PRECISE FORCE MEA-SUREMENT WITH STRAIN GAUGES

Application and use of strain gauges

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1 Summary

The application of strain gauges is of crucial importance for the production of force sensors, as this technology enables precise and reliable measurements of mechanical loads. Strain gauges are extremely sensitive instruments that react to changes in the geometry of the material to which they are attached. When a force is applied to an object, it causes a deformation that can be quantified as either elongation or compression. The strain gauges convert these mechanical deformations into electrical resistance changes, which in turn are converted into proportional electrical signals.

The primary advantages of strain gauges are their high accuracy and sensitivity. They enable the detection of even the slightest strains, which is crucial for ensuring accurate and repeatable measurements. This accuracy is crucial for applications for which precise force measurement is required.

Other key factors include the ruggedness and durability of strain gauges. They are able to function reliably even under extreme conditions, such as high temperatures or corrosive environments. This makes them ideal for use in challenging environments and ensures that the force sensors provide precise and consistent measurements over long periods of time.

However, the exceptional characteristics of force measurement using strain gauge sensors necessitate a high-quality bond between the strain gauge sensor and the surface of the base body. The sensor must be directly on the metal. Foreign particles, oxides or unsuitable surface structures directly change the measurements.

RAFI has decades of experience in the application of strain gauge sensors from its manufacture of precise trackless joysticks. Drawing on this expertise, automated processes for the high-volume production of strain gauge sensors were developed.

2 Strain gauges at RAFI

RAFI applications

As a major manufacturer of human-machine interfaces, RAFI's portfolio includes joysticks as well as switches, keyboards, and touch controls. In addition to travel-based joysticks, there are also force-based joysticks. Strain gauges are applied to the joystick shafts, and the force is measured. Depending on the application, either the torsion of the joystick axis or a directed force is measured. In addition to the applications in the area of joysticks, RAFI has also implemented force measurements for electric drives in high volumes. As electrification advances, the prevalence of this type of application will rise, given that force frequently serves as a crucial control variable.

Figure 1: Example of armrest with complex RAFI joystick that measures a force when the joystick axis is rotated

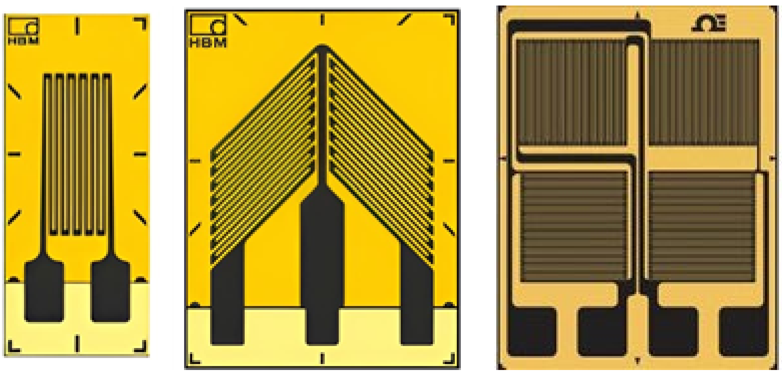
Challenges

The quality of the measurement data from a strain gauge sensor depends heavily on the factors of the mechanical system, electronic processing of the signals, and the manufacturing process. The challenge here was to automate the application of the strain gauge sensors. The boundary conditions for the quality of strain gauge sensor signals (strain gauges) are crucial for precise measurements and reliable data. Key factors include temperature stability, as temperature fluctuations can affect signal accuracy and mechanical strain, which requires correct assembly and calibration. The signals from the strain gauge sensors are in the single-digit mV range and must be amplified. It is therefore important to prevent noise and signal distortion. The quality of the signal processing electronics plays a role, as it directly affects the accuracy and resolution of the sensor signals.

All of these boundary conditions must be carefully monitored to ensure the best possible quality of the measurement data.

Types of strain gauges

There are different types and shapes of strain gauges. Strain gauges can be ordered from the manufacturer as individual components (quarter bridge, half bridge, and full bridge). There are also differences in the structures for the measurement direction. Figure 2 provides an overview of common strain gauges. The respective manufacturers of strain gauges provide a significantly broader selection of strain gauges.
For example, there are strain gauges for linear measurement (see Figure 2a), which are used for measuring bending strain. There are also structures in which two measuring grids are offset by 45° to the measuring axis in order to measure torsional or shear strain (see Figure 2b).



a b c

Figure 2: Different strain gauges

(a) Meander component for measuring bending stress
(b) Measurement of torsional and shear stress
(c) Full bridge with four meander components

3 Application of strain gauges

The application of strain gauges is similar in most cases, but individual steps may differ. This is due to the way in which the strain gauges are attached. Figure 3 shows a standard industry procedure for gluing strain gauges.

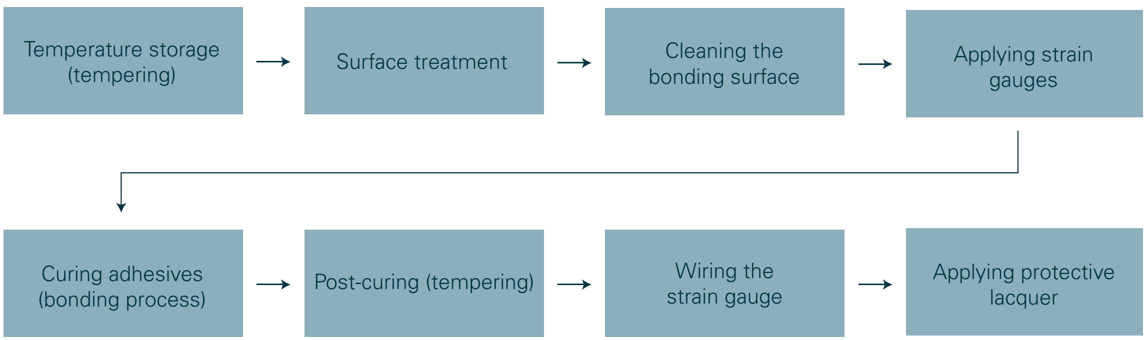


Figure 3: Process workflow

Temperature storage

In the first step, temperature storage is performed. Experience has shown that temperature storage at 180 °C for approx. 2 h produces good results with aluminum. However, the correct temperature must be determined, depending on the material. The aim is to relieve residual stress in the material, which may have formed during production of the test object. This process is intended to relieve residual stresses in the material that may have developed during manufacture of the test object, for example.

Surface treatment

With an epoxy resin adhesive, the surface must have a certain surface roughness. There are different specifications about this in the literature. Reinhard Kaufmann describes a surface roughness depth of “0.4 µm to 1.6 µm” for this adhesive (Kaufmann, 2024), while Stefan Keil recommends an average roughness depth of “2 µm to 4 µm” (Keil, 2017). This surface structure can be brought about by sandblasting, grinding, or the use of a laser.

Manual process

The simplest process to achieve the desired roughness is to use sandpaper of a certain grain size. When working with sandpaper, care must be taken to avoid introducing a directional grain into the material.

Automation

Sandblasting and lasering are among the more complex options. Suitable equipment must be available for each process, and empirical data must be collected for the respective materials. To avoid this step, the required surface roughness can already be ensured during mechanical production of the base body.

In addition, the oxide layer must be removed from the test object after the desired roughness has been achieved. The sandpaper can be used again for this. However, care must be taken to ensure that there is no directional grain in the material. An alternative to sandpaper is laser cleaning of the surface. As with the roughness depth, the corresponding parameters must be determined. Laser cleaning is much more suitable for a series process, as the result is always identical and cannot vary from employee to employee, as is the case with sandpaper. The oxide layer is just a few nm thick. As the oxide layer has very hard properties that can have a negative effect on the transmission of mechanical strain to the strain gauge, it must be removed completely. Removing the oxide layer can rule out the introduction of a damping property (Kaufmann, 2024) (Keil, 2017).

Cleaning the surface

Immediately after the surface treatment, the bonding surface must be cleaned with an appropriate agent. Isopropyl alcohol is well-suited for this purpose, as it removes impurities and oils from the bonding surface.

Manual process

The appropriate instructions must be followed when using these cleaning agents. Cotton swabs are particularly suitable for cleaning the surface. These swabs are soaked once in the cleaning agent so that the particles adhering to the swab do not contaminate the cleaning agent after the cleaning process. After the surface has been cleaned with the swab, you must dispose of it. This process step is repeated until no more residue can be found on the cotton swab. The cleaning step is then carried out one last time to ensure that there are no more residues on the bonding surface (Kaufmann, 2024) (Keil, 2017).

Automation

The number of cleaning steps can be minimized using laser cleaning. The base material is not removed, and the oxide layer is vaporized by the laser. Alternatively, an ultrasonic bath can be used to clean the bonding surface. This makes it possible to automate the process in order to always achieve a constant cleaning quality. However, the cost-effectiveness must be evaluated to determine at what production volume automated cleaning becomes more economical than manual cleaning.

Application of strain gauges

The strain gauge must be free of residues on its adhesive side, and the same applies to the bonding surface on the test object. It is therefore advisable not to touch it with your fingers but to use a tool such as tweezers. The manufacturer's application instructions for the respective adhesive must be observed. For example, when using M-Bond 610, the adhesive is applied evenly to the back of the strain gauge and to the test object. Both are then left in the air for a few minutes so that the solvents in the adhesive dissolve and evaporate in the air.

Figure 4: Automated application with vacuum pipette

They must be fully evaporated to prevent gas bubbles from forming in the oven during the bonding process. This would have a negative influence on the measurement result. After that, the strain gauge is placed in the correct position on the test object and pressed onto the bonding surface using a fixture. A contact pressure of 3 to 4 bar is recommended here (Kaufmann, 2024). Strain gauge manufacturers recommend a contact pressure of 5 bar for the adhesive to ensure better adaptation of the strain gauge to the surface of the test object. However, this recommendation is solely based on experience and is therefore not authoritative.

Curing of the adhesive – the bonding process

During curing of the adhesive, a constant contact pressure (3 to 5 bar) is required to produce a uniform bond. This requires a suitable fixture to hold and press the strain gauge in place in the oven. To maintain consistent pressure, a design that includes a spring component is preferred. There should be a thin Teflon film and a silicone pad between the metal plates and the spring. This ensures that the strain gauge is optimally pressed and conforms to the surface. Thanks to Teflon's non-stick properties, the gauge does not adhere to the silicone pad after curing, allowing the pressing fixture to be easily removed.

Due to the sliding properties of Teflon, no lateral forces act on the strain gauge, which has a positive effect on the measurement result. The silicone pad provides protection from the metal plates so that they do not act directly on the strain gauge (Kaufmann, 2024). The spring keeps the contact pressure at a constant level over temperature and time. As the material properties of the spring and the silicone change at a higher temperature, the contact pressure will deviate over time and no longer correspond to the set pressure at room temperature (Kaufmann, 2024). The dwell time and temperature in the oven are important. Depending on the adhesive, the time can be shortened by increasing the temperature. For epoxy resin adhesives, the temperature should be at least 30 K above the maximum application temperature (Keil, 2017). However, the manufacturer's instructions must be followed. The test object must have cooled down to at least 50 °C in the oven before the pressing device can be removed.

Post-curing – tempering

As in the previous step, tempering is also carried out at a temperature that is at least 30 K above the curing temperature and takes around two hours (Keil, 2017). It is recommended to use a temperature of approx. 180 °C for aluminum. It is important in this step that the temperature storage takes place without contact pressure. This eliminates or greatly reduces mechanical "residual strain" (Kaufmann, 2024) that have arisen in the strain gauge. The strain is caused by pressing on the strain gauge and during the polymerization of the adhesive (Kaufmann, 2024). As this residual tension cannot be prevented, this step must always be carried out after the bonding process. The advantage here is that the test object can be placed directly in an oven that has already been heated up, which means that the temperature does not need to be gradually increased (Kaufmann, 2024). In addition, post-curing improves the durability of the bonded surface (Keil, 2017).

Wiring the strain gauge

In most applications, soldering is used. Wire bonding can represent significant added value in terms of process reliability and processing time. It has the advantage that no solder paste, flux, or the like, is required. Residue from solder paste or flux make it necessary to clean the PCB and the strain gauge. These residues can have a negative effect on the leakage current or the insulation resistance. The insulation resistance can have a negative influence on the measurement result. These impacts can become apparent only later in the product. Depending on production volume, fully automated systems can also be used, improving economic efficiency in series production.

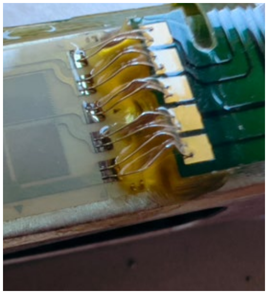


Figure 5: Wire bonding as a joining technique for series production

Protection against moisture

In the final step, a protective coating is applied to the measuring point of the test object to protect the strain gauge from environmental influences. This point must be taken very seriously. Humidity can have a very negative effect on the "long-term zero stability" (Kaufmann, 2024). In most cases, it is a foil-type strain gauge, and the foil is made of polyimide in many strain gauges. This base material can absorb moisture, causing it to expand. That expansion transfers to the strain gauge structures and results in a false strain reading. The protective coating must be selected based on the requirements. Alternatively, complete areas are also encapsulated in series production to protect them from environmental influences.

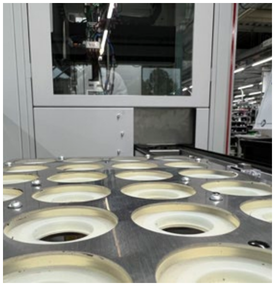


Figure 6: Automated encapsulation as an alternative to coating with lacquer

Testing and calibration

As a result of the mechanical influences on the strain gauges, a small offset manifests itself, which can be minimized by the preceding temperature storage, but complete elimination is not possible. The offset of the bridge circuit must be determined by a corresponding measurement in order to be able to calibrate the zero position of the joystick afterwards.

The same applies to the temperature dependence of the measurement. There are two strategies here:

- Reduce the temperature dependency of the system by taking suitable measures, such as using a full-bridge strain gauge sensor
- Use an additional temperature sensor and perform temperature-based calibration to compensate for tolerances

4 Conclusion

There are several crucial factors for ensuring high accuracy with strain gauge sensors over a long service life. Key factors include temperature stability, as temperature fluctuations can affect signal accuracy and mechanical strain, which requires correct assembly and calibration.
First, choosing the right sensor and calibrating it carefully is essential to enabling precise measurements. Correct mounting on the surface of the test object is also of great importance, with it being necessary to ensure an even distribution of the adhesive and to avoid air bubbles.

Temperature stability plays a key role, as temperature fluctuations can falsify the measurement results. The use of high-quality adhesives and protective coatings is necessary to ensure long-term stability and minimize environmental influences from moisture and chemical substances.

In addition, electromagnetic interference (EMI) must be minimized in order to reduce signal noise. High-quality signal processing electronics and suitable filters also help to improve measurement accuracy. Regular maintenance and calibration of the system are required to ensure long-term accuracy. Together, these measures ensure high precision and a long service life for the strain gauge sensor signals.

5 Literature

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