.35) and Ni-Cr alloy (Kl=Kw=Kc=-1.18～1.2).

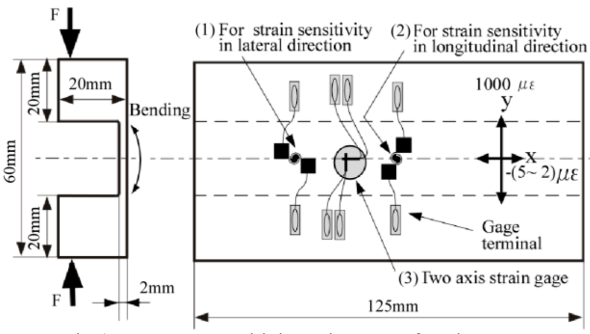


Fig.4 Transverse sensitivity ratio tester of strain gauge

TABLE II
GAUGE FACTOR

Sensor form	Sensor Alloy	Gauge factor (≈ Strain sensitivity) Kc	
		Kl (Longitudial)	Kw (Lateral)
Twin-arc	Cu-Mn-Ni (I)～(V)	-0.25～-0.35	-0.25～-0.35
	Ni-Cr alloy	1.18~1.20	1.18~1.20

III. MULTI-LAYER TYPE OIL FILM PRESSURE SENSOR

A. Development outline

In the engine sliding parts, there is a portion of the deformation in the piston skirt and the like. In such parts in addition to the method of reducing strain sensitivity due to twin arc type sensor shown in Fig.2 (b), it is necessary to lower the further strain sensitivity. Therefore, we developed a multilayered thin film pressure sensor by forming a Ni-Cr alloy on the conventional Cu-Mn-Ni alloy. Cu-Mn-Ni alloy has a negative sensitivity to the strain. In addition, Ni-Cr alloy has a positive sensitivity to strain. By optimizing the film thickness ratio of the Cu-Mn-Ni alloy and Ni-Cr alloy, it is possible to reduce the additional strain sensitivity.

B. Structure

The shape of the sensor is the same as twin arc type shown in Fig.2(b), the structure of the films was two-layer structure of different Cu-Mn-Ni alloy and Ni-Cr alloy of film thickness shown in Fig.5.

The main sensor layer is a Cu-Mn-Ni alloy, the sub-sensor layer is a Ni-Cr alloy, the film thickness ratio is as follows.

Thickness ratio = (Ni-Cr alloy) / (Cu-Mn-Ni alloy)× 100(%)

We examined the sensor characteristics for the Cu-Mn-Ni (I) ~ (V) alloys and the film thickness ratio of Ni-Cr alloy.

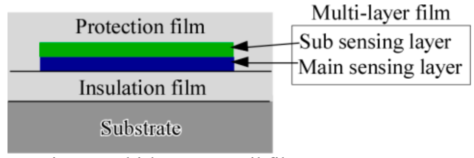


Fig.5 Multi-layer type oil film pressure sensor

C. Pressure sensitivity

Fig.6 shows the characteristics of the pressure sensitivity in a case of changing the thickness ratio of the Cu-Mn-Ni alloy and the Ni-Cr alloy.

Changing the two alloy of film thickness ratio, pressure sensitivity the same as in the case of the Cu-Mn-Ni alloy single-layer (film thickness ratio of 0%) is αP = (18.0 ~ 21.0) × 10^{-6}[(Ω/Ω)/MPa]. In addition, changes in pressure sensitivity by changing the composition of the Cu-Mn-Ni alloy(1)~(5) was not.

D. Strain gauge sensitivity

Fig.7 shows the characteristics of the Strain gauge sensitivity in a case of changing the thickness ratio of the Cu-Mn-Ni alloy and the Ni-Cr alloy. Kc with increasing film thickness ratio is gradually increased. In the case of the film thickness ratio of 25%, Kc was almost zero. Influence due to the deformation than this has developed a thin film pressure sensor of the little gauge factor Kc ≒ 0 .

E. Temperature sensitivity

Multi-layered type sensor was able to almost zero the strain sensitivity, but the problem that the temperature sensitivity is increased to 60 × 10-6 [(Ω/Ω)/MPa] occurs. However, by the low temperature sensitivity is used for Cu-Mn-Ni alloy, Multi-layered type sensor was able to reduce the temperature sensitivity without changing the strain sensitivity and pressure sensitivity.

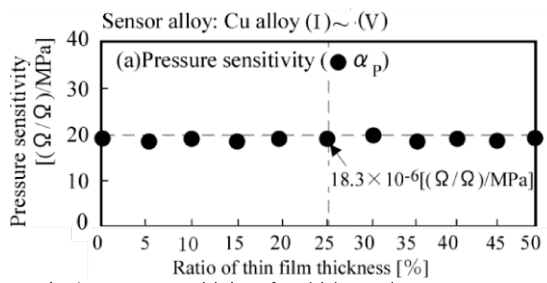


Fig.6 Pressure sensitivity of multi-layered type sensor according to the ratio of film thickness

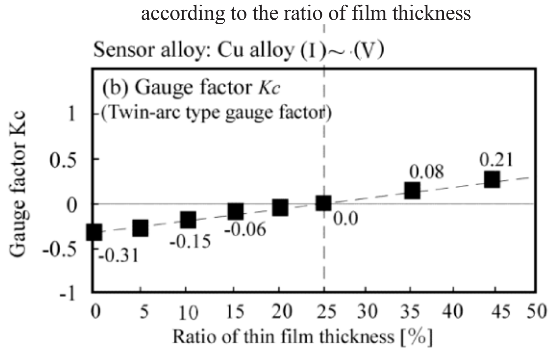


Fig.7 Gage factor of multi-layered type sensor according to the ratio of film thickness

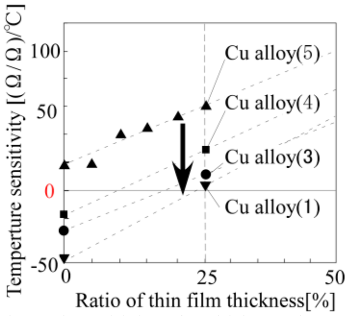


Fig.8 Thermal sensitivity of multi-layered type sensor according to the ratio of film thickness

IV. THIN-FILM GAP SENSOR

A. Structure

Thin-film gap sensor is made by applying the principle of the eddy current type displacement sensor. Fig.9 shows the shape of the Thin-film gap sensor. In addition, Fig.10 shows the film structure of a sensor.

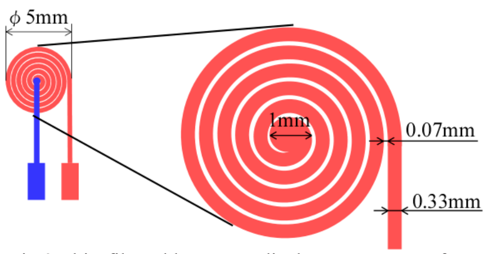


Fig.9 Thin-film eddy current displacement sensor form

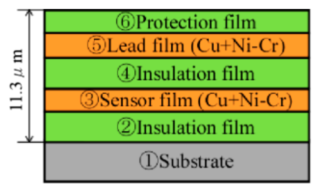


Fig.10 Structure of thin-film eddy current displacement sensor

B. Output characteristic

Fig.11 shows the result of the comparison between the commercially available sensors. The output compared to a commercially available sensor is reduced approximately 80%, but confirmed the linearity of the output. This thin-film sensor has been found to be used as a distance sensor.

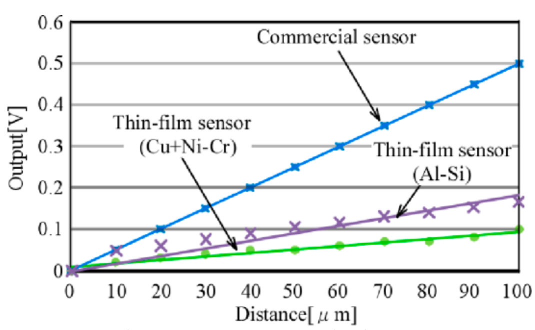


Fig.11 Measurement result of sensor

C. Application Example

Fig.12 shows the case that provided in the main bearing of the engine sliding parts.

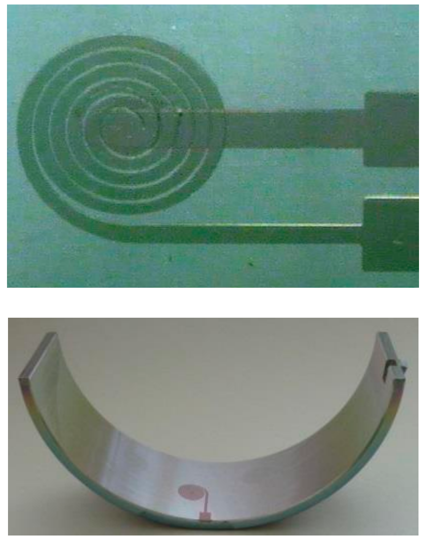


Fig.12 Example of t displacement sensor

V. DLC PROTECTION FILM

A. DLC (diamond-like carbon)

DLC (diamond-like carbon) is an amorphous carbon film of which can be in the course of the diamond gas phase synthesis. However, DLC has excellent properties as a sliding material such as a low coefficient of friction, less prone to welding or adhesion though chemically stable. We adopted the DLC in the protective film by have such characteristics.

B. Specific quality by Raman spectroscopy

By Raman spectroscopy, DLC can be separated into two peaks of Graphite Peak, and Disorder Peak, which emits light by the vibration of the double bond carbons.

The DLC used for this protection film was specified quality by Raman spectroscopy. TABLE III shows the results of Raman spectroscopy of the DLC that was used for the protective film. Fig.13 shows the DLC structure classification by Raman spectroscopy.

TABLE III
THE RESULTS OF RAMAN SPECTROSCOPY

Graphite Peak	Disorder Peak
1543	1362

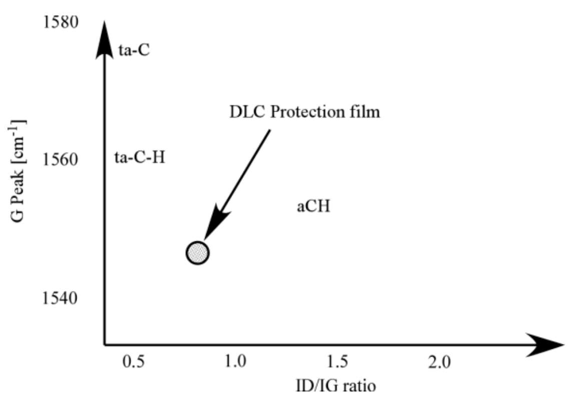


Fig.13 Structural analysis of DLC by Raman spectroscopy

C. Application Example

Fig.14 shows the state of the protection film of the piston skirt after the experiment. Fig.14 (a) has occurred destruction of the film at the time of low speed and low load in the Al_20_3 protection film. However, Fig.14 (b) did not occur even destruction of the membrane in the environment of the time after the high rotation load DLC protection film.

(a) Al_2O_3 protection film (b) DLC protection film

Fig.14 The state of the protection film of the piston skirt after the experiment

VI. CONCLUSIONS

(1) A thin-film sensor that has an extremely minimal effect on the measurement target, and it does not change it shape, reduce its stiffness or increase its mass.
(2) Thin-film pressure sensor by varying the composition of the Cu-Mn-Ni alloy, it was possible to reduce the temperature sensitivity without changing the pressure sensitivity.
(3) Multi-layered type sensor could be reduced strain sensitivity by a two-layer structure. In addition, the problem of temperature sensitivity to increase could be reduced by changing the composition ratio of Cu-Mn-Ni. Thus, to allow measurement of the engine sliding parts which large deformation.
(4) A thin-film gap sensor was developed and confirmed output. This thin-film sensor has been found to be used as a distance sensor.
(5) Durability of the thin-film sensor was confirmed by the DLC protective film.

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