Sensors and Transducers

CH6: strain gauge

5/12 - Tue

Strain Gauge

Types of strain gauges:

1- Metallic strain gauges

2- Piezoresistive (semiconductor) strain gauges

تتغير مقاومتها استجابة للتغيير في الأبعاد الميكانيكية الناتج عن الإجهاد.

الترجمة الحرفية

Strain Gauge

* تتغير المقاومة بناءً على الـ stress الـ المطبق وال strain الي بصير للـ conductance.

1- **Metallic strain gauges** (the resistance of which changes in response to the change in the mechanical dimensions caused by the strain).

- Metallic strain gauges are of two types: 1 **bonded strain gauges** consisting of a metallic foil glued to a metallic component; and 2 **unbonded strain gauges** usually made of wires stretch between columns.

مستخدم أكثر

Strain Gauge

The **bonded** resistance strain gage is by far the **most widely used** strain measurement tool for today’s experimental stress analyst. It consists of a grid of very fine wire (or, more recently, of thin metallic foil) bonded to a thin insulating backing called a carrier matrix. The **electrical resistance** of this grid material **varies linearly with strain.** In use,

عينة

the carrier matrix is attached to the test specimen

لاصق

with an **adhesive**.

Strain Gauge

التغير في المقاومة هو الي منوجد منه ال stress وال strain

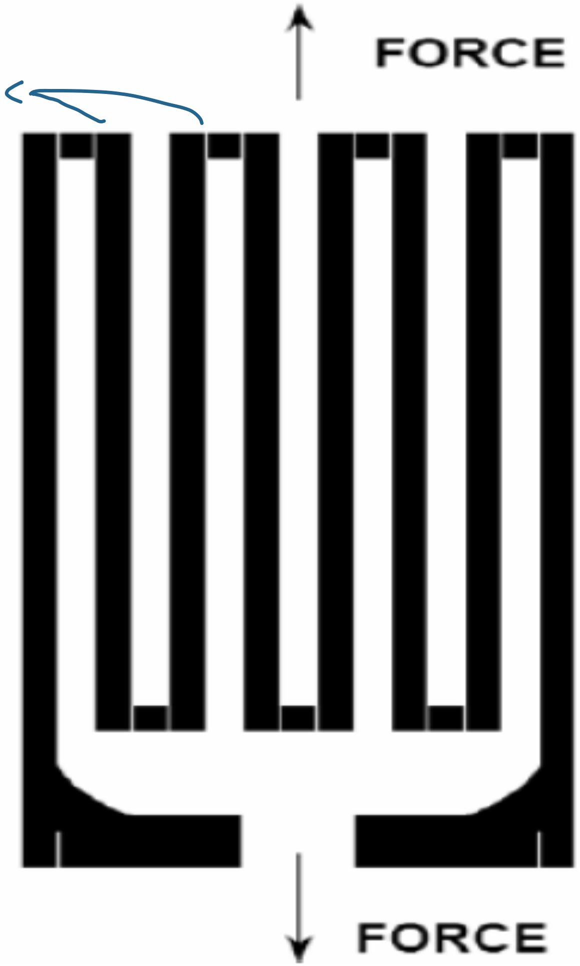
When the specimen is loaded, the strain on its surface is transmitted to the grid material by the adhesive and carrier system. The strain in the specimen is found by measuring the change in the electrical resistance of the grid material. The bonded resistance strain gauge is **low in cost**, can be made with a **short gage length**, is only **moderately affected by temperature changes**, **has small physical size and low mass**, and has **relatively low sensitivity to strain.** It is suitable for measuring both **static and dynamic strains**

مميزاته:

The metal foil strain gage

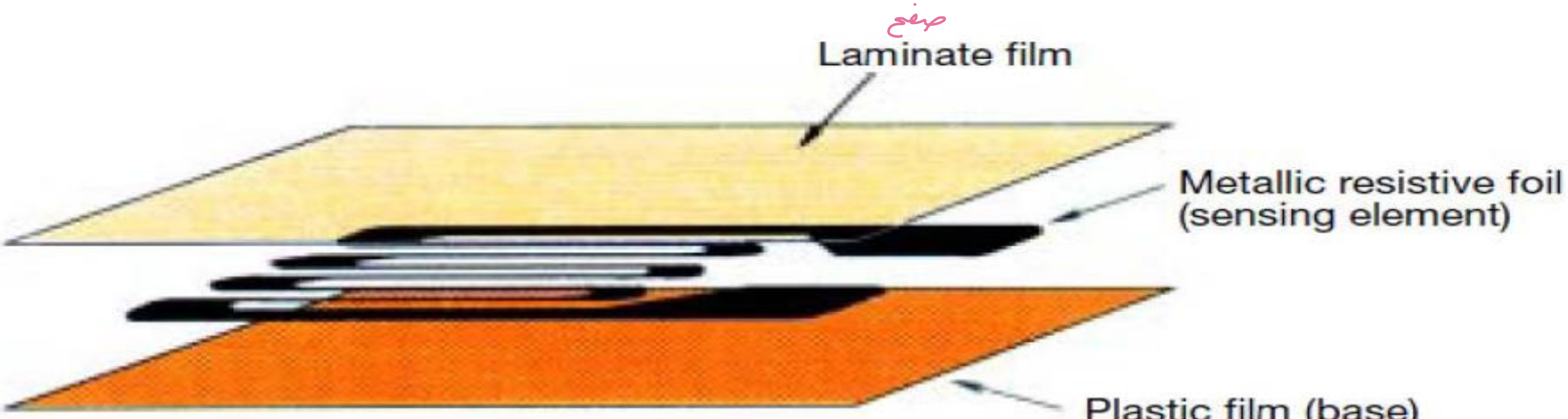
عنا أكثر من واحدة
حتى يلحظ أقل تغير
في الطول.

* إذا صار في زيادة
في الطول بسبب
الـ force، رح تجمع.
بكون التغير في الطول
قليل فلما نجمعه
مع كل واحدة منهم
بصير كمية منيحة
وبصير عنا تغير محسوس
في المقاومة.



- PHOTO ETCHING TECHNIQUE
- LARGE AREA
- STABLE OVER TEMPERATURE
- THIN CROSS SECTION
- GOOD HEAT DISSIPATION

Structure of Strain Gauge



Strain Gauge

Typically, the nominal unstrained resistances of metallic strain gauges are usually **120 Ω, 350 Ω or 1000 Ω**. The following is a typical **set of parameters for a strain gauge:**

- Unrestrained resistance: 120Ω±1Ω
- Gauge factor: 2.0-2.2
- Linearity: ±0.3%
- Maximum tensile strain: $+2\text{x}10^{-2}$
- Maximum compressive strain:$-1\text{x}10^{-2}$
- Maximum operating temperature: 150 °C
- Maximum gauge current: 15 mA to 100 mA

Strain Gauge

Ideally we would like the material to have a **low coefficient of resistance.** The **alloy Advance** is used as the basis of many strain gauges has the following **characteristics:**

- Composition: 54% Copper, 44% Nickel, 1% Manganese
- Temperature coefficient of resistance: $2x10^{-5}$ K^{-1}

Strain Gauge

2- Piezoresistive elements (the resistance of which changes in response to a change in resistivity caused by the strain).

- These are also sometimes referred to as **semiconductor** strain gauges to distinguish them from metallic strain gauges. The semiconductor strain gauge is based on the **piezoresistive effect** in certain semiconductor materials such as silicon and germanium. Semiconductor gauges have **elastic behaviour** and can be produced to have either **positive or negative** resistance changes when strained.

Strain Gauge

They can be made physically small while still maintaining a high nominal resistance. The strain limit for these gages is in the **1000 to 10000 $\mu\varepsilon$ range**, with most tested to **3000 $\mu\varepsilon$** in tension. Semiconductor gauges exhibit a **high sensitivity to strain**, but the **change in resistance with strain is nonlinear**. Their resistance and output are **temperature sensitive**, and the high output, resulting from changes in resistance as large as **10-20%**, can cause measurement problems when using the devices in a bridge circuit.

→ strain

Strain Gauge

بقدر
أتفاداها
كلها
عند استخدام
أجهزة يتم
التحكم فيها
بواسطة
الحاسوب

However, mathematical corrections for temperature sensitivity, the nonlinearity of output, and the nonlinear characteristics of the bridge circuit (if used) can be made automatically when using computer controlled instrumentation to measure strain with semiconductor gauges. They can be used to measure both **static and dynamic strains.** When measuring **dynamic strains**, temperature effects are usually less important than for static strain measurements and the high output of the semiconductor gauge is an advantage.

Strain Gauge

Comparison between metallic strain gauges and piezoresisitve sensors

1- The main advantage of piezoresistive sensors over metallic strain gauges is their high gauge factor. The Poisson ratio for most metals ranges from 0.25 to 0.35 giving a gauge factor ranging from 1.9 to 2.1. However, in piezoresistive sensors the resistivity term is the dominant term with much higher values. For example p-doped Silicon has a value of +100 to +175, while n-doped Silicon has a value ranging from -100 to -140 (a positive value denotes an increase in resistance with strain, while a negative value denotes a decrease in resistance with strain).

Strain Gauge

2- The main disadvantage of piezoresistive sensors is their nonlinearity and high temperature dependence. For example the gauge factor could change from 135 down to 120 when the temperature changes from 0 to 40 °C .

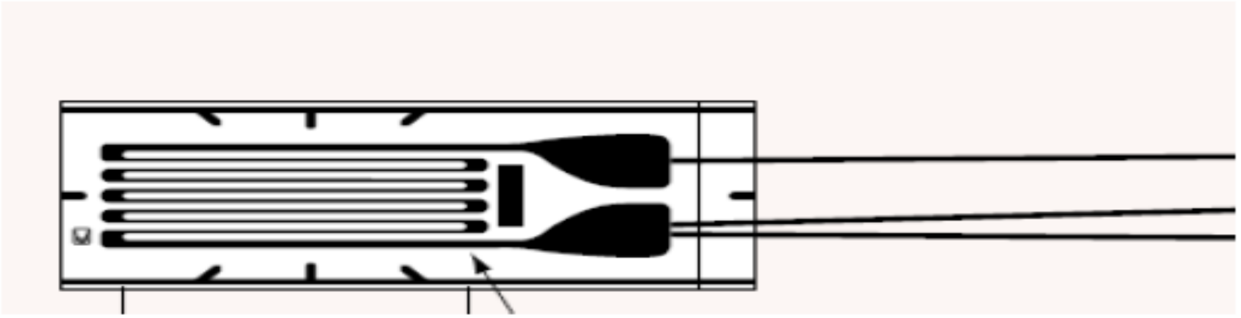
Strain Gauge

PARAMETER	METAL STRAIN GAGE	SEMICONDUCTOR STRAIN GAGE
Measurement Range	0.1 to 40,000 με	0.001 to 3000 με
Gage Factor	2.0 to 4.5	50 to 200
Resistance, Ω	120, 350, 600, ..., 5000	1000 to 5000
Resistance Tolerance	0.1% to 0.2%	1% to 2%
Size, mm	0.4 to 150 Standard: 3 to 6	1 to 5

لاحظي
إنه ال
gauge factor
في حالة ال
Semiconductor
عالي

Steps in fitting a strain gauge to a surface

1- **Select strain gauge:** Select the strain gauge model and gauge length which meet the requirements of the measuring object and purpose.

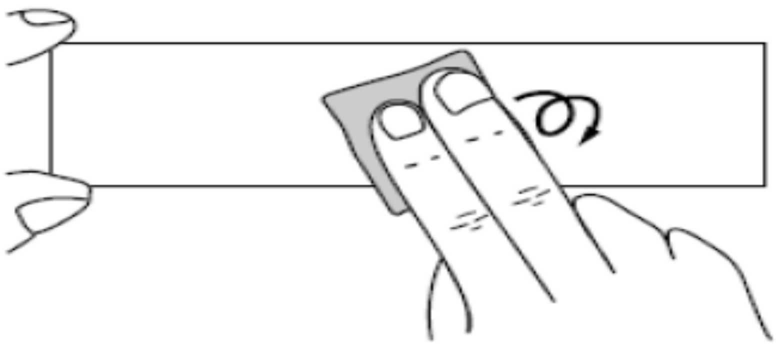


Steps in fitting a strain gauge to a surface

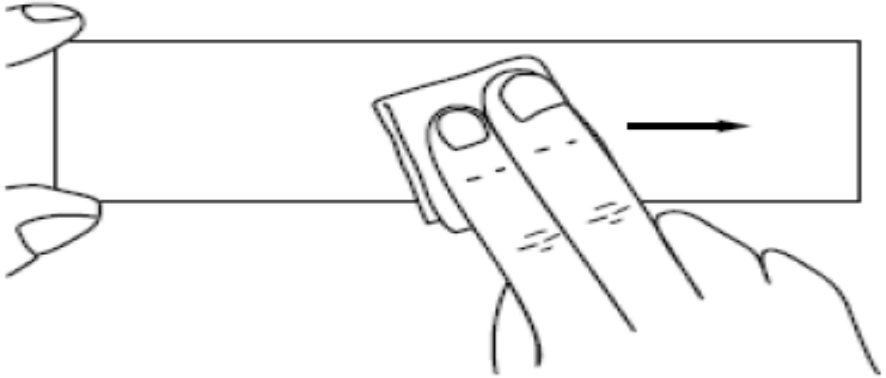
تحضير السطح وتنظيفه

2- Prepare the surface: This will involve removing any rust, and making the surface very polished. Application of certain acids and conditioners is also required.

①



②



Steps in fitting a strain gauge to a surface

3- **Mark the correct orientation:** The orientation of the strain gauge on the surface has to be marked. This ensures that the strain gauge is oriented exactly in the right direction of the strain to be measured.

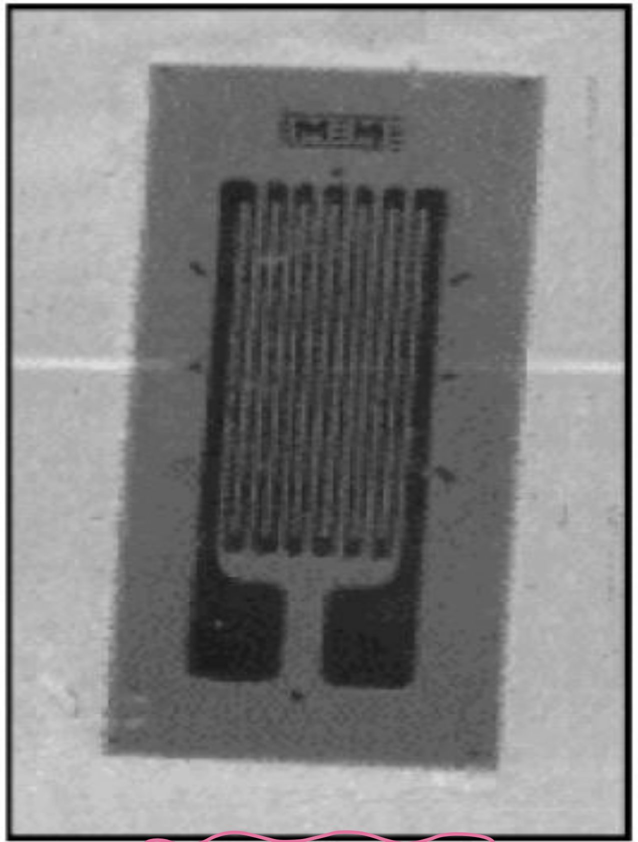
4- **Prepare the Gauge for Mounting:** The gauge is then prepared for mounting, by the use of special sticky tape.

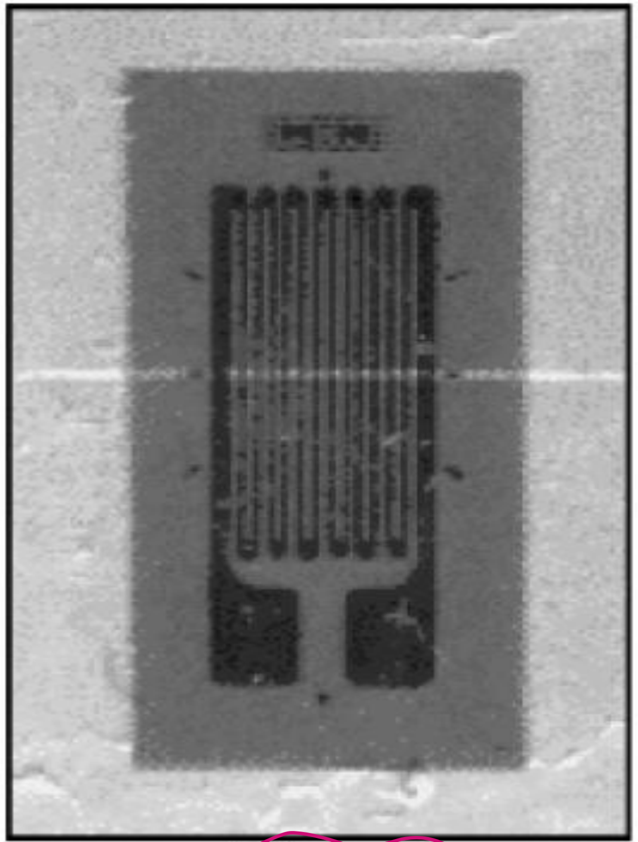
Steps in fitting a strain gauge to a surface

5- **Position gauge on the shaft:** The gauge is then positioned on the shaft. This has to be done accurately to ensure that the orientation is correct.

6 -**Glue the gauge:** The gauge is then glued onto the shaft by the use of super-glue. It is held in position for a period of time to ensure that the super-glue has dried.

Steps in fitting a strain gauge to a surface





غير مستقيم X ⇐ Misaligned

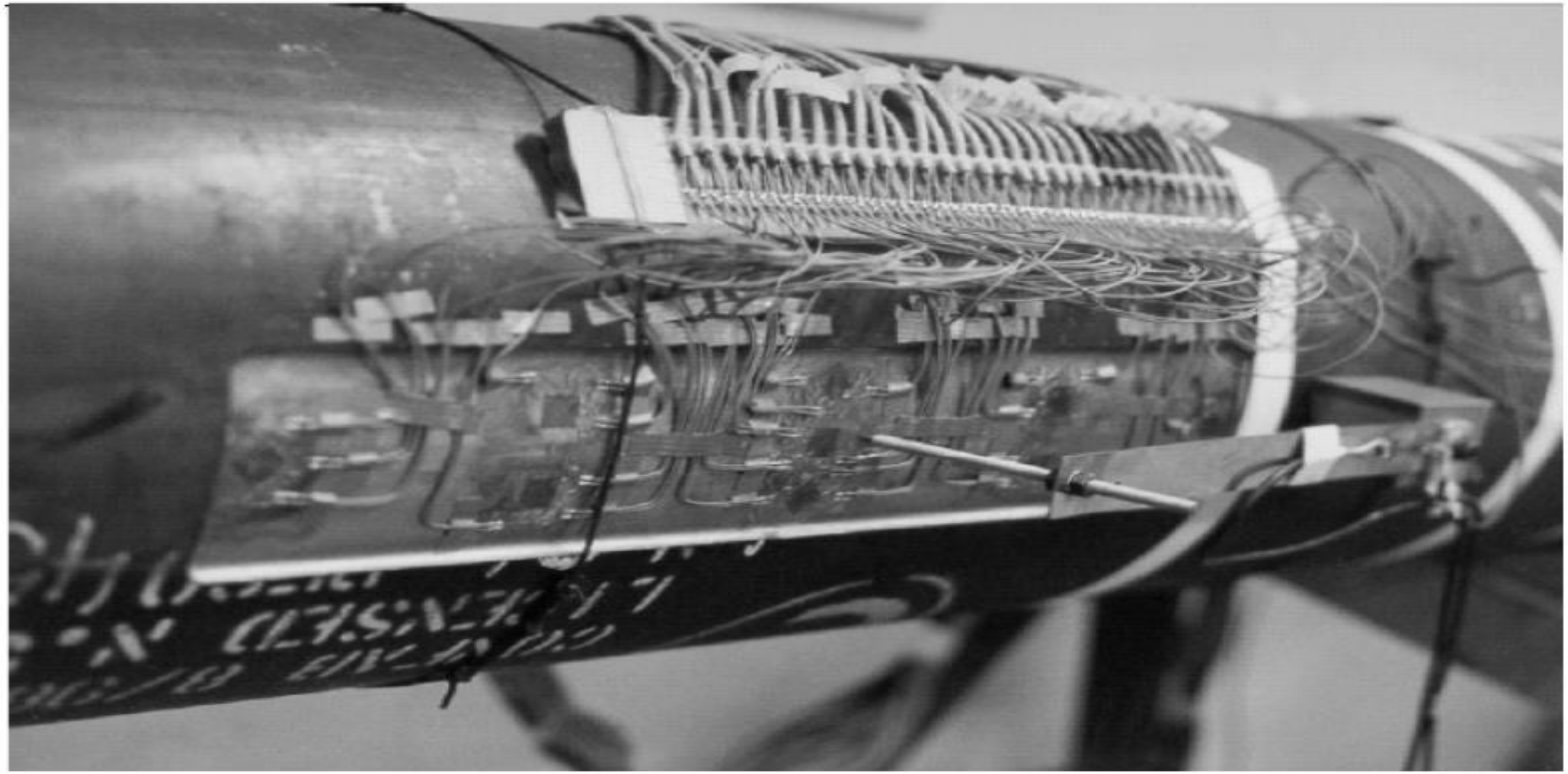
Aligned → مستقيم

Steps in fitting a strain gauge to a surface

7- **Connect the lead wires:** The lead wires are then soldered onto the pads. Some solder is first applied onto the pad. The wires are then ملحومة soldered.

8- **Protect the strain gauge:** The strain gauge can be protected by the application of a certain طلاء varnish. This provides electrical insulation. This can also be followed by physical protection (e.g., cover).

Steps in fitting a strain gauge to a surface



skipped

Strain Gauge

7/12 - Thu

Thermal Effect on Strain Gauge

- Fluctuations in ambient and in operating temperatures produce the most severe effects generally dealt with in strain measuring circuitry.
- The problems arise primarily from two mechanisms:

1. **Changes in the gage resistivity with temperature.**
2. **Temperature induced strain in the gage element.**
3. **Additionally, for certain bridge circuits in which the elements are widely separated (20-100 feet), the thermally induced resistance changes in the lead wires may also be significant.**

Thermal Effect on Strain Gauge

Changes in the gauge resistivity with temperature

- Several alloys have obviously been chosen for their very low temperature coefficient of resistivity. The “constantan” alloy is probably the most common material for general static applications.“Isoelastic” alloy is frequently used for gages which are subjected to dynamic strains but when interest is in the measurement of peak-to-peak values only. In this case the higher gage factor is attractive while the thermally induced change in resistance appears as a steady state offset and is not recorded in peak-to-peak measurements.

Thermal Effect on Strain Gauge

Changes in the gauge resistivity with temperature

Material	Composition	Use	GF	Resistivity (Ohm/mil-ft)	Temp. Coef. of Resistance (ppm/F)	Temp. Coef. of Expansion (ppm/F)	Max Operating Temp. (F)
Constantan	45% Ni, 55% Cu	Strain Gage	2.0	290	6	8	900
Isoelastic	36% Ni, 8% Cr, 0.5% Mo, 55.5% Fe	Strain gage (dynamic)	3.5	680	260		800
Manganin	84% Cu, 12% Mn, 4% Ni	Strain gage (shock)	0.5	260	6		
Nichrome	80% Ni, 20% Cu	Ther-mometer	2.0	640	220	5	2000
Iridium-Platinum	95% Pt, 5% Ir	Ther-mometer	5.1	135	700	5	2000
Monel	67% Ni, 33% Cu		1.9	240	1100		
Nickel			-12	45	2400	8	
Karma	74% Ni, 20% Cr, 3% Al, 3% Fe	Strain Gage (hi temp)	2.4	800	10		1500

Thermal Effect on Strain Gauge

Temperature induced strain in the gauge element

- One of the problems of strain measurement is thermal effect. Besides external force, changing temperatures elongate or contract the measuring object with a certain linear expansion coefficient. Accordingly, a strain gage bonded to the object bears thermally-induced apparent strain. Temperature compensation solves this problem.

1. **Active-Dummy method**
2. **Self-Temperature-Compensation Method**

Thermal Effect on Strain Gauge

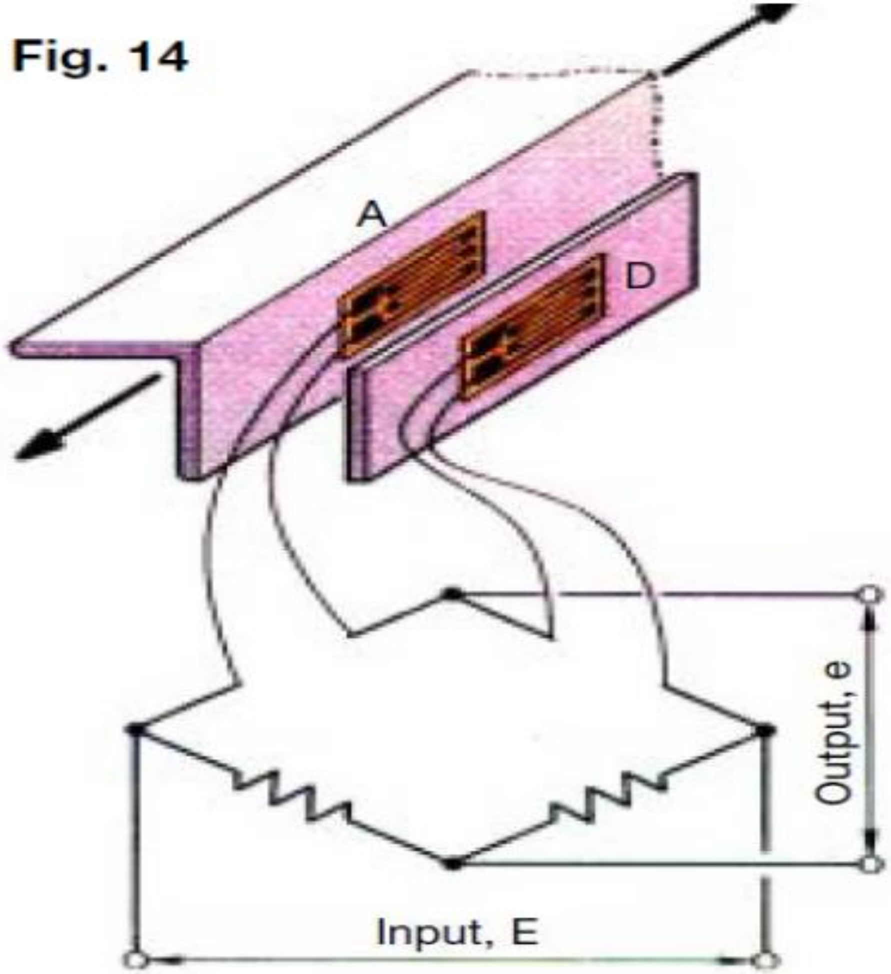
Active-Dummy method

- The active-dummy method uses the 2-gage system where an active gage, A, is bonded to the measuring object and a dummy gage, D, is bonded to a dummy block which is free from the stress of the measuring object but under the same temperature condition as that affecting the measuring object. The dummy block should be made of the same material as the measuring object. As shown in the following figure, the two gages are connected to adjacent sides of the bridge. Since the measuring object and the dummy block are under the same temperature condition, thermally-induced elongation or contraction is the same on both of them. Thus, gages A and B bear the same thermally-induced strain, which is compensated to let the output, e, be zero because these gages are connected to adjacent sides.

Thermal Effect on Strain Gauge

Active-Dummy method

Fig. 14



Thermal Effect on Strain Gauge

Self-Temperature-Compensation Method

- Theoretically, the active-dummy method described above is an ideal temperature compensation method. But the method involves problems in the form of an extra task to **bond two gages** and install the **dummy block**. To solve these problems, the **self-temperature-compensation gage** was developed as the method of compensating temperature with a **single gage**. With the self-temperature-compensation gage, the <u>temperature coefficient of resistance of the sensing element is controlled based on the linear expansion coefficient of the measuring object.</u> Thus, the gage enables strain measurement without receiving any thermal effect if it is matched with the measuring object.

Thermal Effect on Strain Gauge

Self-Temperature-Compensation Method

- Suppose that the linear expansion coefficient of the measuring object is (βs) and that of the resistive element of the strain gage is (βg). When the strain gage is bonded to the measuring object as shown in the following figure, the strain gage bears thermally-induced apparent strain/°C, (ε_T), as follows:

$$\varepsilon T = \frac{\alpha}{Ks} + (\beta s - \beta g)$$

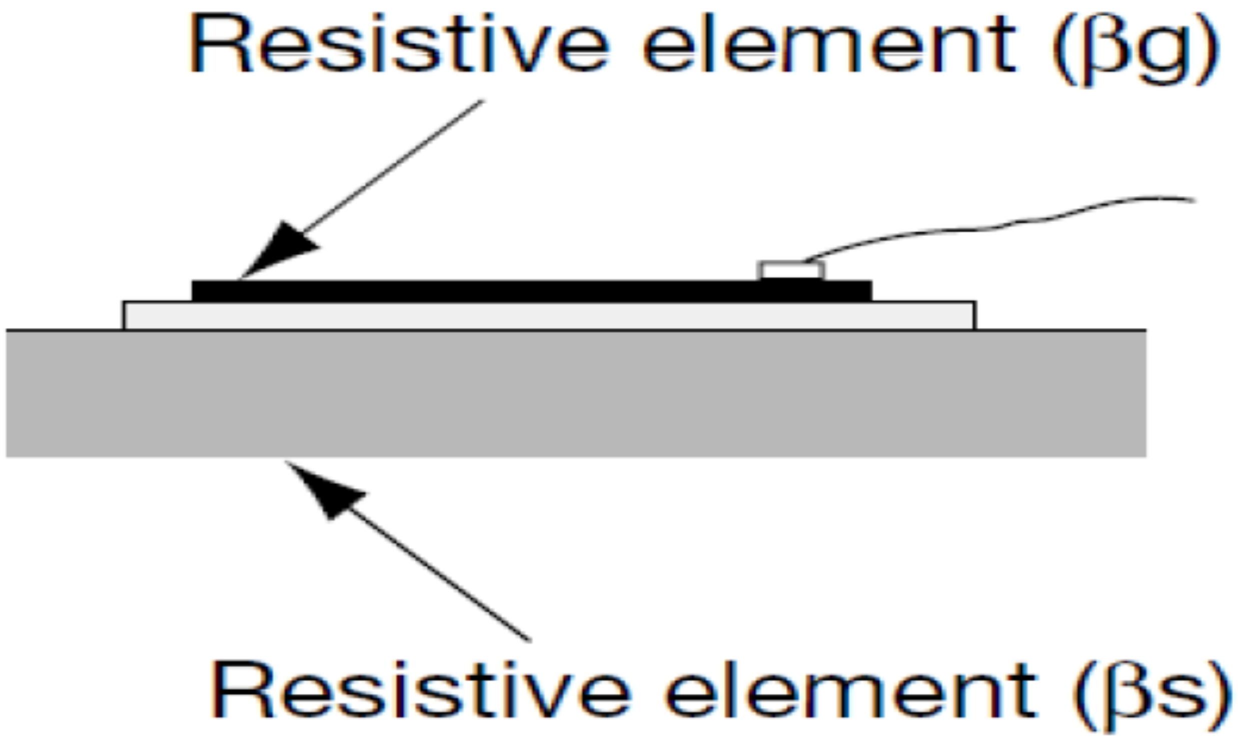
- **Where:**

α: Temperature coefficient of resistance of resistive element

Ks: Gage factor of strain gage

Thermal Effect on Strain Gauge

Self-Temperature-Compensation Method



Thermal Effect on Strain Gauge

Self-Temperature-Compensation Method

- The gage factor, Ks, is determined by the material of the resistive element, and the linear expansion coefficients, βs and βg, are determined by the materials of the measuring object and the resistive element, respectively.
- Thus, controlling the temperature coefficient of resistance, α, of the resistive element suffices to make the thermally-induced apparent strain, ε_T, zero in the above equation.

$$\alpha = -Ks\,(\beta s - \beta g)$$

Thermal Effect on Strain Gauge

Self-Temperature Compensation Method

- The temperature coefficient of resistance, α, of the resistive element can be controlled through **heat treatment in the foil production process**.
- Since it is adjusted to the linear expansion coefficient of the **intended measuring object**, application of the gage to other than the intended materials **not only voids temperature compensation but also causes large measurement errors.**

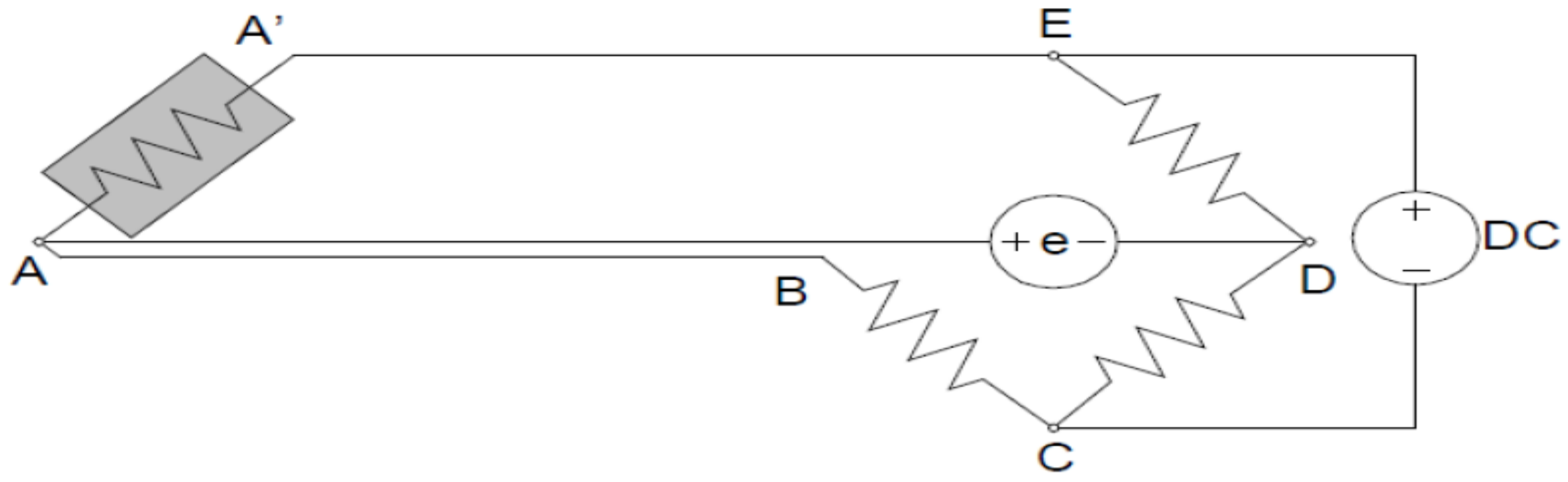
Thermal Effect on Strain Gauge

Self-Temperature-Compensation Method

- The self-temperature-compensation gage is designed so that ε_T in the above equation is approximated to zero by controlling the resistive temperature coefficient of the gage's resistive element according to the linear expansion coefficient of the measuring object.

Thermal Effect on Strain Gauge

Temperature induced strain in the leadwires



Leadwires compensation

Strain Gauges

- Stress measurements
- Strain gauge bridge applications

5.14.3. Theory of Strain Gauges

When a strain gauge is subjected to tension (*i.e.*, positive strain) its length *increases* while its cross-sectional area *decreases*. Since the resistance of a conductor is proportional to its length and inversely proportional to its area of cross-section, the resistance of the gauge increases with positive strain. The change in the value of resistance of strained conductor is more than what can be accounted for an increase in resistance due to dimensional changes. The extra change is the value of resistance is attributed to a *change in the value of resistivity of a conductor when strained; this property is known as* **piezo-resistive** *effect.*

Strain gauges are most commonly used in wheatstone bridge circuits to measure the change of resistance of grid of wire for calibration proposes; the "**gauge factor**" *is defined as the ratio of per unit change in resistance to per unit change in length.*

i.e., $$\text{Gauge factor } (G_f) = \frac{\Delta R / R}{\Delta L / L} \qquad \ldots(5.8)$$

where, ΔR = Corresponding change in resistance R, and

ΔL = Change in length per unit length L.

The resistance of the wire of strain gauge R is given by:

$$\rho = \frac{\rho L}{A}$$

where, ρ = Resistivity of the material of wire (of strain gauge),

L = Length of the wire, and

A = Cross-sectional area of the wire,

$= KD^2$, K and D being a constant and diameter of the wire respectively.

As earlier stated, when the wire is strained its length increases and lateral dimension is reduced as a function of Poisson's ratio(μ); consequently there is an increase in resistance.

Now,

$$R = \frac{\rho L}{KD^2}$$

Differentiating it, get we

$$dR = \frac{KD^2(\rho.dL + L.d\rho) - \rho L(2KD.dD)}{(KD^2)^2}$$

$$= \frac{1}{KD^2}\left[(\rho.dL + L.d\rho) - 2\rho L.\frac{dD}{D}\right]$$

or,

$$\frac{dR}{R} = \frac{\frac{1}{KD^2}\left[\rho.dL + L.d\rho - 2\rho L.\frac{dD}{D}\right]}{\frac{\rho L}{KD^2}}$$

$$= \frac{dL}{L} + \frac{d\rho}{\rho} - 2\frac{dD}{D}$$

Now, Poisson's ratio, $\mu = \dfrac{\text{Lateral strain}}{\text{Longitudinal strain}} = \dfrac{-dD/D}{dL/L}$

or,

$$\frac{dD}{D} = -\mu \times \frac{dL}{L}$$

For small variations, the above relationship can be written as:

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} + 2\mu\frac{\Delta L}{L} + \frac{\Delta\rho}{\rho} \quad ...(5.9)$$

Gauge factor, $G_f = \dfrac{\Delta R / R}{\Delta L / L}$

or,

$$\frac{\Delta R}{R} = G_f \cdot \frac{\Delta L}{L} = G_f \times e \quad ...(5.10)$$

where, e = strain = $\dfrac{\Delta L}{L}$

The *gauge factor* can be written as :

$$G_f = 1 + 2\mu + \frac{\Delta\rho/\rho}{e} \quad ...(5.11)$$

$$= 1 + 2\mu + \frac{\Delta\rho/\rho}{e}$$

= Resistance change due to change of length + Resistance change due to change in area + Resistance change due to piezo-resistive effect.

or

$$G_f = 1 + 2\mu + \frac{\Delta\rho/\rho}{\Delta L/L} \quad ...(5.12)$$

The strain is usually expressed in terms of *microstrain*; 1 micro strain = 1μm/m

If the change in the value of resistisity of a material when strained is *neglected*, the gauge factor can be rewritten as:

$$G_f = 1 + 2\mu \quad ...(5.13)$$

Eqn. (5.13) is valid only when *piezo-resistive effect* (*i.e.*, change in resistisity due to strain) is *almost negligible*.

- The Poisson's ratio for all metals lies between 0 and 0.5. This give G_f as 2 approximately. In case of wire wound strain gauges where the common value for Poisson's ratio is 0.3, the value of G_f amounts to 1.6.
- The value of the gauge factor varies from material to material but it is generally assumed that it remains constant in the working range of strain required. *Its value is determined experimentally.*
- *Knowing the gauge factor (G_f), the strain in the member can be directly found out by the change of resistance.*

Properties of gauge materials:

The grid material for its proper functioning must possess the following desirable *properties*:

1. High resistivity.
2. High gauge factor.
3. High mechanical strength.
4. High electrical stability.
5. Low temperature sensitivity.
6. Low hysteresis.
7. Low thermal e.m.f. when joined with other materials.
8. Good corrosion resistance.
9. Good weldability.

Example 5.18. *The gauge factor of a resistance wire strain gauge using a soft iron wire of small diameter is 4.2. Neglecting the piezo-resistive effect, calculate the Poisson's ratio.*

Solution. *Given:* $G_f = 4.2$

When the piezo-resistive effect is neglected, the gauge factor is given by:

$$G_f = 1 + 2\mu \quad \text{(Eqn 5.13)}$$

$$4.2 = 1 + 2\mu$$

or,

$$\therefore \quad \mu = \frac{4.2 - 1}{2} = 1.6 \quad \textbf{(Ans.)}$$

Example 5.19. *A simple electrical strain gauge of resistance 120Ω and having a gauge factor of 2 is bonded to steel having an elastic limit stress of 400 MN/m² and modulus of elasticity is 200 GN/m². Calculate the change in resistance.*

(i) due to a change in stress equal to $\frac{1}{10}$ of the elastic range;

(ii) due to change of temperature of 20°C if the material is advance alloy. The resistance temperature coefficient of advance alloy is 20×10^{-6}/°C.

Solution. *Given:* $R = 120\Omega$; $G_f = 2$; Elastic limit stress = 400 MN/m²; Modulus of elasticity = 200 GN/m²; Resistance temperature coefficient, $\alpha_0 = 20 \times 10^{-6}$/°C.

Change in resistance:

(i)

$$\text{Change in stress} = \frac{1}{10} \times 400 \text{ MN/m}^2 = 40 \times 10^6 \text{ N/m}^2$$

$$\text{Modulus of elasticity} = 200 \text{ GN/m}^2 = 200 \times 10^{12} \text{ N/m}^2$$

$$\text{Strain, } e = \frac{\text{Stress}}{\text{Modulus of elasticity}} = \frac{40 \times 10^6}{200 \times 10^{12}} = \frac{1}{5} \times 10^{-6}$$

$$\text{Gauge factor } G_f = \frac{\text{Per unit change in resistance}}{\text{Per unit change in length}}$$

or,

$$G_f = \frac{\Delta R/R}{e} \quad \text{or} \quad \Delta R = R\, G_f\, e$$

or,

$$\Delta R = 120 \times 2 \times \frac{1}{5} \times 10^{-6} = 48 \times 10^{-6}\ \Omega = 48\ \mu\Omega \quad \textbf{(Ans.)}$$

(ii)

$$R_{t2} = R_{t1}\,[1 + \alpha_0 (t_2 - t_1)]$$

$$\therefore \text{ Change is resistance } R_{t2} - R_{t1} = R_{t1}\, \alpha_0 (t_2 - t_1)$$

or

$$\Delta R = R_{t2} - R_{t1} = 120 \times 20 \times 10^{-6} (20)$$

$$= 48 \times 10^{-3}\ \Omega = 48 \text{ m}\Omega \quad \textbf{(Ans.)}$$

Example 5.20. *A strain of 6 micro-strain is a caused in a structural member when subjected to a compressive force. Two separate strain gauges are attached to the structural member, one is a nickel wire strain gauge (gauge factor = – 12.1) and other is nichrome wire strain gauge (gauge factor = 2). If the resistance of strain gauges before being strained is 110Ω, calculate the change in the value of resistance of the gauges after they are strained.*

Solution. $e = -6 \times 10^{-6}$ ($\because$ 1 micro-strain = 1 μm/m); negative sign is taken, since the strain is compressive one. $(G_f)_{\text{nickel}} = -12.1$; $(G_f)_{\text{nich}} = 2$; $R = 110\ \Omega$.

The value of resistance of the gauges after they are strained:

We know that, $\dfrac{\Delta R}{R} = G_f \times e$

$\therefore$ Change in the value of resistance of *nickel wire strain gauge*, $\Delta R = R \times G_f \times e$

$$= 110 \times (-12.1) \times (-6 \times 10^{-6})$$
$$= 7.988 \times 10^{-3}\ \Omega = 7.986\ m\Omega \quad \text{(Ans.)}$$

Thus there is an *increase of 7.986 mΩ in the value of resistance*.

For nichrome wire strain gauge, the change in value of resistance,

$$\Delta R = 110 \times (2) \times (-6 \times 10^{-6})$$
$$= -1320 \times 10^{-6}\ \Omega = -1.32\ m\Omega \quad \text{(Ans.)}$$

Thus there is a *decrease of 1.32 mΩ in the value of the resistance*.

Example 5.21. *A resistance wire strain gauge with a gauge factor of 2 is bonded to a steel structural member subjected to a stress of 120 MN/m². The modulus of elasticity of steel is 200 GN/m². Calculate the percentage change in the value of the gauge resistance due to the applied stress. Comment upon the results.*

Solution. *Given:* $G_f = 2$; Stress, $\sigma = 120\ MN/m^2$; $E = 200 GN/m^2$

Percentage change in the value of resistance ($\Delta R/R$):

$$\text{Strain} = \frac{\sigma(\text{Stress})}{E(\text{Modulus of elasticity})}$$

$$= \frac{120 \times 10^6}{200 \times 10^9} = 600 \times 10^{-6}\ \text{(600 micro-strain)}$$

Also, $\dfrac{\Delta R}{R} = G_f \times e = 2 \times 600 \times 10^{-6} = 0.0012 = 0.12\%$ **(Ans.)**

Comments. The above results indicate that a very heavy stress of 120 MN/m² results in resistance change of only 0.12 per cent, which is by all means a *very small change. This may lead to difficulties in measurement.* Lower stresses produce still lower changes in resistance which may not be perceptible at all or the *methods required* to detect these may have to be *highly accurate*. To overcome this difficulty *we must use strain gauges which have a high gauge factor and hence produce large changes in resistance when strained.*

Example 5.22. *A strain gauge is bonded to a beam which is 12 cm long and has a cross-sectional area of 3.8 cm². The unstrained resistance and gauge factor of the strain gauge are 220Ω and 2.2 respectively. On the application of load the resistance of the gauge changes by 0.015Ω. If the modulus of elasticity for steel is 207 GN/m², calculate:*

(i) The change in length of the steel beam.

(ii) The amount of force applied to the beam.

Solution. *Given:* $L = 12$ cm $= 0.12$ m; $A = 3.8\ cm^2 = 3.8 \times 10^{-4}\ m^2$; $R = 220\Omega$; $G_f = 2.2$; $\Delta R = 0.015\Omega$; $E = 207\ GN/m^2$.

(i) The Change in length of steel beam, ΔL:

$$\text{Gauge factor, } G_f = \frac{\Delta R / R}{\Delta L / L}$$

$$\Delta L = \frac{(\Delta R / R).L}{G_f} = \frac{(0.015/220) \times 0.12}{2.2} = 3.72 \times 10^{-6} \text{ m (Ans.)}$$

(ii) The amount of force applied to the beam, F:

$$E = \frac{\text{Strers}}{\text{Strain}} = \frac{\sigma}{e}$$

$$\sigma = E \times e = E \times \frac{\Delta L}{L}$$

$$= (207 \times 10^9) \times \frac{3.72 \times 10^{-6}}{0.12} = 6.417 \times 10^6 \text{ N/m}^2$$

$$\text{Force, } F = \sigma \cdot A = 6.417 \times 10^6 \times 3.8 \times 10^{-4} \text{N} = 2.438 \text{ kN (Ans.)}$$