Metal-foil Strain Gauges

Introduction

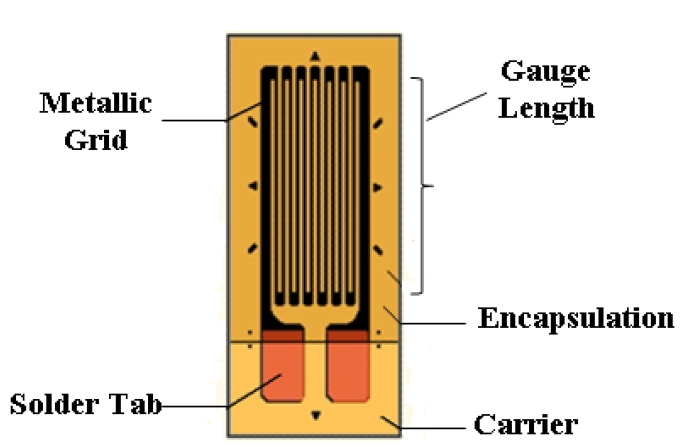
Strain gauges are the most commonly used sensors to measure surface strain. In order to design a structure, it is important to know the stresses formed in each of its components during loading. A usual method followed is to measure the surface strain using a strain gauge which is then related to the stress component at that point. Strain gauges are also used as integral elements in devices like load cells, pressure sensors to measure load and pressure respectively.

Strain gauge works on the principle that the change in resistance is proportional to the strain produced in the wire. This relationship between resistance and strain of a wire was first reported by Lord Kelvin (1856). Later, Simmons and Ruge (1938) independently developed the first strain gauge known as SR-4 gauge which is a wire bonded to the surface of the test specimen. With the emergence of printed circuits, Saunders and Roe (1952) developed a metal-foil strain gauge by etching the pattern for the gauge from a thin metal-foil. Wire gauges were replaced by metal-foil gauges because of the advantages such as ease of alignment and higher resistance offered by the later compared to the former.

The change in resistance of a wire is also caused by a change in temperature. One of the important aspects and challenges in strain measurement is how to isolate the temperature effects.

Strain Gauge - Structure

A strain gauge consists of a metallic grid along with the solder tabs placed on a plastic base. Sometimes an encapsulation is placed over the metallic grid to prevent from environmental effects. The gauge length of the strain gauge is defined as the strain sensitive length of the grid. The strain gauge measures the component of strain along the gauge length.



Structure of a strain gauge

Strain Sensitivity of a Wire and a Strain Gauge

The resistance of a wire is given as,

$$R = \frac{\rho L}{A} \qquad (1)$$

where ρ - specific resistance
A - cross sectional area of the wire

Change in resistance is given as,

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dL}{L} - \frac{dA}{A} \qquad (2)$$

Cross sectional area of the wire is,

$$A = \frac{\pi}{4}D^2 \Rightarrow \frac{dA}{A} = 2\frac{dD}{D} = -2\nu\frac{dL}{L} \qquad (3)$$

where ν – Poisson's ratio

From Eq. (2), one gets

$$\frac{dR}{R} = \frac{d\rho}{\rho} + (1+2\nu)\frac{dL}{L} \qquad (4)$$

Strain sensitivity, S_A of the wire is given as,

$$S_A = \frac{dR/R}{dL/L} = \left(\frac{d\rho/\rho}{dL/L}\right) + 1 + 2\nu \qquad (5)$$

In a strain gauge, the wire is formed into a grid to reduce its length. This makes the wire sensitive to axial, transverse and shear strains. Thus, the response of the strain gauge subjected to strain is,

$$\frac{dR}{R} = S_a\varepsilon_a + S_t\varepsilon_t + S_s\gamma_{at} \qquad (6)$$

where ε_a - axial strain, S_a - axial strain sensitivity
ε_t - transverse strain, S_t - transverse strain sensitivity
γ_{at} - shear strain, S_s - shear strain sensitivity

In general, S_s is small and can be neglected which results in,

$$\frac{dR}{R} = S_a(\varepsilon_a + K_t\varepsilon_t) \qquad (7)$$

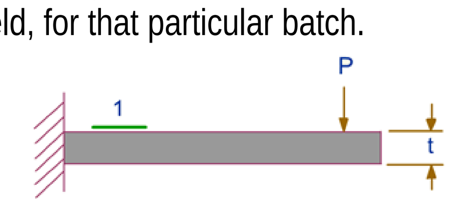
Such that, $K_t = \frac{S_t}{S_a}$

where K_t is the transverse sensitivity factor

Thus, to relate change in resistance to the strain experienced by the gauge, S_a and K_t should be specified.

Gauge Factor

In practice though, the Strain gauge manufacturer supplies a gauge factor, S_g (rather than S_a) which is experimentally determined for an uniaxial stress field, for that particular batch.



Cantilever beam with strain gauge

To determine S_g, the strain gauge is pasted on a cantilever beam which is subjected to transverse loading as shown in the figure. The gauge factor is evaluated by relating the strain gauge readings with the analytical values of the axial strain i.e.

$$\frac{dR}{R} = S_g\varepsilon_a \qquad (8)$$

For a beam, transverse strain is given as, $\varepsilon_t = -\nu_o\varepsilon_a$

Comparing Eq. (7) and (8), one gets

$$S_g = S_a(1-\nu_o K_t) \qquad (9)$$

S_g relates dR to axial strain only when $K_t = 0$ or in a uniaxial stress field where

$$\nu_o = 0.285$$

Wheatstone Bridge

A Wheatstone bridge is used to measure the change in resistance in the strain gauge. A Wheatstone bridge consists of four arms having resistance which can be either constant (resistors) or varying (strain gauges). The bridge is initially balanced making the potential difference between opposite vertices, *E* to be zero. Hence, any change in resistance in one or more arms can be measured by measuring *E*.

From the figure,

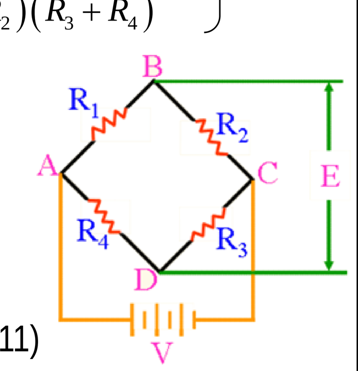
$$\left.\begin{aligned} V_{AB} &= \frac{R_1}{R_1+R_2}V \quad V_{AD} = \frac{R_4}{R_3+R_4}V \\ E &= V_{BD} = V_{AB} - V_{AD} = \frac{R_1R_3 - R_2R_4}{(R_1+R_2)(R_3+R_4)}V \end{aligned}\right\} \qquad (10)$$

For the bridge to be balanced initially,

$$E = 0 \Rightarrow R_1R_3 = R_2R_4$$

For an incremental change in resistances, change in potential will be

$$\Delta E = V\frac{R_1R_2}{(R_1+R_2)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) \qquad (11)$$



Wheatstone bridge

From Eq. (11), one can infer that similar strains in opposite arms add and adjacent arms subtract. This concept can be used to amplify the signal output from the Wheatstone bridge and also to remove the temperature influence on the strain gauge reading.

Types of Wheatstone Bridge Circuits

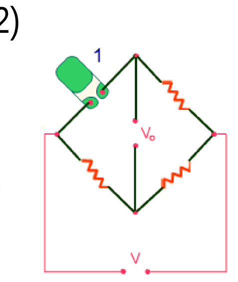
Quarter bridge circuit

A quarter bridge circuit has a strain gauge in one arm and resistors in the rest of them. Using Eq. (11), the signal output (ΔE) will be,

$$\Delta E = V\frac{R_1R_2}{(R_1+R_2)^2}\left(\frac{\Delta R_1}{R_1}\right) \qquad (12)$$

In Eq. (12), $\Delta R_1 = \Delta R_S + \Delta R_T$

where ΔR_S - change in resistance due to strain
ΔR_T - change in resistance due to temperature variation



Quarter bridge circuit

Consider the cantilever beam pasted with a strain gauge, subjected to transverse loading. The strain gauge readings will have both strain and temperature effect. A single strain gauge in a Wheatstone bridge quarter bridge circuit cannot eliminate the temperature effect.

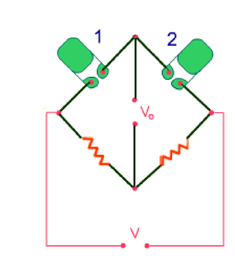
Cantilever Beam with strain gauge

Half Bridge Circuit

A half bridge circuit has two strain gauges connected in adjacent arms and resistors in the remaining arms. From Eq. (11), the signal output (ΔE) will be,

$$\Delta E = V\frac{R_1R_2}{(R_1+R_2)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2}\right) \qquad (13)$$

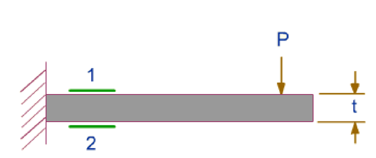
Consider the cantilever beam specimen pasted with two strain gauges subjected to transverse loading. According to beam theory, the top surface (gauge 1) is in tension and the bottom surface (gauge 2) is in compression. However, the temperature effect is the same in both the strain gauges.



Half bridge circuit

Thus,

$$\Delta R_1 = \Delta R_S + \Delta R_T \quad \Delta R_2 = -\Delta R_S + \Delta R_T$$



Cantilever Beam with strain gauges

From Eq. (13), one gets

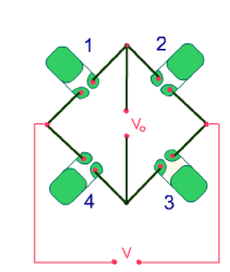
$$\Delta E = V\frac{R_1R_2}{(R_1+R_2)^2}\left(\frac{2\Delta R_S}{R_1}\right)$$

Thus, a half bridge circuit amplifies the strain output from the specimen and also eliminates the effect due to temperature variation.

Full Bridge Circuit

A full bridge circuit has strain gauges connected in all the four arms. The signal output (ΔE) is given by Eq. (11).

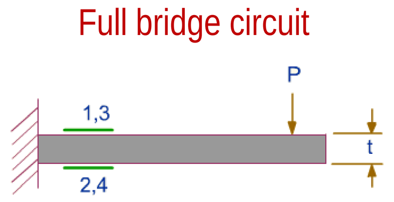
Consider the cantilever beam specimen pasted with four strain gauges subjected to transverse loading. According to beam theory, the top surface (gauges 1, 3) is in tension and the bottom surface (gauges 2, 4) is in compression. However, the temperature effect is the same in all the strain gauges. Thus,



Full bridge circuit

$$\Delta R_1 = \Delta R_S + \Delta R_T \quad \Delta R_2 = -\Delta R_S + \Delta R_T$$

$$\Delta R_3 = \Delta R_S + \Delta R_T \quad \Delta R_4 = -\Delta R_S + \Delta R_T$$



Cantilever Beam with strain gauges

From Eq. (11), one gets

$$\Delta E = V\frac{R_1R_2}{(R_1+R_2)^2}\left(\frac{4\Delta R_S}{R_1}\right)$$

Thus, a full bridge circuit amplifies the strain output from the specimen and also eliminates the effect due to temperature variation.

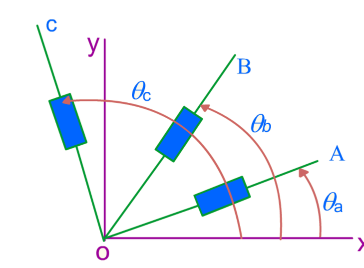
Strain at a Point

In many applications, one wants to measure the plane strain on a surface. In such a case, three components of strain are to be determined. As a single strain gauge can only measure the strain component along its gauge length, a strain gauge rosette consisting of three strain gauges, is used to measure the strain at the point of interest. Using strain transformation equations, strain in the gauges in a rosette is given as,

$$\varepsilon_j = \varepsilon_{xx}\cos^2\theta_j + \varepsilon_{yy}\sin^2\theta_j + \gamma_{xy}\sin\theta_j\cos\theta_j \qquad (14)$$

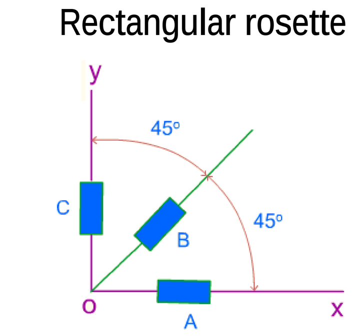
where *j* = *a, b, c*

Common types of Strain gauge rosettes used for measurement are rectangular and delta rosettes. These rosettes vary from one another with respect to the angular orientation of the strain gauges.

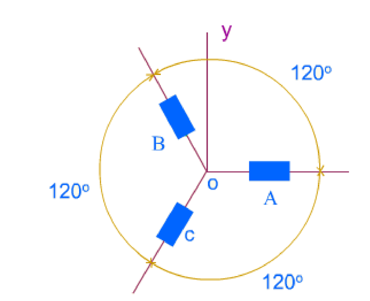


A Generic strain gauge rosette

Rectangular rosette



Delta rosette



Here, $\theta_a = 0^o; \theta_b = 45^o; \theta_c = 90^o$

Here, $\theta_A = 0^o; \theta_B = 120^o; \theta_C = 240^o$

By substituting above values of θ in Eq. (14) and solving for both the cases, one gets

$$\varepsilon_{xx} = \varepsilon_a \qquad \varepsilon_{yy} = \varepsilon_b \qquad \gamma_{xy} = 2\varepsilon_b - \varepsilon_a - \varepsilon_c$$

$$\varepsilon_{xx} = \varepsilon_A \qquad \varepsilon_{yy} = \frac{2(\varepsilon_B + \varepsilon_C) - \varepsilon_A}{3} \qquad \gamma_{xy} = \frac{2(\varepsilon_C - \varepsilon_B)}{\sqrt{3}}$$

Temperature Compensation

For a strain gauge, the temperature induced resistance is given as

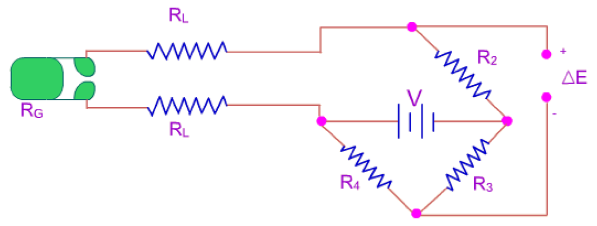
$$\left(\frac{dR}{R}\right)_{\Delta T} = S_g(\alpha_s - \alpha_g)\Delta T + S_T\Delta T \qquad (15)$$

where S_T – Sensitivity of gauge to temperature
α_s – Coefficient of linear expansion of specimen material
α_g – Coefficient of linear expansion of Gauge material

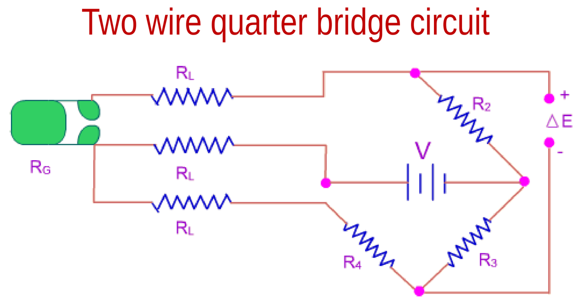
Temperature compensation in strain measurements is obtained by

(i) Adjusting the gauge parameters, S_T and α_g so that Eq. (15) is zero. This concept is used in self temperature compensated (STC) gauges. These gauges can be used only for applications involving small temperature variation. In quarter bridge circuits, use of STC gauges is always recommended.

(ii) Canceling the temperature effects using the signal conditioner. This concept is used in Wheatstone bridge circuits. As discussed in the earlier section, half bridge and full bridge circuits use additional strain gauges for temperature compensation.



Two wire quarter bridge circuit



Three wire quarter bridge circuit

Many strain gauge applications use quarter bridge circuit for strain measurement. In a quarter bridge circuit, the STC gauge is connected to the Wheatstone bridge using lead wires as a two wire circuit. These wires have some measureable resistance (R_L).

In applications where the strain gauge installation is at large distances from the measurement system, the resistance offered by the lead wires becomes significant in strain measurement. This results in desensitization of the gauge factor of the strain gauge and also causes an initial imbalance of the circuit. This is overcome by the use of a three wire circuit in which the lead wires are attached to the adjacent arms of the Wheatstone bridge. This arrangement cancels the effect of one lead wire by the other, thus resulting in a reduction in the loss in sensitivity, elimination of initial imbalance problems and also reduction of error due to temperature change in lead wires.

Strain Gauge Installation

The Accuracy of measurements using a strain gauge depend on how well the strain gauge is installed on the test specimen. The steps involved in strain gauge installation are briefly discussed below. For further information, one can refer to the references.

(a) Surface Preparation

The purpose of surface preparation is to develop a chemically clean surface giving a roughness appropriate to the gauge installation requirements, a surface alkalinity of correct pH, and visible gauge layout lines for locating/orienting the strain gauge. Surface preparation for aluminium alloys and steels requires five basic operations which are

1. Solvent degreasing
2. Surface abrading
3. Application of gauge layout lines
4. Surface conditioning
5. Neutralizing

(b) Strain Gauge Bonding

The performance of the strain gauge is absolutely dependent on the bond between itself and the test part. Strain gauge bonding involves the following steps

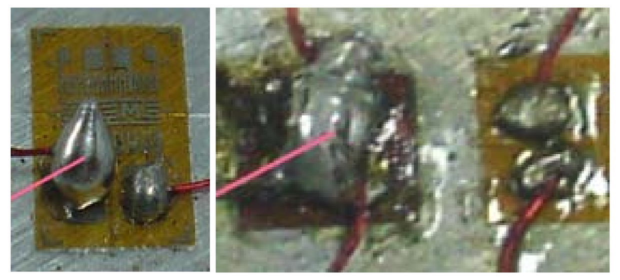
1. Strain gauge handling
2. Strain gauge alignment
3. Catalyst application
4. Strain gauge bonding with adhesive

(c) Soldering

Soldering involves the following steps

1. Masking the gauge
2. Tinning tabs and terminals
3. Tinning the lead wire
4. Lead wire attachment
5. Cleanup and inspection

Improper soldering can lead to degraded performance in strain gauge installation. Examples of soldering are shown below



Faulty Soldering

Good Soldering

(d) Strain Gauge Installation Testing

The following tests are performed on the installed strain gauge to check for proper installation

1. Test for voids in bonding system
2. Test for complete curing of adhesive by strain cycle/temperature cycle
3. Use of strain gauge installation tester to test insulation resistance and gauge installation

Reference

[1] K Ramesh: e-book on Experimental Stress Analysis, IIT Madras (2009).ISBN: 978- 81-904235-6-4, http://apm.iitm.ac.in/smlab/kramesh/book_5.htm

[2] NPTEL Experimental Stress Analysis (Video lecture series), Prof. K Ramesh

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Gift from *Prof. K. Ramesh*, Digital Photomechanics Laboratory, IIT Madras, India