Design and application study of an oil-free high-sensitivity pressure sensor

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Key words

Piezoresistive, oil-free, MEMS, strain sensor, pressure sensor for sanitary use, torque sensor

The piezoresistive pressure sensor in our pressure and differential-pressure transmitters ensures high stability not only in atmospheric conditions but also in high humidity. Taking advantage of this characteristic, we decided to test whether it could handle the stress placed on a pressure sensor under sanitary specifications. Products for sanitary use must meet a number of requirements, and there are currently no sensors that satisfy the requirement for oil-free operation in particular. We welded a MEMS sensor element of our own design to a metal pressure-receiving diaphragm to directly detect strain. We were able to demonstrate that such a device could provide high-accuracy pressure sensing rivaling that of a liquid-filled sensor even without the use of oil. We also report on the technical verification of this technology with a view to applying it to force sensors for robot arms and hands.

1. Introduction

Pressure transmitters and differential-pressure transmitters, which are core products of Azbil, are versatile industrial instruments that are used in many places around the world. A piezoresistive MEMS pressure sensor element [1] is incorporated into pressure and differential-pressure transmitters. Pressure received by the metal barrier diaphragm that contacts the process fluid is transmitted by a liquid such as silicone oil sealed inside and is detected by the silicon diaphragm formed within the sensor element. The pressure-sensing unit is filled with the sealed liquid, and since it can maintain a stable condition, the product remains reliable for a long time.

In the food sector, however, pressure sensors that do not have a sealed oil diaphragm are in demand from the perspective of safety. Unfortunately, oil-free pressure sensors are inferior to sealed sensors in terms of performance and quality. For this reason, a complete changeover in the industry has not been made at this point. From our previous development of a pressure sensor using a proprietary process, we had the results of drift testing in which performance in a 60 °C dry environment was compared with performance in a high-humidity 60 °C, 90 % RH environment. We found that the pressure sensor had high stability equivalent to that of a sealed pressure sensor element incorporated into an existing product (figs. 1 and 2). That is why we decided to develop a new piezoresistive pressure sensor that does not use a sealed liquid.

Fig. 1. Pressure sensor (models PTG60S, PTG70S)

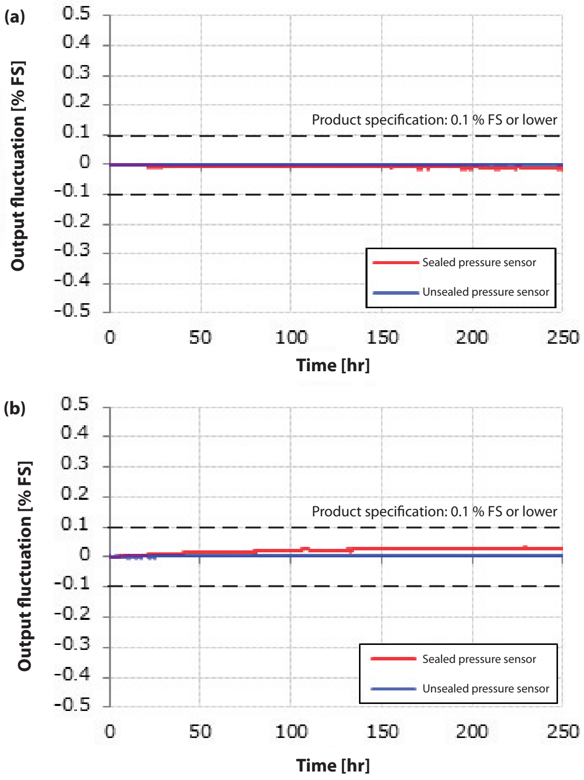


Fig. 2. Comparison of pressure sensor output drift in (a) a dry environment and (b) a high humidity environment

2. Pressure sensor overview

2.1 Pressure sensors for sanitary use

There are several requirements for pressure sensors for sanitary purposes used in manufacturing lines in facilities such as food plants.

(1) Corrosion resistance

Materials with corrosion resistance, such as stainless steel, ceramics, and titanium, must be used for wetted parts (parts that come in contact with the fluid whose pressure is being measured).

(2) Cleanliness

Cleaning using high-temperature steam is performed periodically, so a diaphragm that is as smooth as possible is needed in order to prevent washing residue from remaining. At the same time, thermal shock resistance against steam washing is required.

(3) Reliability

A highly rigid diaphragm that does not break and does not contain sealed oil is required.

(4) Versatility

A detachable ferrule coupling is generally used, and sensor zero point offset cannot occur when the coupling is fastened with a clamp band.

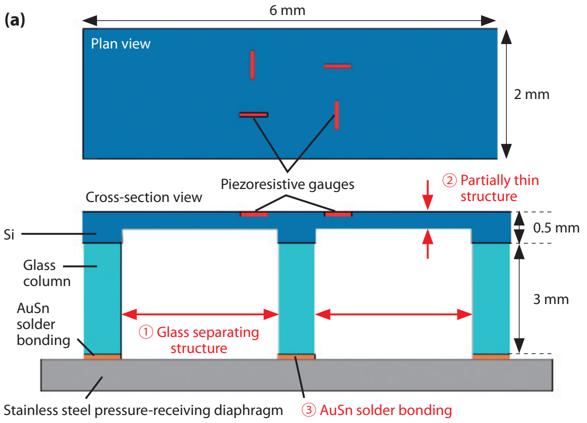
Since these requirements affect the sensor's performance, increasing its accuracy is not easy. In particular, if the minute strain on the highly rigid metallic diaphragm is detected by attaching strain gauges made of thin metal film, the sensitivity is low and the accuracy with which multiple strain gauges are attached affects the sensor characteristics. For this reason, there are problems such as large variance.

2.2 Oil-free pressure sensor development

We have developed an oil-free pressure sensor incorporating a silicon piezoresistive strain sensor that can sense minute deformations of the diaphragm at the micron level with high sensitivity, even taking the aforementioned requirements into consideration.

As shown in figure 3, three glass columns are bonded below the silicon layer forming the piezoresistive gauge, and the difference in deformation between the center and outside of the diaphragm is transmitted to the silicon layer. For example, the difference in deformation between the center and outside of the glass columns when a pressure of 1 MPa is applied to a stainless steel diaphragm with a diameter of 23 mm and a thickness of 0.5 mm is as minute as 10 μm. However, we have been able to achieve a sensitivity approximately 80 times that of a strain gauge attached to the same diaphragm by having the deformation effectively conveyed to the silicon layer. In addition, in order to minimize output fluctuation caused by temperature changes, we have achieved a high signal-to-noise ratio by placing the piezoresistive gauges in locations where output fluctuation due to the different linear expansion coefficients of the stainless steel diaphragm and sensor element do not occur (fig. 4).

(a)



(b) **A signal corresponding to the pressure is output by transmitting to the silicon sensor unit the difference in vertical deformation between the columns.**

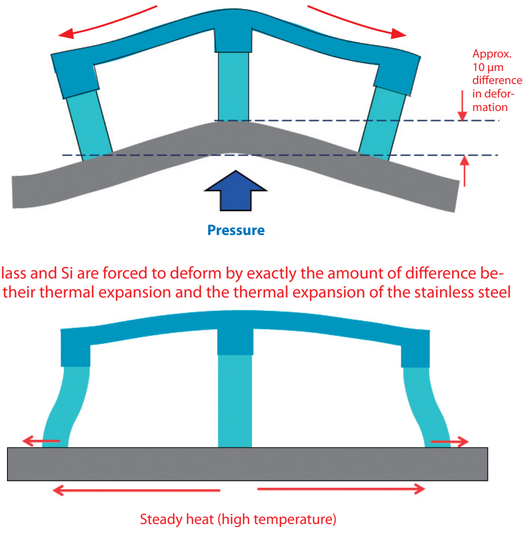


Fig. 3. (a) Diagram of the oil-free pressure sensor element
(b) Operating principle of the oil-free pressure sensor

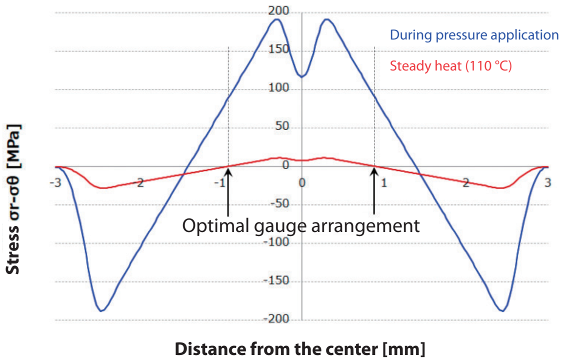


Fig. 4. Si surface stress distribution during pressure/heat application

2.2.1 Important points in the design

To achieve high sensitivity, effective transmission of the minute deformations of the stainless steel diaphragm to the silicon layer is important. Therefore, we adopted the following three items (fig. 3):

① Separate glass columns
② Partially thin silicon layer
③ Bonding with AuSn solder

The benefit of ① is that the difference in deformation that occurs between the columns can be effectively transmitted to the silicon layer and the area that is bonded to the stainless steel diaphragm can be minimized. In addition, making the glass columns long suppresses the temperature increase on the surface of the silicon during steam cleaning, and the difference in the linear expansion coefficients of silicon and stainless steel is absorbed by the deformation of the glass columns. For ②, there is a risk of damage because a thick silicon layer is more rigid, which places a strain on the glass columns and bonded sections when deformation is transmitted. By making the silicon layer thin in places, deformation can be transmitted without hindrance. Also, by forming partially thin places, the locations where stress is generated can be minimized, thus making it possible to reduce the size of the element. In the bonding of the sensor element in ③, the desired sensitivity could not be obtained with an adhesive. Therefore, we adopted AuSn solder bonding, which has higher rigidity and a lower bonding temperature. On the stainless steel diaphragm and bottom surfaces of the glass columns, gold film is formed by means of sputtering or plating, and a ribbon of AuSn solder is inserted in between them, which is then melted in a furnace for bonding. If the sensor element expands in the longitudinal direction, the amount of deformation transmitted is larger, which makes it possible to obtain higher sensitivity; however, this also increases the stress occurring during solder bonding and the chip element cost, and therefore requires an optimal design according to the required specifications, such as the operating temperature range and pressure range.

2.2.2 Thermal shock characteristics

Periodic pipe cleaning using high pressure steam at plants includes the pressure-receiving diaphragm among the wetted parts of pressure sensors. When steam contacts the wetted parts, the diaphragm's surface temperature is momentarily high and causes a large heat distribution, resulting in deformation of the diaphragm. Moreover, the heat is transferred to the entire housing over time, and the pressure sensor output fluctuates accordingly. In some plants, an interlock may be activated if the output fluctuation is too large. For this reason, it is necessary to minimize the amount of fluctuation as much as possible. In the case of a sealed liquid sensor, there is more distance between the pressure-receiving diaphragm and the sensor element since the sealed liquid is between them, eliminating the effect of thermal shock almost completely. On the other hand, if the sensor element were directly attached to the pressure-receiving diaphragm, the effect of thermal shock would presumably be large. To investigate, we created the steam/thermal fluid analysis model shown in figure 5 and used a simulation to analyze the temperature changes during steam cleaning. By using the results as the boundary conditions for the coupled analysis simulation of transient heat transfer and structure, we created a method of analysis for efficient stress distribution that reduces the cost of calculation.

We reduced the amount of sensor output fluctuation when contact is made with steam to ±3 % FS or less (one tenth or less that of previous products) for a pressure sensor designed using this method, achieving a significant improvement in the thermal shock characteristics (fig. 6).

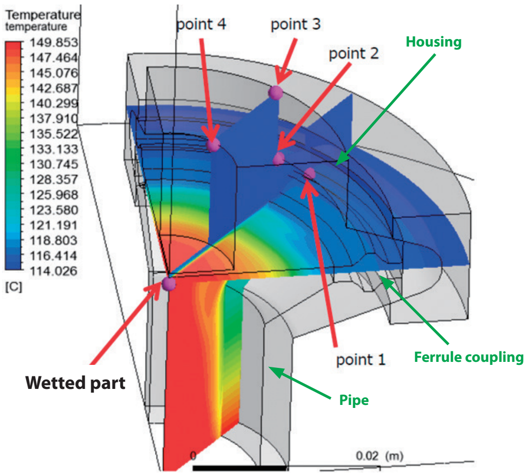


Fig. 5. Thermal fluid analysis model (steam cleaning)

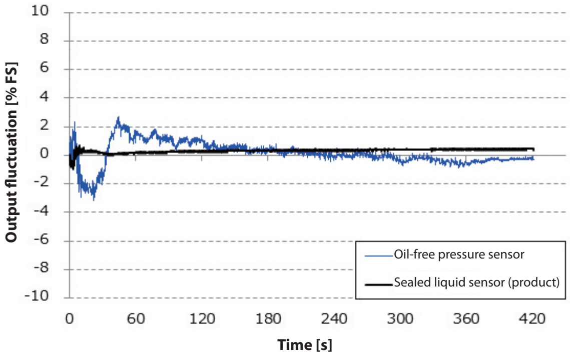


Fig. 6. Sensor output fluctuation upon contact with steam

2.2.3 Future prospects

We achieved a significant improvement in sensitivity over conventional oil-free sensors and now have a prospect of achieving accuracies equivalent to those of sealed liquid sensors. We plan to research and satisfy the specifications and customer value required by the food and beverage market, both domestically and globally.

3. Application to the force sensors of robots

We have developed a next-generation smart robot [2] that incorporates the aforementioned high-sensitivity strain sensor technology. This is a cooperative robot arm (fig. 7). The force (torque) sensor, which is mounted on each of the robot's joints, enables high-precision arm control and high-sensitivity detection of contact with the robot by a person. In addition, by mounting a sensor for bending force on the hand as well, we enabled the robot to hold delicate objects such as eggs or sponge cake.

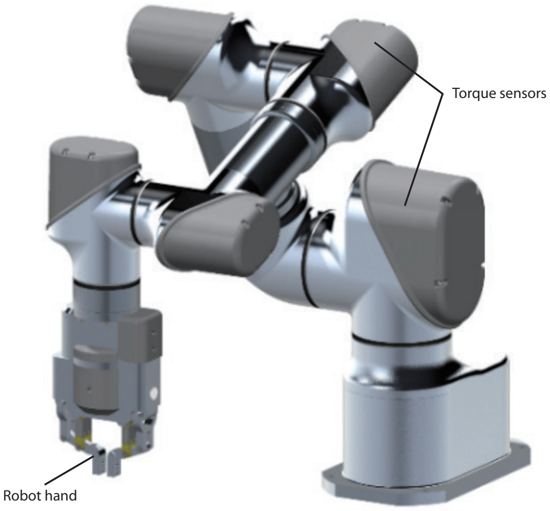


Fig. 7. Drawing of Azbil smart robot

3.1 Torque sensor

A torque sensor may be constructed by mounting a strain sensor element on a part that generates strain, called the strain-generating body (fig. 8). The configuration of the sensor element is the same as that for a pressure sensor, but without the separating function of the glass layer. When torque is applied, a stress distribution at 45° occurs on the surface of the sensor element, as shown in the stress distribution diagram. To efficiently detect this stress, we have created a sensor with high sensitivity and good temperature characteristics by arranging four piezoresistive gauges in the center at 45° angles (fig. 9). This sensor has sensitivity over ten times higher than conventional strain gauges, and can suppress hysteresis to ±0.5 % FS or lower. The torque sensor's characteristics are shown in figure 10. From figure 10, it is clear that the sensor has superior linearity and reproducibility.

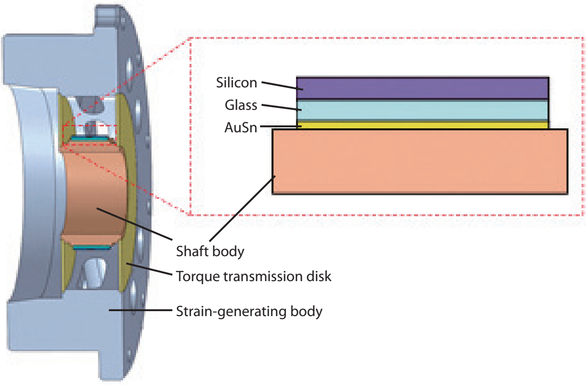


Fig. 8. Torque sensor diagram (strain-generating body, sensor element)

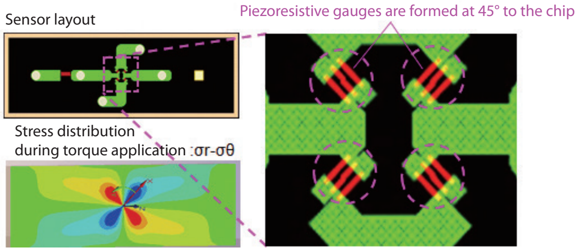


Fig. 9. Piezoresistive gauge arrangement in high-sensitivity strain sensor

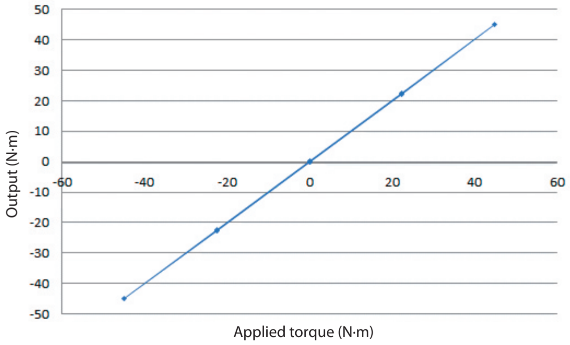


Fig. 10. Torque sensor characteristics

4. Conclusion

The effect of a high-sensitivity strain sensor cannot be verified by the sensor element alone. Therefore, it is necessary to optimize it in combination with the diaphragm and other strain-generating members. Since the stress generated in the sensor element is less than 1/50 that of the strength of the base material of silicon at the current point, the potential of the material is not yet being fully utilized, and we believe that there is room for further improvement in sensitivity and accuracy. We aim to develop the technology more fully by considering other applications of it.

References

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