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Measurement of Oil-film Pressure Distribution in Engine Sliding Surface Using Thin-film Sensor

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Abstract - **In order to measure the oil-film pressure in engine bearings, we developed a new piezo-resistive thin-film sensor made of Cu-Mn-Ni alloy with twin-arc shape and reduced and uniform strain sensitivity. This allowed to correct the error in measured pressure due to strain using a thin-film strain sensor made of Ni-Cr-Al alloy effectively. The error in measured pressure due to temperature influence could be also reduced by optimizing the composition of Cu-Mn-Ni alloy. This paper introduces the measurement method and a measurement result in engine bearings using thin-film sensor.**

Keywords - **Pressure sensor, Thin-film, Internal combustion engine, Tribology**

I. INTRODUCTION

Pressure measurement using piezo-resistive method was first introduced by Bridgeman [1] applying metals, especially an alloy of copper, manganese and nickel. Using this alloy, Kannel et al. [2] have developed a thin-film pressure sensor to measure the oil-film pressure between two rollers. This sensor has the advantages of very small size and of enabling the measurement of high pressure exceeding 1000 [MPa]. It has, therefore, been used in research of the elasto-hydrodynamic lubrication (EHL) of machine elements such as rollers [3]. Using the same technique, the present authors have measured the oil-film pressure by thin-film sensors deposited on to the sliding surface of the engine bearings [4-6]. However, temperature change and deformation of the sliding surface affected the sensor output in engine operation, and made the correction necessary, as the oil-film pressure in the plain bearing is of the order of only 10 [MPa] to 100 [MPa]. In this paper, it should be reported, how the temperature influence could be reduced by developing a new material composition and how the influence of bearing deformation could be reduced by developing a new shape of the sensor.

II. MEASUREMENT PRINCIPLE

The electrical resistance of thin-film sensor changes under pressure. This change in resistance is converted into the voltage change through the Wheatstone bridge circuit and is amplified and recorded. The change in resistance is mostly attributable to the piezo-resistive effect, which is the change in electrical resistivity ρ of the alloy caused by pressure. The electrical resistance R of this sensor depends on pressure P, temperature T and strain ε : $R = (P, T, \varepsilon)$. In linearity range, the change in these variables will result in the change ΔR of the resistance:

$$\Delta R / R = \alpha_P \cdot \Delta P + \alpha_T \cdot \Delta T + \alpha_\varepsilon \cdot \Delta\varepsilon \qquad [1]$$

where $\alpha_P = (dR/R)/dP$, $\alpha_T = (dR/R)/dT$ and $\alpha_\varepsilon = (dR/R)/d\varepsilon$ is the pressure sensitivity, the temperature sensitivity and the strain sensitivity of the pressure sensing alloy, respectively. In applying equation [1] for pressure measurement, the second and third terms, which represent errors, should be negligibly small compared to the first term.

III. STRUCTURE OF THIN-FILM PRESSURE SENSOR

Fig.1 shows the structure of the thin-film sensor for the measurement of pressure sensitivity, temperature sensitivity and strain sensitivity of alloy materials. As seen in Fig.1, the isolation film (2) of 2~2.5 μm thickness was deposited on the substrate (1) of a stainless steel (75 mm, long, 25 mm wide, 2 mm thick). Then a sensitive part of straight line type (3 mm long, 30 μm wide, 0.1~0.3 μm thick) was deposited by photolithography method.

With a 1~2 μm thick protection film deposited on the sensor film, the total film thickness of the sensor is 3~5 μm. For the two lead parts shown in Fig.1 (a), the error ratio, defined by equation [2] should be made as small as possible.

$$\text{Error ratio} = 100\, R_L / (R_A + R_L)\ \% \qquad [2]$$

where R_A is the resistance of the sensitive part and R_L is the total resistance of the lead parts. The sensor shown in Fig.1 (a) resulted in error ratio equal to or less than 1%.

IV. OPTIMIZATION OF Cu-Mn-Ni ALLOY COMPOSITION

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 1 and measured the pressure sensitivity and temperature sensitivity. No. (6) is an Ni-Cr-Al alloy, which will be referred to in later sections

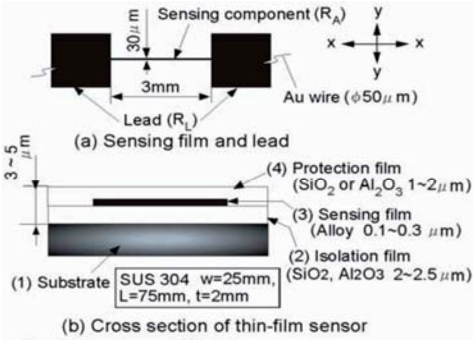


Fig.1 Structure of thin-film pressure sensor

Table 1 Alloy composition
(Thin-film, straight-line type)

Alloy No.	Composition ratio [mass%]
● (1)	82.0Cu, 15.0Mn, 3.0Ni
▲ (2)	87.8Cu, 8.75Mn, 3.45Ni
▼ (3)	86.0Cu, 12.0Mn, 2.0Ni
◆ (4)	86.6Cu, 11.0Mn, 2.4Ni
■ (5)	87.4Cu, 9.6Mn, 3.0Ni
○ (6)	70.5Ni, 18.5Cr, 11.0Al

A. Reduction of temperature sensitivity

Fig.2 (a) shows the temperature sensitivity for the various compositions in Table 2. The composition (2) showed positive sensitivity $\alpha_T(2) = (27\sim80)\times10^{-6}$ [(Ω/Ω)/ºC], while the composition (1), (3) and (4) showed negative one. The composition (5) showed both positive and negative sensitivity, $\alpha_T(5) = (-20\sim8)\times10^{-6}$ [(Ω/Ω)/ºC]. Among the Cu-Mn-Ni alloys tested, this composition (5) gave the smallest temperature sensitivity including the sensitivity of $\alpha_T(5) = 0$.

B. Pressure sensitivity

As shown in Fig.2 (b), the pressure sensitivities of the Cu-Mn-Ni alloys fell in the range $(18\sim22)\times10^{-6}$ [(Ω/Ω)/MPa], regardless of the composition. From the temperature sensitivity and pressure sensitivity values shown in Figures 2, the error in measured pressure for temperature difference by 1°C is calculated and depicted in Fig.2 (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.

V. STRAIN SENSITIVITY OF SENSOR ALLOY

When the sensor is deformed, the third term $\alpha_\varepsilon \cdot d\varepsilon$ in equation [1] yields an error in measured pressure. We have, therefore, devised following method for reducing this measurement error. Generally, the strain sensitivity (or usually called also gauge factor) K depends on the shape and the material property of the sensor. That one measured by a straight-wire or a straight-line sensor is denoted by K_s in this paper. K and K_s were measured by using a transverse sensitivity tester defined in NAS 942 standard.

A. Measurement results of strain sensitivity

The test results of strain sensitivity in longitudinal or xx direction K_{sl} and those in lateral or y-y direction K_{sw} (Fig.1 (a)) are given in Table 2. All values of K_{sl} of Cu-Mn-Ni alloys (1)~(5) lie between 0.50 and 0.70 and are smaller than those of the other alloys in Table 2. On the other hand, all values of K_{sw} of Cu-Mn-Ni alloys lie between -1.40 and -1.10 and are larger than those of the other alloys.

B. Method of correction for the error in measured pressure due to strain

The sensitivities to temperature and pressure of the Ni-Cr-Al alloy (6) in Table 1 were very small as shown in Fig.2: $\alpha_{T(6)} = (-4\sim0)\times10^{-6}$ [(Ω/Ω)/ºC] and $\alpha_{P(6)} = \pm1.0\times10^{-6}$ [(Ω/Ω)/MPa]. Thus strain can be measured directly without correction by this Ni-Cr-Al in order to compensate for the error in pressure measured by a Cu-Mn-Ni sensor due to strain.

Assuming that the temperature change is negligibly small during the measurement of pressure by the sensor of Cu-Mn-Ni alloy (5), equation [1] is reduced to equation [3]:

$$(\Delta R / R)_C = \alpha_{PC} \cdot \Delta P + \alpha_{\varepsilon C} \cdot \Delta\varepsilon \qquad [3]$$

As α_P and α_T of Ni-Cr-Al are very small, as discussed above, equation [1] is reduced to equation [4]:

$$(\Delta R / R)_N = \alpha_{\varepsilon N} \cdot \Delta\varepsilon \qquad [4]$$

where the suffix C and N refer to the Cu-Mn-Ni and Ni-Cr-Al sensor, respectively. For the strain sensitivities of these materials, following relations hold: $\alpha_{\varepsilon C} = K_C$ and $\alpha_{\varepsilon N} = K_N$. Therefore, introducing the ratio of these strain sensitivities by $a = K_C/K_N$, the corrected pressure ΔP is obtained as follows:

$$\Delta P = \{(\Delta R / R)_C - K_C \cdot \Delta\varepsilon\} / \alpha_{PC}$$
$$= \{(\Delta R / R)_C - a \cdot K_N \cdot \Delta\varepsilon\} / \alpha_{PC} \qquad [5]$$

while equation [4] and $(\Delta R/R)_N = K_N \cdot \Delta\varepsilon$ yield:

$$\Delta P = \{(\Delta R / R)_C - a \cdot (\Delta R / R)_N\} / \alpha_{PC} \qquad [6]$$

Putting the measured $(\Delta R/R)_C$ and $(\Delta R/R)_N$ into equations [6], the corrected pressure ΔP is obtained.

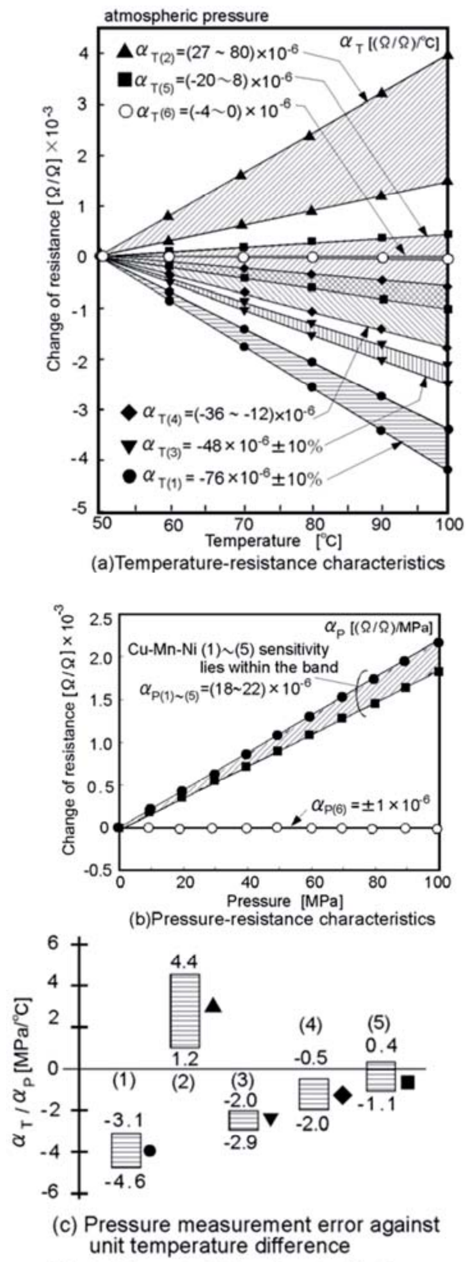


Fig.2 Characteristics of materials for thin-film pressure sensor

Table 2 Strain sensitivity

Alloy	Strain sensitivity K_{sl} (Longitudinal)	Strain sensitivity K_{sw} (Lateral)
Cu-Mn-Ni (1)~(5)	0.50 ~ 0.70	-1.40 ~ -1.10
80Ni-20Cr	2.10 ~ 2.18	- 0.35 ~ - 0.32
Cu-Ni	1.94 ~ 1.97	- 0.05 ~ - 0.02
Ni-Cr-Al	1.40 ~ 1.50	- 0.42 ~ - 0.37

C. Effective shape of the sensitive part for strain correction

If the sensitive part is a straight-line as shown in Fig. 1(a), equation [6] can not be applied directly, because the strain sensitivity ratio *a* has different values in the longitudinal and lateral directions: *a*(*longitudinal*) = $K_{IC}/K_{IN} \approx 0.4$ and *a*(*lateral*) = $K_{wC}/K_{wN} \approx 3$, as shown in Table 3.

Table 3 Strain sensitivity *Ks* and strain sensitivity ratio *a*

Straight-line type (Measured data)

Sensor shape and dimension	Sensor alloy	Strain sensitivity K_s Longitudinal	Strain sensitivity K_s Lateral
w = 30μm, L=3mm, Longitudinal, Lateral	Cu-Mn-Ni	K_{sIC} =0.59	K_{swC} = -1.19
	Ni-Cr-Al	K_{sIN} =1.49	K_{swN} =- 0.40
	Strain sensitivity ratio : *a*	*a* (Longitudinal) $= \frac{K_{sIC}}{K_{sIN}} \approx 0.4$	*a* (Lateral) $= \frac{K_{swC}}{K_{swN}} \approx 3$
		a (Longitudinal) ≠ *a* (Lateral)	

D. Effect of reduced strain sensitivity

By introducing a twin-arc type sensor shown in Table 4, also the absolute value of strain sensitivity could be reduced. Namely, the longitudinal strain sensitivity of straight line type, K_{slC} = 0.59, was reduced to K_{IC} = -0.30, while the lateral strain sensitivity of straight line type, K_{swC} = -1.19, was reduced to K_{wC} = -0.30. As a result, no correction is needed in pressure measurement when the strain $\Delta\varepsilon$ is relatively small.

Table 4 Strain sensitivity *K* and strain sensitivity ratio *a*

Twin-arc type (Measured data)

Sensor shape and dimension	Sensor alloy	Strain sensitivity *K* Longitudinal	Strain sensitivity *K* Lateral
0.95mm, 0.4mm, w = 20~30μm, Longitudinal, Lateral	Cu-Mn-Ni	K_{IC} =- 0.30	K_{WC} =- 0.30
	Ni-Cr-Al	K_{IN} =0.55	K_{WN} =0.54
	Strain sensitivity ratio : *a*	*a* (Longitudinal) $= \frac{K_{IC}}{K_{IN}} \approx -0.55$	*a* (Lateral) $= \frac{K_{wC}}{K_{wN}} \approx -0.56$
		a (Longitudinal) ≈ *a* (Lateral)	

VI. MESUREMENT RESULTS OF OIL-FILM PRESSURE IN CONNECTING ROD BEARING

A. Test engine and measurement environment

A water-cooled four-cylinder turbo-charged diesel engine of 5307 cm^3 piston displacement was used for oil-film pressure measurement in the connecting rod bearing. As shown in Fig.3, the thin-film sensors were deposited on the bottom axial line of connecting rod bearing surface at 5 different points with equal distance 4 mm. 7 films of extending from each sensing parts to the bearing ends represent the 0.2 μm thick lead film made of aluminum. In order to investigate the effects of the bearing metal deformation on the measurement of oil-film pressure, we deposited the Ni-Cr-Al strain sensor in the same positions as the pressure sensors in Fig.3. Fig.4 shows the locations of the installed thin-film sensors. The measurement was made on the fourth (from the front side of the engine) connecting rod bearing.

B. Measurement results and correction method

Fig.5 shows the results of the experiment at an engine speed of 2500[rpm] and supply oil temperature of 90[ºC] under full and no load. The sensor was located in the center of the bearing. Curve (1) represents the results of measurement using a thin-film strain sensor, curve (2) the correction for pressure measurement calculated by equation (4), curve (3) the oil-film pressure measured by Cu-Mn-Ni alloy, curve (4) the corrected pressure, which is the sum of (2) and (3). Curve (5) represents the value of the bearing load calculated by a simple method, and curve (6) the measured cylinder pressure that was used for the bearing load calculation.

C. Axial oil-film pressure distribution in the big-end bearing

Fig.6 depicts a series of axial oil-film pressure distributions in the operating condition of 2500 rpm with full load at crank angles from -28 to 12 degrees, when the bearing load acting on the connecting rod is sharply increased from 32 [kN] to 75 [kN] (unit load: from 23 [MPa] to 54 [MPa]). All the oil-film pressures in Fig.6 are corrected data, as shown on (4) in Fig.5.

VII. CONCLUSION

(1) The best composition of Cu-Mn-Ni alloy for measuring pressure was 87.4Cu-9.6Mn-3.0Ni [mass%]. It showed the smallest temperature sensitivity $\alpha_{T(5)}$ = $(-20\sim8)\times10^{-6}$ [(Ω/Ω)/ºC], among the tested alloy compositions. On the other hand, pressure sensitivity of Cu-Mn-Ni alloy fell in the range of $(18\sim22)\times10^{-6}$ [(Ω/Ω)/MPa], regardless of alloy compositions. Thus the 87.4Cu-9.6Mn-3.0Ni alloy composition showed the smallest error (α_T/α_P) in measured pressure due to temperature difference of 1ºC. Its value was (-1.1~0.4) [MPa/°C].

(2) The longitudinal strain sensitivity K_{sl} of the Cu-Mn-Ni alloy was between 0.50 and 0.70, while its lateral strain sensitivity K_{sw} was between -1.40 and -1.10.

(3) We devised a twin-arc type sensor, of which the longitudinal and lateral strain sensitivity, K_l and K_w are equal theoretically. Really, this type of sensor gave the results K_l = -0.3 and K_w = -0.3 for Cu-Mn-Ni alloy and K_l = 0.55 and K_w = 0.55 for Ni-Cr-Al alloy. Thus the strain sensitivity ratio a for both materials could be made equal in longitudinal and lateral directions, and the error in measured pressure due to strain could be corrected.

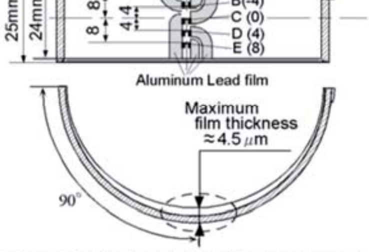


Fig. 3 Thin-film pressure sensor on engine connecting rod big-end bearing (Total 5 sensors)

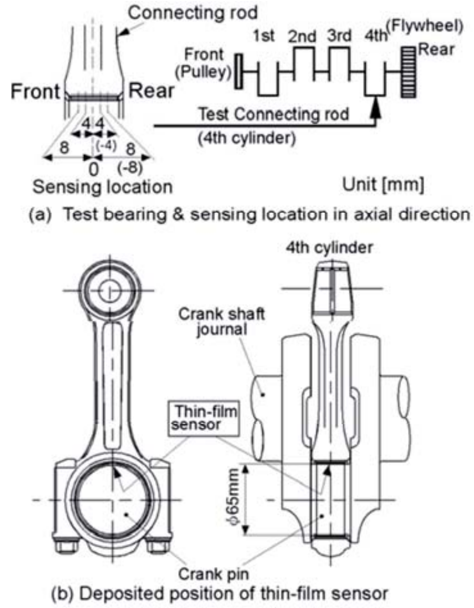


Fig.4 Test connecting rod bearing in diesel engine

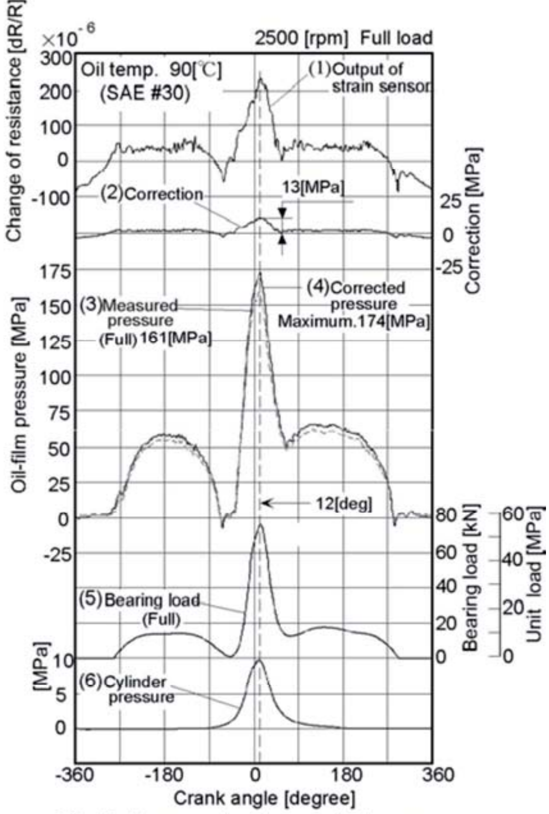
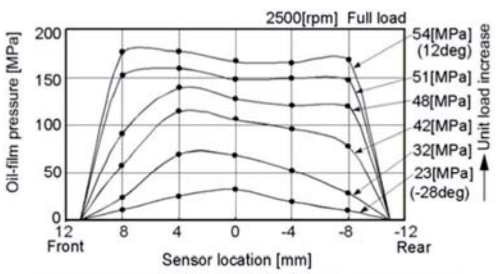


Fig. 5 Measured and corrected pressure in connecting rod bearing



Variation of oil-film pressure distribution with the bearing load

Fig. 6 Axial oil-film pressure distribution in connecting rod bearing

(4) By introducing a twin-arc type sensor, the absolute value of strain sensitivity could be also reduced nearly to a half or a quarter of its original value.
(5) The ratio *a* of strain sensitivities for Cu-Mn-Ni alloy and Ni-Cr-Al alloy are dependent of temperature. This should be taken into account, when the effect of strain on measured pressure is to be compensated under variable temperature.
(6) The oil-film pressure in a big-end bearing of an engine connecting rod could be measured successfully by the new thin-film sensor.

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