Temperature-compensating strain gages - a practical experiment for student training

by Martin Stockmann

Strain-gage output signals which are solely produced by thermal effects are examined in a students' practical session. Strain gages with temperature responses matched to steel, aluminum and epoxy resin are bonded to these three materials and the output signals measured for correct and incorrect matching. The high quality of the temperature compensation obtained by correct matching is impressively demonstrated. The article describes the measurement system formed by a UGR 60 Multipoint Measuring Unit linked to a PC and explains the theoretical principles of the resistance changes in the strain gage.

Introduction

Strain-gage measuring points are subject to a large number of interference effects, including temperature which plays a significant role. However, the use of "temperature compensating" strain gages has now become widely established for compensating the temperature dependence of the zero point. When mounted, these gages compensate for the thermal extension of the component by the temperature response of their resistance.

The objective of the test is to give the students a theoretical and practical impression of the principles of modern temperature compensating strain gages. Particular attention is drawn to the effects of using strain gages that are incorrectly matched to the material to which they are bonded.

Principles

The term temperature dependence of the zero point means the variation due to temperature changes of the output voltage of a Wheatstone bridge circuit which has been balanced to zero. The bridge circuit has a temperature response which is caused by unsymmetrical proportions of temperature dependent resistances within the bridge. If, as is usual in stress analysis, the quarter bridge circuit is employed with compensation for the effects of resistance in the connection leads using the three or four-wire technique, then the temperature response of the bridge circuit mainly results from response of the strain gage itself.

When correcting for this error, is should be noted that the measurement task is to only find those proportions of elastic strain ε_{tot} on the component that are associated with mechanical stresses. This means that from the total strain ε_{tot}, formed according to Equation (1) from an elastic and a thermal part ε_{th}, only the elastic part should be displayed.

$$\varepsilon_{tot} = \varepsilon_{el} + \varepsilon_{th} \tag{1}$$

In electrical leads, temperature variations always cause a change in the electrical resistance. The cause for this lies in the volume expansion described by the thermal expansion coefficient α and in the temperature dependence of the specific resistance which is decoupled from it. In electrical engineering usually both causes are combined so that for a free conductor the variation in the electrical resistance can be represented by only one temperature coefficient α_R as represented by Equation (2):

$$\left(\frac{\Delta R}{R_0}\right)_{free} = \alpha_R \cdot \Delta T \tag{2}$$

If the electrical conductor is connected to a component for which the thermal expansion coefficient does not match that of the conductor, then longitudinal strain on the conductor is forced by the substrate.

The proportion of additional strain ε_{forced} that occurs can be calculated as shown in Equation (3) from the change in temperature ΔT and the difference between the expansion coefficient of the component material α_C and that of the conductor in the strain gage α_{gage}.

$$\varepsilon_{forced} = (\alpha_C - \alpha_{gage})\Delta T \tag{3}$$

Assuming that the conductor in the strain gage is only affected by the thermal strain forced by the component in the longitudinal direction, the following total resistance change is produced:

$$\frac{\Delta R}{R_0} = k \cdot \varepsilon_{forced} + \left(\frac{\Delta R}{R_0}\right)_{free} \tag{4}$$

$$\frac{\Delta R}{R_0} = [(\alpha_c - \alpha_{gage})\, k + \alpha_R]\Delta T \tag{5}$$

$$\alpha_R = (\alpha_{gage} - \alpha_c)k \tag{6}$$

The main consideration in the design of temperature compensating strain gages consists of offsetting the unavoidable variation in resistance for different expansion coefficients of the conductor and the substrate by altering the temperature coefficient of resistance α_R according to Equation (6).

This compensation is made possible because α_R can be adjusted to certain values in production by applying suitable measures such as heat treatment and rolling techniques. It can be said that the exact matching of different types of strain gages to a wide range of base materials requires a great deal of experience in the technical field on the part of the manufacturer in order to be able to maintain the specified parameters in series production. Having said this, with temperature compensating strain gages there is always, due to technical reasons, a residual error which is small within a specified temperature range, but which cannot be neglected outside of this range. This is because the coefficients α_C, α_{gage} and α_R are themselves functions of temperature which cannot be compensated over a wider temperature range.

The use of strain gages with temperature compensation is therefore associated with a certain base material as well as a specified temperature range.

Experimental set-up

In the experiment three strain gages were bonded to each of the base materials steel (St 38), aluminum (AlMg1Si1F28) and epoxy resin (Epilox EG1, similar to Araldite B). In each case only one of the three strain gages had the correct temperature response to suit the base material.

The three base objects are joined stress-free at the side with a thick seam of SG 25 Silicone Rubber and are located on a hot plate with temperature control. During the measurement the base objects are thermally insulated in the upwards direction by a cover.

Standard strain gages from HBM's Y Series were selected with a measuring length of 6 mm (0.24 in). These were

LY61 6/120 matched to steel with $\alpha_C = 10.8 \cdot 10^{-6}$/K

LY13 6/120 matched to aluminum with $\alpha_C = 23 \cdot 10^{-6}$/K

LY58 6/120 matched to plastic with $\alpha_C = 65 \cdot 10^{-6}$/K

The strain gages are connected via a VT 10A Distribution Board to the UGR 60 Measuring Amplifier (UMH 3209 Selector Module). The leads were connected right up to the strain gages using the four-wire technique.

The block diagram of the experimental set-up showing the individual components is illustrated in **Fig. 1**. The positions of the separate strain gages on each of the individual base objects are identical. The correctly matched strain gages are shown marked with a dark border.

In addition to the recording of the temperature output signals from the strain gages, the temperature is measured by a Pt100 temperature sensor connected to the UGR 60 Measuring Unit via the UMH 3204A Selector Module.

The complete acquisition using only one instrument substantially simplifies the evaluation. Both the instrument control and the measurement acquisition and storage takes using a personal computer linked by a standard-fitted serial interface (RS232) to the UGR 60 Measuring Amplifier. The measurements are output on the monitor during the experiment in a specially created display depicting the measurement arrangement. The students can then directly observe the effect of temperature variations on the thermal output signal with clear, unambiguous assignment of the measurements to the strain gage and the base material. During the measurement the diagonal of correctly matched strain gages stands out amongst the absolute thermal output signals.

Figure 2 illustrates the set-up for the practical experiment. The arrangement of the base objects with the strain gage measuring points can be seen diagram-

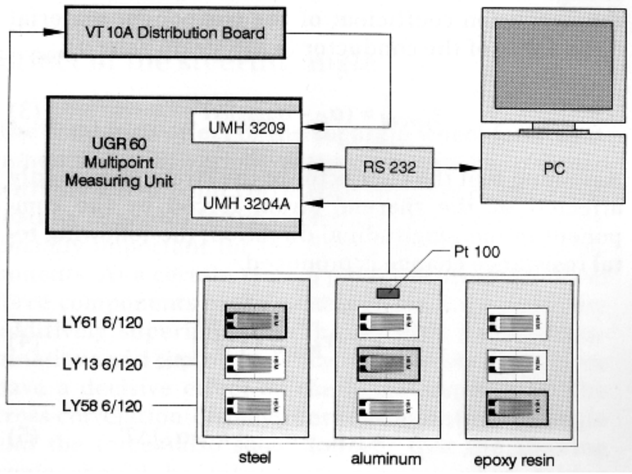

Fig. 1: Diagram showing the set-up for the practical experiment.

Fig. 2: Overall view of the experimental equipment with the thermal insulating cover removed.

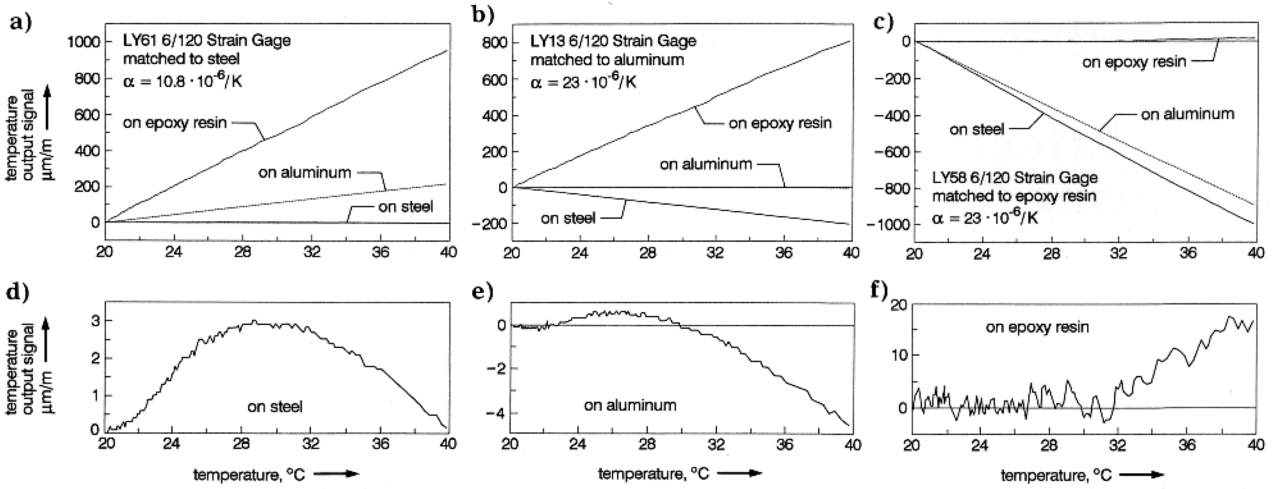

Fig. 3: Display of the results from a typical test:
a) to c) Signals from the three different strain gages installed on each of the component materials.
d) to f) Showing the signals in high resolution from strain gages correctly matched to the component materials.

matically displayed on the screen. The measurement appears at the strain gage position shown on the screen during the measurement process.

During the test the temperature of the base objects is slowly increased manually from 20°C to 40°C (68°F - 104°F) using the hot-plate and a set of measurements consisting of the temperature and the thermal output signals from the nine strain gages is stored automatically at specified time intervals of say 10 s. The time/temperature curve is not important, because the change in temperature takes place so slowly that an almost constant temperature field exists locally under the thermally insulating cover at the time of measurement. The results shown below were recorded with a temperature gradient of about 0.7K/min. The test took about 30 min.

Results

In the experiment the thermal output signals from the strain gages are recorded at discrete temperatures by the students and then displayed graphically for each type of strain gage and for the different base materials. This form of display shows the quality of the strain gage's temperature compensation for the correctly matched strain gages and the very noticeable temperature response for incorrect matching. The results of a representative practical experiment are shown combined in **Fig. 3**. In a) to c) of this figure the signals from all strain gages are shown for each component material. The excellent temperature compensation of the strain gages matched to the component material can be seen. In **Figs. 3d to 3f** the signals from the matched strain gages are shown in high resolution in order to be able to assess the tolerance of the gage compensation.

Strain gage	Base material	Zero-point deviation	Temperature range
		in µm/m	in °C
LY61 6/120	St 38	0 to 3	20 to 40
LY13 6/120	AlMg1SiF28	-4.5 to 0.5	20 to 40
LY58 6/120	Epilox EG1	-5 to 20	20 to 40

Table 1: Table showing the measured zero-point deviations.

It can be concluded that with the correct use of high quality temperature compensating strain gages the temperature response of the zero point in the important, commonly used temperature range between 20°C and 40°C is very low. The measured zero-point deviations are shown in **Table 1** for the separate types of strain gage and base material. They all lie below the manufacturer's specifications. These results are reproducible and the deviations are reduced still further if the temperature range is restricted to between 25°C and 35°C (77°F to 95°F).

A second important result is the enormous temperature response of the zero point where matching is incorrect. The use of the strain gage matched for steel, but mounted on aluminum, in the specified temperature range results in a zero-point drift of approximately 220 µm/m. Even more extreme values are obtained when this strain gage is mounted on epoxy resin. Here, a temperature variation of 20 K produces a zero-point drift of 1,000 µm/m.

By obtaining their own practical experience, it is clear to the students that the correct choice of strain gage, also taking into account the component material, is very important when working with electrical strain gages in the field of stress analysis. The quality of the temperature compensation provided by high performance strain gages that are correctly mounted often astonishes those participating in the experiment. It makes a more lasting impression than can be achieved by theoretical explanations alone.

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