Strain Measurements With Resistance Strain Gauges

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Abstract

This laboratory is to learn about the general principle of strain gauge and its use in measuring the strain, which can generate the Young's modulus of different materials. For this experiment, strain is measured by strain gauge. Strain gauge was connected to simple Wheatstone bridge in quarter-bridge configuration to generate the voltage value which gives value of the corresponding strain. By measuring the corresponding value of stress, Young's modulus of the specimen can be concluded.

Introduction

Stress and strain are are important aspects of Mechanical Engineering especially in structural design.(1)Young's modulus is always an important property of a material and it can decide the ability it can be against tensile stress. Young's modulus is determined from the slope of stress-strain diagram below the region of being elastic.

Theoretical Background

The lab handout (2) written by stated that V.L. Tagarielli:

"Resistance strain gauges make use of the phenomenon discovered by Lord Kelvin that the resistance of an electrical conductor varies if this is deformed. The gauge is essentially a conducting element which is securely bonded to the surface on which the strain is to be measured, so that any strain on the surface is equal to the strain in the strain gauge conductor. The surface strain is found by measuring the change in resistance of this conductor. Strain gauges have their conductive element oriented in a specific direction, and measure strains in that direction."

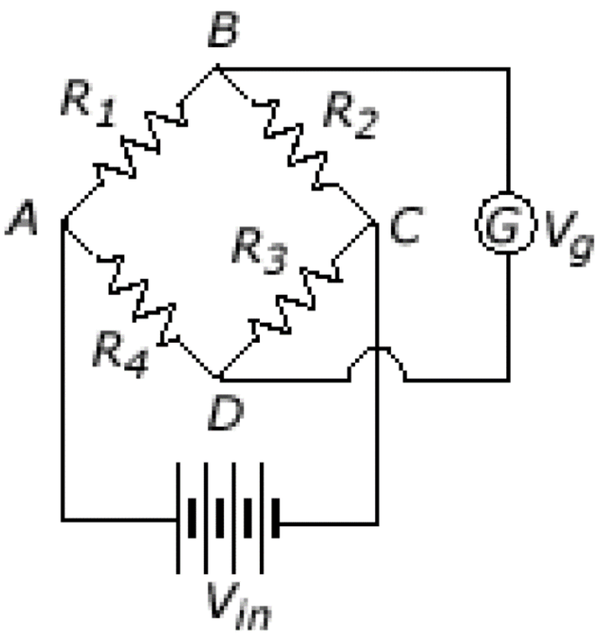
For the electrical resistance wire strain gauge used in this experiment, the equation between the resistance of and length is given by:

$$R = \rho \frac{L}{A} \tag{1}$$

Where ρ here is the resistivity of the used material, L is the length of the wire and A is the cross-sectional area. If the strain change of the gauge is not very big, the change of the resistance will be proportionately to the change of the length. The constant of proportionality between strain and relative change in resistance is called the gauge factor S (V.L. Tagarielli, 2018):

$$\frac{\Delta R}{R*S} = \varepsilon \qquad (2)$$

Wheatstone Bridge is a kind of circuit which connects for resistance together as below:



Wheatstone Bridge, strain gauge that needs test should be connected to the first arm of the bridge(R1). Here, if the magnitudes of four resistors are equal (*R1 = R2 = R3 = R4 = R*), the output voltage on Vg will be given by the equation below:

$$V_g = \frac{V_{in}}{4}\left[\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right] = V_{in}\frac{\Delta R_1 - \Delta R_2 + \Delta R_3 - \Delta R_4}{4R} \qquad (3)$$

If R2, R3, R4 in upper diagram are replaced by fixed resistors which will not vary its value during the experiment, the equation will be shown as below:

$$V_g = V_{in}\frac{\Delta R_1}{4R} \Rightarrow \varepsilon = \frac{\Delta R / R}{S} = \frac{4V_g}{V_{in}S} \qquad (4)$$

An issue that will affect the experiment a lot is the thermal effect induced by increase in temperature. In order to eliminate this effect, the 'dummy gauge' is used in the position of R2. The dummy gauge can only change the its value when there is thermal effect. Due to the actual equation of change of R1 will be like:

$$\Delta R_1 = \Delta R_{thermal} + \Delta R_{actual} \tag{5}$$

After using of 'dummy gauge', the thermal effect on R1 will cancel out and thus output of Vg will be:

$$V_g = V_{in} \frac{\Delta R_1 - \Delta R_2}{4R} = V_{in} \frac{\Delta R_{thermal} + \Delta R_{actual} - \Delta R_{thermal}}{4R} = V_{in} \frac{\Delta R_{actual}}{4R} \tag{6}$$

Also, the Vg will actually be very small, which will make the experiment result not precise, the amplifier will be used to enlarge the output of Vg. Thus the output that will be obtained is:

$$\overline{V}_g = GAIN \cdot V_g \tag{7}$$

By application of the equation of strain, the equation of strain of the tested material will be concluded to:

$$\varepsilon = \frac{\Delta R / R}{S} = \frac{4\overline{V}_g}{V_{in} S \cdot GAIN} \tag{8}$$

Experimental Apparatus and Procedure

In this experiment, three round dogbone specimens made of different materials were used. A hand-operated tensile machine was also used in this experiment to measure exert force of different magnitudes on the material. The wires of the strain gauge inside the specimen were connected to simple Wheatstone bridge in quarter-bridge configuration. The amplifier was connected to Vg to amplify the output and the gain is about 500. Voltmeter was given to measure the voltage after amplification. In the beginning of the experiment, the diameter of each specimen was measure by Vernier caliper three times and then average. Gauge factor of corresponding specimen was noted. The next step is to install the specimen on the hand-operated tensile machine and make sure that the load of the machine is zero. Then bridge was switched off and voltage which was Vin over the battery was measured. While the load was still 0, switch on the bridge and record the value of the voltage output. To make the bridge balanced, turn the dial of the potentiometer over the bridge until the output is almost 0. After this, operate the wheel of the hand-operated tensile force machine slowly to increase the applied force from 0 to 3.5 kN with the step of 0.5kN and record the corresponding voltage output. Then slowly decrease the applied load to 0 via the step of 0.5kN and record the value of the output at the same time. When the process of one specimen was finished, switch to the specimen with different material and repeat the whole process again until all the specimens had their own data.

Results

<u>MATERIAL 1: ALUMINIUM</u>

Table 1 Average diameter of the aluminum alloy

Diameter 1 / m	Diameter 2 /m	Diameter 3 /m	Average Diameter /m
0.00595	0.00596	0.00595	0.00595

Cross-sectional area of the aluminum alloy specimen:

$\pi \times (\frac{\text{Average Diameter}}{2})^2 = \pi \times (\frac{0.00595\text{ m}}{2})^2 = 2.78 \times 10^{-5}\text{ m}^2$

Table 2

Force / $\times 10^3$ N	Voltage of Amplifier ($\overline{V_g}$) / V		Stress (σ) / $\times 10^6$ Nm^{-2}	Strain (ε) / $\times 10^{-3}$	
	LOADING	UNLOADING		LOADING	LOADING
0	0	0.002	0	0	0
0.5	0.065	0.088	18.0	0.5	0.065
1.0	0.149	0.169	36.0	1.0	0.149
1.5	0.216	0.251	54.0	1.5	0.216
2.0	0.303	0.334	71.9	2.0	0.303
2.5	0.378	0.408	90.0	2.5	0.378
3.0	0.465	0.473	107.9	3.0	0.465
3.5	0.544	0.543	125.9	3.5	0.544

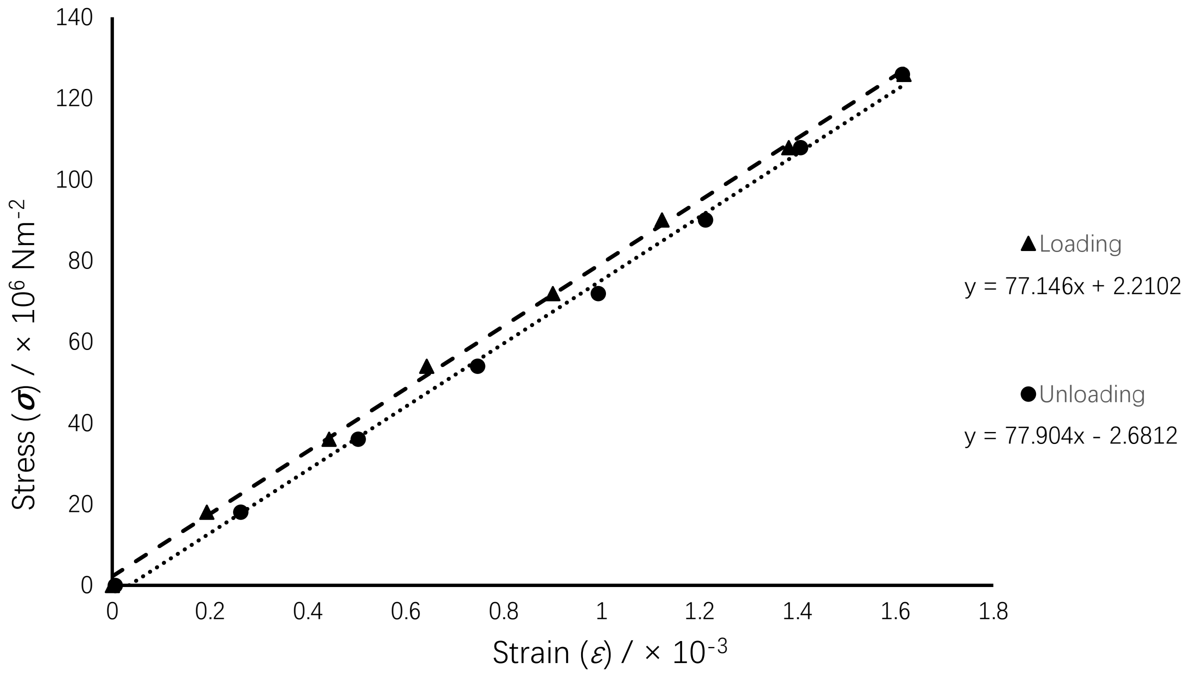


Figure 1 A graph to show the relationship between stress and strain during loading and unloading of Material 1: Aluminium

<u>MATERIAL 2: BRASS</u>

Table 3 Average diameter of the aluminum alloy

Diameter 1 / m	Diameter 2 /m	Diameter 3 /m	Average Diameter /m
0.00595	0.00595	0.00595	0.00595

Cross-sectional area of the aluminum alloy specimen:

$\pi \times (\frac{\text{Average Diameter}}{2})^2 = \pi \times (\frac{0.00595\text{ m}}{2})^2 = 2.78 \times 10^{-5}\text{ m}^2$

Table 4

Force / × 10^3 N	Voltage of Amplifier ($\overline{V_g}$) / V		Stress (σ) / × 10^6 Nm^{-2}	Strain (ε) / × 10^{-3}	
	LOADING	UNLOADING		LOADING	UNLOADING
0	0	-0.003	0	0	-0.009
0.5	0.042	0.062	18.0	0.125	0.184
1.0	0.115	0.133	36.0	0.342	0.395
1.5	0.168	0.196	54.0	0.499	0.582
2.0	0.233	0.266	71.9	0.692	0.790
2.5	0.294	0.325	90.0	0.874	0.966
3.0	0.354	0.390	107.9	1.052	1.159
3.5	0.411	0.411	125.9	1.221	1.221

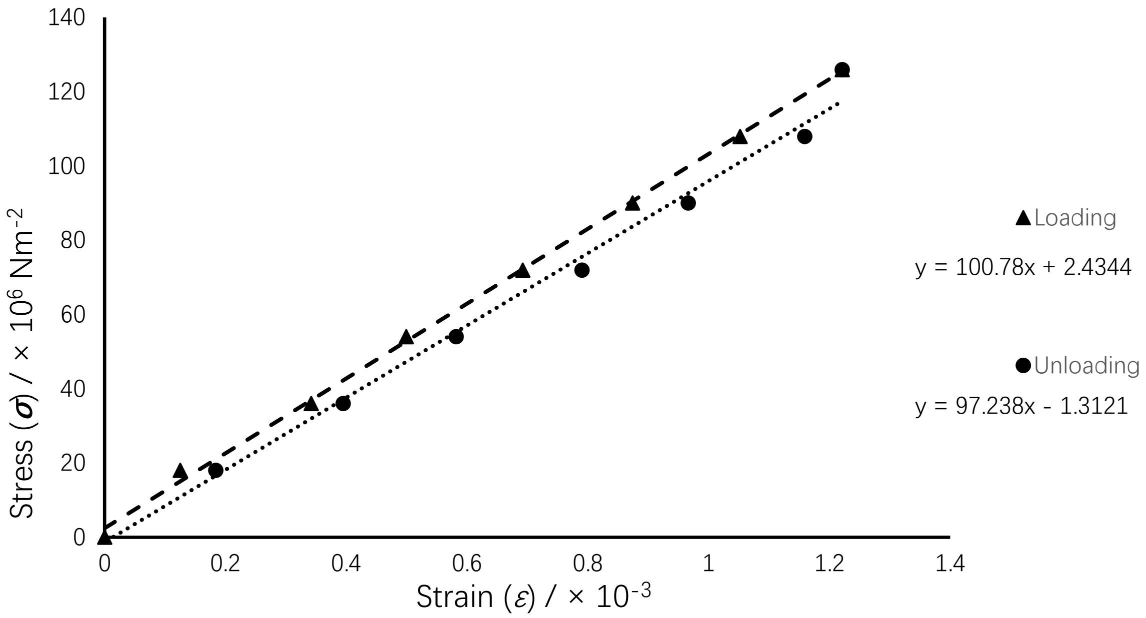


Figure 2 A graph to show the relationship between stress and strain during loading and unloading of Material 2: Brass

<u>MATERIAL 3: COPPER</u>

Table 5 Average diameter of the aluminum alloy:

Diameter 1 / m	Diameter 2 /m	Diameter 3 /m	Average Diameter /m
0.00596	0.00596	0.00593	0.00595

Cross-sectional area of the aluminum alloy specimen:

$\pi \times (\frac{\text{Average Diameter}}{2})^2 = \pi \times (\frac{0.00595\ \text{m}}{2})^2 = 2.78 \times 10^{-5}\ \text{m}^2$

Table 6

Force / × 10^3 N	Voltage of Amplifier ($\overline{V_g}$) / V		Stress (σ) / × 10^6 Nm^{-2}	Strain (ε) / × 10^{-3}	
	LOADING	UNLOADING		LOADING	UNLOADING
0	0	0.008	0	0	0.024
0.5	0.028	0.038	18.0	0.083	0.113
1.0	0.067	0.081	36.0	0.199	0.241
1.5	0.107	0.126	54.0	0.318	0.374
2.0	0.147	0.170	71.9	0.437	0.505
2.5	0.193	0.219	90.0	0.574	0.651
3.0	0.236	0.255	107.9	0.701	0.758
3.5	0.285	0.285	125.9	0.847	0.847

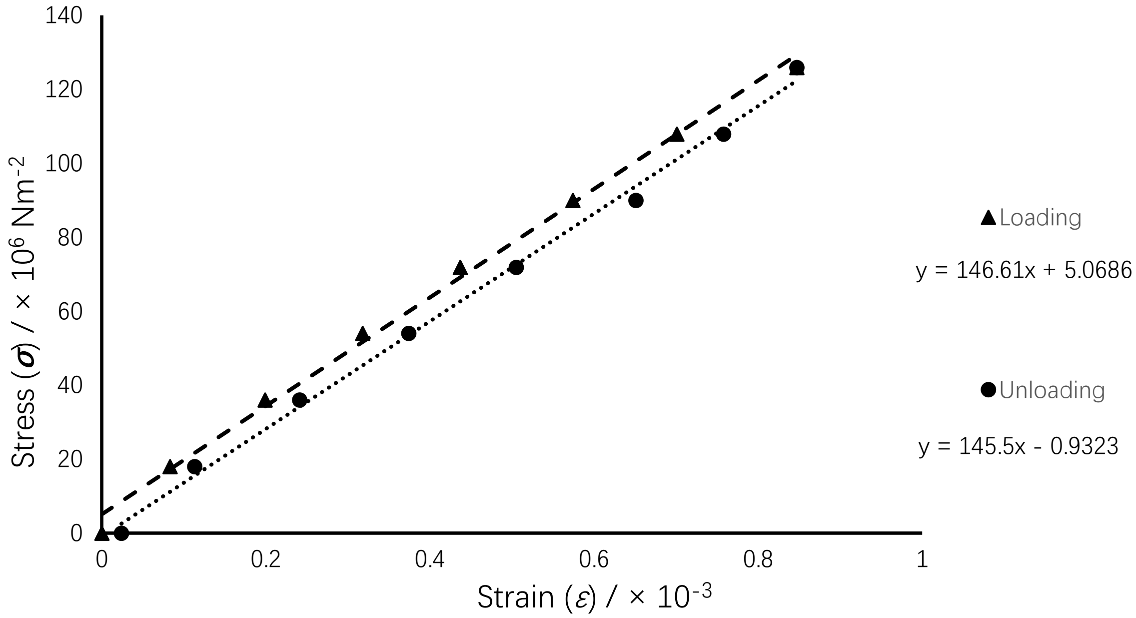


Figure 3 A graph to show the relationship between stress and strain during loading and unloading of Material 3: Copper

From the diagram, we can conclude the Young's modulus for each material.

For Aluminum, the Young's modulus = ((77.146+77.904)/2)*10^9Pa=77.5GPa;

For Brass, the Young's modulus = ((100.78+97.238)/2)*10^9Pa=99.0GPa;

For Copper, the Young's modulus = ((146.61+145.50)/2)*10^9Pa=146.1GPa;

Discussion

The method of obtaining the Young's modulus is different from the normal one. It measures the voltage of the bridge instead of measuring the extension directly, which will increase precision a lot. Also, embedded the strain gauge in the round dogbone specimen made the experiment much easier to operate. It was a completely new way to measure the Young's modulus. Furthermore, the experiment lasted for less than one hour, which means that it is a very quick way to obtain such value. For the standard data of Aluminum, Brass and Copper is 70GPa, 102-125GPa and 117GPa individually and the results from this experiment is 77.5GPa, 99.0GPa and 146.1GPa. It can be seen that the values of Aluminum, Brass are closed while that for Copper varies relatively bigger. To find the origin of the error, it is necessary to recall the process of the experiment. For the apparatus, they all get absolute uncertainty. (Percentage error calculated can be seen in appendix) During the experiment, the biggest error occurred at the hand-operated tensile machine. Force applied on the specimen was not actually the value shown on the screen. Between the parts of the machine, it always had some friction which may require bigger force to reach the value shown on the screen, which means that the specimens got bigger force in each experiment and this made the value of the Young's modulus obtained bigger than it should be. To make the whole experiment more precise, couple of measurements including the diameters of the specimens and the output voltage were taken and averaged. However, the difference between the real value and that from the experiment may also due to the reason that the materials used were not pure. Another drawback of this experiment was that the preparation of the specimens may take a long time as you need to embed the strain gauge into the dogbone material.

Conclusion

To conclude, this experiment aimed to obtain the Young's modulus of three material with the method of combining circuit and strain gauge. The value obtained is not exactly the same as the standard one due to some error occurred on the hand-operated tensile machine. However, it is still a quick and precise way of measuring material's Young's modulus.

Reference

(1) John.M. *Stress,Strain and Strain Gauges*. Penn State University. 2013.

(2) V.L. Tagarielli. *First Year Laboratory Handout.* Imperial College London. CA: Department of Aeronautics. 2018.

Appendix

Table 7 Uncertainty of Stress of all Materials

F/KN	absolute uncertainty of force	Cross-section Area	Percentage uncertainty of Area	Percentage uncertainty of stress
0	0.05	2.78E-05	0.17%	0.17%
0.5	0.05	2.78E-05	0.17%	10.17%
1	0.05	2.78E-05	0.17%	5.17%
1.5	0.05	2.78E-05	0.17%	3.50%
2	0.05	2.78E-05	0.17%	2.67%
2.5	0.05	2.78E-05	0.17%	2.17%
3	0.05	2.78E-05	0.17%	1.83%
3.5	0.05	2.78E-05	0.17%	1.60%

Table 8 Uncertainty of Strain of Aluminium

loading/V	Unloading/V	absolute uncertainty of voltage	Percentage error of strain	loading/V
0	0.002	5.00E-04	25.00%	25.00%
0.065	0.088	5.00E-04	0.77%	0.57%
0.149	0.169	5.00E-04	0.34%	0.30%
0.216	0.251	5.00E-04	0.23%	0.20%
0.303	0.334	5.00E-04	0.17%	0.15%
0.378	0.408	5.00E-04	0.13%	0.12%
0.465	0.473	5.00E-04	0.11%	0.11%
0.544	0.543	5.00E-04	0.09%	0.09%

Table 9 Uncertainty of Strain of Brass

loading/V	Unloading/V	absolute uncertainty of voltage	Percentage error of strain	loading/V
0	-0.003	5.00E-04	-16.70%	-16.67%
0.042	0.062	5.00E-04	1.19%	0.81%
0.115	0.133	5.00E-04	0.43%	0.38%
0.168	0.196	5.00E-04	0.30%	0.26%
0.233	0.266	5.00E-04	0.21%	0.19%
0.294	0.325	5.00E-04	0.17%	0.15%
0.354	0.39	5.00E-04	0.14%	0.13%
0.411	0.411	5.00E-04	0.12%	0.12%

Table 10 Uncertainty of Strain of Copper

loading/V	Unloading/V	absolute uncertainty of voltage	Percentage error of strain	loading/V
0	0.008	5.00E-04	6.25%	6.25%
0.028	0.038	5.00E-04	1.79%	1.32%
0.067	0.081	5.00E-04	0.75%	0.62%
0.107	0.126	5.00E-04	0.47%	0.40%
0.147	0.17	5.00E-04	0.34%	0.29%
0.193	0.219	5.00E-04	0.26%	0.23%
0.236	0.255	5.00E-04	0.21%	0.20%
0.285	0.285	5.00E-04	0.18%	0.18%

Answer to the attached question:

$$\varepsilon xx = -2.095 \times 10^{-3}$$

$$\sigma xx = \Delta p \frac{32.5}{0.11}$$

$$\sigma yy = \Delta P \frac{32.5}{0.22}$$

According to the matrix given,

$$-2.11 \times 10^{-3} = \Delta P \cdot \frac{\sigma xx}{E} + \Delta P \cdot \frac{\sigma yy}{E}$$

Thus $\Delta P = -6.05 \times 10^{5} Pa$