



# Thin-film flexible sensor for omnidirectional strain measurements



Daniel Zymelka<sup>a,\*</sup>, Takahiro Yamashita<sup>b</sup>, Seiichi Takamatsu<sup>c</sup>, Toshihiro Itoh<sup>a,c</sup>,  
Takeshi Kobayashi<sup>b</sup>

<sup>a</sup> NMEMS Technology Research Organization, Chiyoda, Tokyo 101-0026, Japan

<sup>b</sup> National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305-8564, Japan

<sup>c</sup> Department of Human and Engineered Environment Studies, The University of Tokyo, Kashiwa, Chiba 277-8561, Japan

## ARTICLE INFO

### Article history:

Received 20 September 2016

Received in revised form 21 April 2017

Accepted 27 May 2017

Available online 8 July 2017

### Keywords:

Strain measurement

Omnidirectional sensor

Screen printing

Temperature compensation

Printed electronics

## ABSTRACT

Conventional strain sensors are both precise and inexpensive, but can only effectively measure strain in one specific direction. In this paper, we report an omnidirectional flexible strain sensor that operates regardless of the orientation of its installation with respect to the direction of the applied strain. The performance of the developed device was compared to that of conventional foil strain gauges and it was demonstrated that, in contrast to the conventional devices, the omnidirectional strain sensor developed here shows almost uniform sensitivity at various installation angles.

© 2017 Elsevier B.V. All rights reserved.

## 1. Introduction

Strain measurement is an important aspect of materials testing. These measurements enable the durability of the materials under analysis to be determined along with detection of potential failures in the engineering structures under test under the influence of various types of mechanical deformations, including stress, torque, pressure, and vibration. Strain sensors are widely used for this purpose. The principle of operation of these sensors is based on the conversion of mechanical forces into a change in an electrical signal that can be measured using a dedicated measurement system. In terms of the output signals generated, strain sensors can generally be divided into electrically resistive [1–5], piezoresistive [6–9], capacitive [10–12], and piezoelectric [13,14] types. Among the electrically resistive sensors, conventional foil sensors are most widely used because of their relatively low cost and good reliability. Note that in this paper, the term “conventional sensors” is used to refer to commercially available uniaxial strain sensors, which are generally made from constantan alloy.

One drawback of these conventional sensors is that they can only effectively measure the strain in one specific direction. The user must always define the measurement orientation. While it is desirable to measure strain selectively in a single direction

in some applications, other applications require omnidirectional sensing, e.g., crack detection systems, or simply require monitoring of the maximum strain levels in various types of engineering structures. Inappropriate orientation of these sensors with respect to the applied strain always results in very high measurement errors [15,16]. For the latter types of applications, a sensor that enables uniform detection of cracks or any other mechanical deformations, regardless of their directions, is required.

Because of the difficulties involved in performing accurate strain measurements at different sensor orientation angles, this work has focused on the development of an omnidirectional strain sensor. This type of device will enable measurements that are more accurate than those of the conventional sensors, regardless of the direction of its installation. To the best of the authors knowledge, no such sensors have been demonstrated to date. Usually, if omnidirectional sensing is required, rosette-type strain gauges are used. However, this requires the use of three individual sensors, and thus requires more inputs into the data acquisition system. Here, in contrast to the rosette strain gauge solution, we demonstrate the concept of a single sensor structure that enables omnidirectional strain measurements while using only two inputs into the data acquisition system.

One of the most challenging steps in strain sensor development is materials selection, which defines the final characteristics of the sensor (e.g., strain sensitivity, linearity, the temperature coefficient of resistance). Conventional strain sensors are principally made of constantan, a copper–nickel alloy, which is etched on a poly-

\* Corresponding author.

E-mail address: [daniel.zymelka@aist.go.jp](mailto:daniel.zymelka@aist.go.jp) (D. Zymelka).

imide foil. Constantan is commonly used because the fabricated sensors demonstrate sufficient sensitivity and, most importantly, a low temperature coefficient of resistance, which, if high, could significantly affect the sensor output signal.

In this work, strain sensors were fabricated using the screen printing method. This method enables a simple and reliable fabrication process that is suitable for prototyping of designed devices. Because printable constantan inks are not commercially available at present, alternative sensor materials had to be selected. According to previously reported results for the development of printed strain sensors, the most frequently used sensor materials are: silver [1,2,17–20], graphite [2,4,21,22], carbon nanotubes (CNTs) [23–26], poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) [27–29], and their composites [7,30,31]. In this paper, materials selection was conducted based on the required processing conditions, printability and the expected properties of the fabricated sensors. From the materials mentioned above, graphite paste was selected because it exhibits sufficiently high strain sensitivity and excellent printability, and requires simple, low-cost processing. While high sensitivity to temperature variations was expected of this material [1,2,4,32], graphite paste is suitable for evaluation of the proposed omnidirectional strain sensor concept at a selected constant temperature. Nevertheless, we will show that despite the use of materials that are characterized by their high temperature coefficient of resistance, the developed strain sensors can be used in practical applications when an appropriate temperature compensation method is implemented.

## 2. Sensor development

### 2.1. Design of the sensor

The shape of the sensor that was developed in this project differs from that of conventional strain gauges. In contrast to the linear structure of conventional sensors, the omnidirectional sensor shown in Fig. 1 has a symmetrical design that enables more uniform sensing at various sensor orientations. Rather than use the conventional uniaxial active grid, the new sensor has 16 active elements (“arms”) that make it sensitive along eight different axes. The axes are inclined with respect to one another at an angle of 22.5°. The active elements (i.e., the arms or the grid), unlike the terminals and end loops, are the parts of these sensors that have the greatest effect on their sensitivity, i.e., the electrical resistance change of the sensor under mechanical deformation.

To enable comparison of the developed sensor with a conventional uniaxial sensor, both devices had the same length or diameter of 10 mm. The number of arms used (16) was mainly limited by the desired sensor geometry. It will be possible to design a sensor with more arms within the same sensor diameter if the inner radius can be enlarged, which would then provide more space to implement additional sensing arms. However, the lengths of these arms would have to be shorter. It is important to know that these strain sensors measure an average strain value that corresponds to the area covered by the active elements. For this reason, the sensor was designed in such a way that the arms all had a maximum possible length that lay within the defined sensor diameter.

### 2.2. Fabrication steps

A schematic illustration of the fabrication steps required for the proposed sensor is shown in Fig. 2. First, the thermosetting graphite paste (Asahi Chemical Research Laboratory FTU-16R) was screen printed onto a 50 µm poly(ethylene naphthalate) (PEN) substrate. A stainless steel mesh (Asada Mesh HS-D 650/14) was used for this high-resolution printing process.

The printed patterns were then cured in a conventional convection oven at 150 °C for 30 min according to the instructions provided by the graphite paste manufacturer. The fabricated omnidirectional strain sensor is shown in Fig. 3.

After completion of the curing process, the sensors were then attached to an object to be tested (in this study, a metal plate) using cyanoacrylate adhesive. To ensure the electrical connection of the sensor to a data acquisition system, thin electrical wires were attached to the sensor using a silver epoxy conductive adhesive. Finally, the sensors were laminated to protect them from dust and moisture using ordinary poly(ethylene terephthalate) (PET) self-adhesive laminating sheets. The final electrical resistance of the fabricated device was approximately 200 kΩ.

### 2.3. Experimental setup

A 2-mm-thick, 700-mm-long and 120-mm-wide metal plate was installed on a rigid support, as shown in Fig. 4. Three printed sensors and three conventional sensors were attached to the plate close to the support edge. Maximum strain levels were expected in this location. To evaluate each sensor's performance depending on its direction of installation, the sensors were attached with three different orientations: 0°, 45° and 90°. Distances between the support edge and the sensors were 5 cm, measured from their geometric centers. The opposing edge of the plate was mounted on a tensile test machine that moved the plate up and down, causing it to bend, and resulting in the generation of various strains that were measured by the sensors.

The sensors were all individually connected to quarter Wheatstone bridge circuits (Fig. 5). All the Wheatstone bridges were connected in parallel to a single 2.5 V power supply. The output voltage was measured using a 24-bit analog input module (NI-9238, National Instruments). The data acquisition process was controlled using a specifically prepared computer program.

## 3. Sensor evaluation

### 3.1. Sensitivity to applied strain

The electrical resistance of the sensors that are attached to the metal plate varies with the degree of axial bending. To determine the sensitivity of these sensors, the relative change in resistance ( $\frac{\Delta R}{R_0}$ ) was measured as a function of mechanical strain ( $\epsilon$ ). The sensitivity is then defined using the so-called gauge factor (GF), which is expressed using the following formula:

$$GF = \frac{\Delta R/R_0}{\epsilon} \quad (1)$$

Because the conventional strain sensors are calibrated and are relatively stable, the conventional sensor that was installed further along the plate (at an angle of 0°) was used to provide a reference measurement that gives the most accurate strain measurement among the six sensors that were attached to the plate. This sensor was then used to calibrate the developed omnidirectional sensors. The measured strain values are generally very small, and thus the measurements are typically expressed as microstrains (strain  $\times 10^{-6}$ ).

Based on the output of the reference sensor, a maximum strain of approximately 285 microstrains was generated in the proximity of sensors during the calibration process. The collected results are shown in Fig. 6. Within the analyzed strain range, the sensors show linear responses with no hysteresis. The average GF of the three omnidirectional sensors was calculated to be  $3.37 \pm 0.08$ . When the GF error is analyzed, it should be noted that the developed sensors were installed at different orientations. Additionally, in this experiment, the omnidirectional sensor that was set at the angle of 0° was

Download English Version:

<https://daneshyari.com/en/article/5008033>

Download Persian Version:

<https://daneshyari.com/article/5008033>

[Daneshyari.com](https://daneshyari.com)