Study of linear strain gauges at micron scale for the reduction of external factors

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Abstract. In the present article, the design and simulation of a strain gauge is shown, which serves to measure deformation or pressure in different applications of the industry. In this way, the respective simulation was carried out in the COMSOL Multiphysics 5.2 software, where the 3 linear meander gauge was subjected to external factors such as temperature and pressure, with this, the different results obtained were shown the mechanical behavior and of Graphene and Silver grid materials and substrate Paper. On the other hand, in front of the design of the three-way linear strain gauge, M.E.M.S (Microelectromechanical Systems) parameters technology was used to reduce its dimensions in micrometers to reduce the effects of the respective external factors where these produce errors in the measurements.

Keywords: M.E.M.S (Microelectromechanical systems), GF (Gauge Factor), Linear Strain Gauges, simulation, temperature, Strength.

1. Introduction

In the mechanical industry (e.g. Vehicular, aeronautical) a measurement system is required to maintains continuous monitoring of the various mechanical parts. Due to this, the strain gauges appear as a transducer device, which can obtain precise measurements of the variations of the parameters (as is the case of the deformations that the mechanical components) and in turn detect possible ruptures in such as components.

The strain gauges are defined as a transducer based on the extensometric principle, which when are used to some mechanical effect (e.g. tension, pressure, etc.) vary their resistance, being able to convert small deformations of a material in quantifiable measures. On the other hand, the manufacture and miniaturization of strain gauges have shown a visible breakthrough; since the impact of this type of transducers have had on the different fields, (e.g. mechanics) contributing to an improvement in deformation control. Furthermore, the diversity of the parameters within which the strain gauges can work, as well as the structure of these gauges and what are the characteristics that should be taken into account when are used to the design and simulation of strain gauges.

In the Figure 1, the results obtained from the search in some databases such as Science Direct \textsuperscript{®} and ProQuest \textsuperscript{®}, as well as processed with a Bibliometric Tool such as Vantage Point \textsuperscript{®} and VosViewer \textsuperscript{®}. Then as result can be found keywords used as the main input of this research, which indicates that the
work done is located within the global trends. Similarly, it can be seen that in Latin America it is not an area with a high level of research.

Figure 1. Vantage Point word map.

Additionally, in this article we shown the process of design and simulation of linear strain gauges, starting with the basic concepts of this type of transducer, such as the materials used and the parameters to be taken into account, also the equations and the results obtained when implementing these equations used to find the values of the electrical and mechanical parameters of these.

2. Design of strain gauges

2.1 History of strain gauges

In 1856 Lord Kelvin in his research, could applied a force on a conductive wire or a semiconductor, which generated a variation in its electrical resistance. This principle allows measurements of forces of very small magnitude to be taken, which are generated by slight deformations in the conductor material. These precepts were essential for working with transducer devices, among which are strain gauges. Meanwhile, strain gauges were invented in 1938 by Edward E. Simmons, who defined them as passive transducers, which, when adhered to a surface, help to measure the deformation that this suffers when a force is applied on this measure is given in ranges of variation of the strength of the strain gauge. At the same time, the simplest type of gauge is made of a flexible insulating line that is supported by a flat metallic pattern. Therefore, such as gauges are attached to the surfaces by using a special adhesive. In addition, the resistance variations are of very small values, so it is necessary to use a Wheatstone bridge, which results in a measurement of an electrical signal [1].

However, within the main design and simulation conditions of an ex-tensile gauge, there are the materials used, which must have piezo resistive properties, which refer to the ability to transform any deformation into a variation of its resistance and the type of substrate, which is the base on which the sensors are manufactured. Likewise, in a subsequent process such as the manufacture of some tensometric gauges, factors such as sensitivity or gauge factor must be taken into account at the time of being implemented, without neglecting, that have a short time of useful life..
2.2 Materials

Among the materials used in the manufacture of strain gauges are the following:

- **Polymers.** In nature there are huge molecules called macromolecules. Hundreds of thousands of atoms form these molecules, so their molecular weights are very high. Polymers are a particular type of macromolecule, which is characterized by having a unit that repeats throughout the molecule [2].

- **Fiber.** It is a crystalline structure that have their chains ordered and are composed of natural and synthetic, organic and inorganic materials, such as acetate and cellulose [3].

- **Graphene.** It is defined as a thin flat sheet of carbon atoms with sp2 hybridization in two dimensions (2D), forming a structure similar to a bee panel [5].

- **Silver.** It is a lustrous whitish precious metal that is found throughout the world, but most of it is extracted from mines in Mexico, the western United States, Bolivia, Peru, Canada and Australia [6].

2.3 Parts of a strain gauge.

The materials (shown above) are necessary for the Strain Gauge construction, the union of its three main parts, such as [4]:

- **Grid.** It is the metallic part, which varies its resistance as a compression, or tension is applied.

- **Base.** It is the carrier support of the grid and is manufactured in different insulating materials.

- **Tags.** They are used to connect the signal strain.

The material is located between the surface of the object of study and the grid. This provides firmness and support to the grid for the welding of cables to the labels, also provides a manageable surface for gluing the gauge on the object of study and finally providing electrical insulation between the grid of the gauge and the object of study.

It is important to mention that the strain gauge has a relationship between tension that is applied to the object of study and resistance variations, which is called tension sensitivity or gauge factor; which is defined as the change ratio of the electrical resistance of the conductor by varying the relative length. This parameter is dimensionless as mentioned G, Ruiz “… The gauge factor is a function of the tensile sensitivity of the alloy of the metals which the gauge grid was manufactured and other factors such as: Temperature, size, grid configuration and how to measure it” [4].

At the edges of the grid (final curves), a transverse sensitivity is presented. This sensitivity is observed when excessive tension is applied to the gauge, which generates the in-swelling (compression) or stretching (tension) of the gauge, causing the grid edges to vary in length and with this, the gauge has a change in its resistance. In the figure. 2 the parameters of the linear strain gauge are observed.

![Parameters of the linear strain gauge](image)

**Figure 2.** Parameters of the linear strain gauge [4].
To know what the practical values for the design of the strain gauge are; we proceed to formulate equations 1, 2, 3, 4, for its development within the proposed work. Equation 1 shows the variation of the resistance based on the multiplication of the resistivity of the material and the division of the changes in the length of the gauge, the resistance and the area of the conductor.

Eq 1. Change of electrical resistance

\[ \Delta R = \rho \frac{\Delta L}{A} \]  

Where:
- \( \Delta R \) = Changes in electrical resistance (Ω).
- \( \rho \) = Resistivity of the material (Ωm).
- \( \Delta L \) = Change in effective length of the conductive material (m).
- \( A \) = Conductive material area (m).

Equation 2 shows the gauge factor which is obtained by dividing the variation of the electrical resistance, the resistance of the gauge and the unit deformation.

Eq 2. Gauge factor equation

\[ GF = k = \frac{\Delta R}{R_g \Delta L} = \frac{\Delta R}{R \varepsilon} \]  

Where:
- \( GF = K \) = Gauge factor [dimensionless].
- \( R_g \) = Initial gauge resistance (Ω).
- \( L \) = Gauge Length (m).
- \( \varepsilon \) = Unitary Deformation [dimensionless].

Equation 3 shows the value of the stress applied to the object, which is obtained by dividing the tension, force, weight, load between the cross-sectional areas of the structure.

Eq 3. Equation of strain applied to an object [4]

\[ \sigma = \frac{P}{A} \]  

Where:
- \( \sigma \) = Strain applied to the object [N/m²].
- \( P \) = Tension, force, weight, load [N].
- \( A \) = Cross-sectional structure area [m²].

In Equation 4, the value of the deformation is obtained by dividing the change in the length of the object by the initial length of the object.

Eq 4. Unitary Deformation Equation
\[ \epsilon = \frac{\Delta L}{L_0} \]  

(4)

Where:

- \( L_0 \): Initial object length [m].

3. Calculation of mechanical and electrical parameters of strain gauges

The equations presented previously, are proposed for the design, taking into account the proposed geometries characteristics, which can be evidenced in Table 1.

Table 1. Measurement of the designs of linear strain gauges.

| Name      | Number | Description      |
|-----------|--------|------------------|
| h_sust    | 1 [cm] | Substrate height |
| a_sust    | 0.5 [cm] | Substrate length |
| p_subst   | 50 [µm] | Depth of Substrate |
| h_grid    | 0.65 [cm] | Grid height |
| a_grid    | 197.36 [µm] | Grid width |
| p_grid    | 50 [µm] | Grid depth |
| posh_grid | 2.4 [mm] | Grid position |
| d_grid    | 625 [µm] | Grid distance |
| a_electrode | 300 [µm] | Electrode width |

Related to table 1, different variations were made, among which are the number of meanders of 1, 2, 3 and 5 with round, square and 5 meander edges with triangular edges. It is also important to mention the use of substrate in paper fiber materials and grating material of graphene and silver type material.

![Graph showing variation of the electrical resistance of graphene](image)

Figure 3. Variation of the electrical resistance of graphene
Figure 4. Variation of the electrical resistance of silver

In the figure 3. It's shown a variation of the electrical resistance of graphene. On the other hand, the figure 4, shown the variation of the electrical resistance of the silver, which is dependent on the value of the variation of the length of the material.

Figure 5. Unitary deformation of the grid using graphene.

In the figure 5 shows the slope of the unitary deformation, which indicates the value of the deformation suffered by the material (graphene) as a function of the variation in length.
In Figures 6 and 7, the behavior of the Gauge Factor can be observed depending on the variation in the length of graphene and the theoretically obtained silver. The theoretically obtained values of the Gauge Factor are observed for the silver and graphene materials used in the designs, these materials behaved in very different ways, with graphene having higher values compared to silver.

**Figure 6.** Silver Gauge Factor.

**Figure 7.** Graphene Gauge Factor.
4. Analysis of the results in the simulations performed

The simulations were worked on in the COMSOL MULTIPHYSICS 5.2 ® program where various geometries (mentioned above) were generated, which underwent changes in temperature and in the force applied to the linear strain gauge. In Figures 8 and 9, the 3-gauge linear strain gauge with square edges, paper substrate and graphene grid material is observed, which was subjected to various forces of 2N and 8N.

![Figure 8](image)

Figure 8. Linear strain gauge of 3 meanders with square edges, paper substrate and graphene grating material subjected to 2N.

The results of the deformations obtained, respectively, were the graphene, which showed the best performance compared to those of silver grid material. Similarly, variations in color that indicate the concentration of stresses in the material are observed.

![Figure 9](image)

Figure 9. Linear strain gauge of 3 meanders with square edges, paper substrate and graphene grating material subjected to 8N.
The design of the linear strain gauge also underwent temperature variations that started at 26.85°C up to a maximum temperature of 226.89°C. The results are illustrated in the following figures 10 and 11, the linear strain gauge is observed which it was subjected to a temperature of 26.85 °C and 226.89 °C and it is evidenced that the material is not affected in large quantities, which indicates that it will not suffer large variations in the measurements as its temperature is increased in the measurement environment.

![Figure 10](image1.png)

**Figure 10.** Linear strain gauge 3 meanders with square edges (temperature range 26.85°C)

![Figure 11](image2.png)

**Figure 11.** Linear strain gauge 3 meanders with square edges temperature range 226.89°C

The temperature variations in the designed linear strain gauges, present a behavior that was observed in the temperature of 26.85°C or 300 K. They had no major effects on their materials on both the paper substrate and in the silver or Graphene meanders, when is increasing this temperature flow to 226.85°C or 500 K temperature (which is maximum point near supported by the paper before its combustion of 233 K).
5. Conclusions
This article showed that simulations were performed in which variations were generated in the materials used in the designs of linear strain gauges, paper in the substrate, silver and graphene in the meanders, in addition to the different geometries evaluated and the variables to which these designs were subjected to temperature and force.

In the tensile gauge of 5 meanders with square edges it has a value of $6.0444 \times 10^{17}$ unlike the gauge of 3 meanders that is of a tension value of $7.90812 \times 10^{10}$, this maximum tension decreases exponentially implying that the greater number of meanders, the strain gauge is more rigid. In the same way, it can be seen that the greater the force to which the strain gauge is subjected, there is a greater tension, and from another point of view, it is evident that at a lower number of meanders there is a decrease in the maximum tension.

It was found to vary in different ways the affection generated and this depending on the type of geometry and materials used in the design, with the geometry of 3 meanders with square edges being the one that suffered the least damage as the temperature increased.

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