Strain Gages and Instruments | Tech Note TN-504-1

Strain Gage Thermal Output and Gage Factor Variation with Temperature

1.0 Introduction

Ideally, a strain gage bonded to a test part would respond only to the applied strain in the part, and be unaffected by other variables in the environment. Unfortunately, the resistance strain gage, in common with all other sensors, is somewhat less than perfect. The electrical resistance of the strain gage varies not only with strain, but with temperature as well. In addition, the relationship between strain and resistance change, the *gage factor*, itself varies with temperature. These deviations from ideal behavior can be important under certain circumstances, and can cause significant errors if not properly accounted for. When the underlying phenomena are thoroughly understood, however, the errors can be controlled or virtually eliminated by compensation or correction.

In Section 2.0 of this Tech Note, thermal output (sometimes referred to as "temperature-induced apparent strain") is defined, and the causes of this effect are described. Typical magnitudes of the thermal output are then given, followed by the commonly used methods for compensation and correction. Section 3.0 treats gage factor variation with temperature in a similar but briefer manner since this error source is generally much less significant. Methods for the simultaneous correction of both thermal output and gage factor errors are given in Section 4.0, accompanied by numerical examples.

2.0 Thermal Output

Once an installed strain gage is connected to a strain indicator and the instrument balanced, a subsequent change in the temperature of the gage installation will normally produce a resistance change in the gage. This temperature-induced resistance change is independent of, and unrelated to, the mechanical (stress-induced) strain in the test object to which the strain gage is bonded. It is purely due to temperature change, and is thus called the *thermal output* of the gage.

Thermal output is potentially the most serious error source in the practice of static strain measurement with strain gages. In fact, when measuring strains at temperatures remote from room temperature (or from the initial balance temperature of the gage circuit), the error due to thermal output, if not controlled, can be much greater than the magnitude of the strain to be measured. At any temperature, or in any temperature range, this error source requires careful consideration; and it is usually necessary to either provide compensation for thermal output or correct the strain measurements for its presence.

Thermal output is caused by two concurrent and algebraically additive effects in the strain gage installation. First, the electrical resistivity of the grid conductor is somewhat temperature dependent; and, as a result, the gage resistance varies with temperature. The second contribution to thermal output is due to the differential thermal expansion between the grid conductor and the test part or substrate material to which the gage is bonded. With temperature change, the substrate expands or contracts; and, since the strain gage is firmly bonded to the substrate, the gage grid is forced to undergo the same expansion or contraction. To the extent that the thermal expansion coefficient of the grid differs from that of the substrate, the grid is mechanically strained in conforming to the free expansion or contraction of the substrate. Because the grid is, by design, strain sensitive, the gage exhibits a resistance change proportional to the differential expansion.

Each of the two thermally induced resistance changes may be either positive or negative in sign with respect to that of the temperature change, and the net thermal output of the strain gage is the algebraic sum of these. Thus, expressed in terms of unit resistance change, the thermal output becomes:

$$\left(\frac{\Delta R}{R_0}\right)_{T/O} = \left[\beta_G + F_G\left(\frac{1+K_t}{1-\nu_0 K_t}\right)(\alpha_S - \alpha_G)\right]\Delta T \qquad (1)$$

where, in consistent units:

$\left(\frac{\Delta R}{R_0}\right)_{T/O}$ = unit change in resistance from the initial reference resistance, R_0, caused by change in temperature resulting in thermal output.

β_G = temperature coefficient of resistance of the grid conductor.

F_G = gage factor of the strain gage.†

K_t = transverse sensitivity of the strain gage.

ν_0 = Poisson's ratio (0.285) of the standard test material used in calibrating the gage for its gage factor.

† In this Tech Note, the gage factor of the strain gage is identified as F_G, to distinguish it from the gage factor setting of the measuring instrument, denoted here by F_I. This distinction is important, since the gage factor setting of the instrument may sometimes, as a matter of convenience or utility, be different from that of the gage.

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$(\alpha_S - \alpha_G)$ = difference in thermal expansion coefficients of substrate and grid, respectively.

ΔT = temperature change from an arbitrary initial reference temperature.

The correction factor for transverse sensitivity $[(1 + K_t)/(1 - \nu_0 K_t)]$ is included in Equation (1) to account for the fact that the strain in the gage grid due to differential thermal expansion is equal-biaxial, while the gage factor, F_G, refers to the strain sensitivity as calibrated in a uniaxial stress state, with a principal strain ratio of 1/(–0.285).

It should not be assumed from the form of Equation (1) that the thermal output is linear with temperature change, because all of the coefficients within the brackets are themselves functions of temperature. The equation clearly demonstrates, however, that thermal output depends not only on the nature of the strain gage, but also on the material to which the gage is bonded. Because of this, thermal output data are meaningful only when referred to a particular type of strain gage, bonded to a specified substrate material.

For convenience in correcting measured strain data for thermally induced resistance changes, the thermal output of the gage is usually expressed in strain units. Thus, dividing Equation (1) by the gage factor setting of the instrument,

$$\varepsilon_{T/O} = \frac{\left(\frac{\Delta R}{R_0}\right)_{T/O}}{F_I} = \frac{\left[\beta_G + F_G\left(\frac{1+K_t}{1-\nu_0 K_t}\right)(\alpha_S - \alpha_G)\right]\Delta T}{F_I} \qquad (2)$$

where: $\varepsilon_{T/O}$ = thermal output in strain units; that is, the strain magnitude registered by a strain indicator (with a gage factor setting of F_I), when the gage installation is subjected to a temperature change, ΔT, under conditions of free thermal expansion for the substrate.

When measuring stress-induced strains at a temperature different from the initial balance temperature, the thermal output from Equation (2) is superimposed on the gage output due to mechanical strain, causing the measurement to be in error by that amount. Many factors affect the thermal output of strain gages. Some of the more important are: test specimen material and shape, grid alloy and lot, gage series and pattern, transverse sensitivity of the gage, bonding and encapsulating materials, and installation procedures. It is never possible for Micro-Measurements to predict exactly what the thermal output of any gage will be when the user has bonded it to a test structure. Even in cases where applications involve the same material as that used by Micro-Measurements in its tests, differences can be expected since structural materials vary in thermal expansion characteristics from lot to lot. The best practice is always to evaluate one or more gages under thermal conditions as nearly like those to be encountered in the testing program as possible.

Figure 1 shows the variation of thermal output with temperature for a variety of strain gage alloys bonded to steel. These data are illustrative only, and not for use in making corrections. It should be noted, in fact, that the curves for constantan and Karma are for non-self-temperature-compensated alloys. With self-temperature compensation (Section 2.1.2), as employed in Micro-Measurements strain gages, the thermal output characteristics of these alloys are adjusted to minimize the error over the normal range of working temperatures.

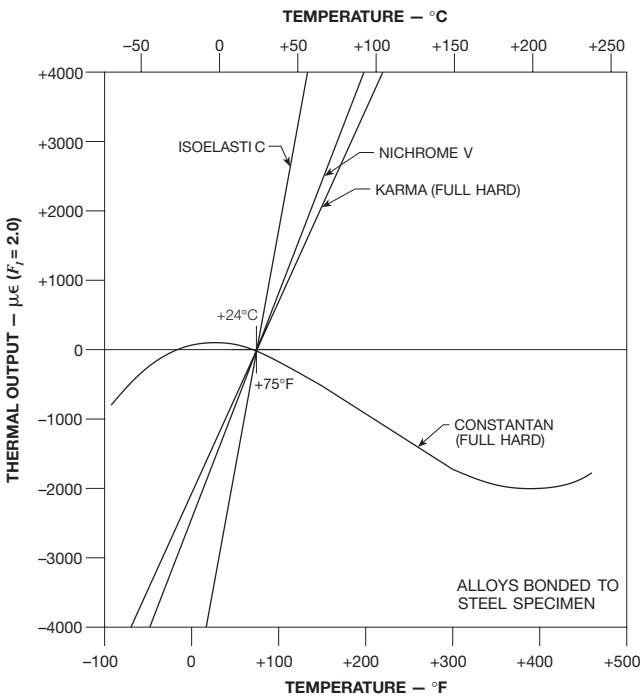

Figure 1. Thermal output variation with temperature for several strain gage alloys (in the as-rolled metallurgical condition) bonded to steel.

As indicated by Figure 1, the errors due to thermal output can become extremely large as temperatures deviate from the arbitrary reference temperature (ordinarily, room temperature) with respect to which the thermal output is measured. The illustration shows distinctly the necessity for compensation or correction if accurate static strain measurements are to be made in an environment involving temperature changes.

With respect to the latter statement, it should be remarked that if it is feasible to bring the gaged test part to the test temperature *in the test environment*, maintaining the test part completely free of mechanically or thermally induced stresses,

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and balance the strain indicator for zero strain under these conditions, no thermal output error exists when subsequent strain measurements are made *at this temperature*. In other words, when no temperature change occurs between the stress-free and stressed conditions, strain measurements can be made without compensating or correcting for thermal output. In practice, however, it is rare that the foregoing requirements can be satisfied, and the stress analyst ordinarily finds it necessary to take full account of thermal output effects.

Also, in the case of purely dynamic strain measurements, where there is no need to maintain a stable zero-strain reference, thermal output may be of no consequence. This is because the frequency of the dynamic strain signal is usually very high with respect to the frequency of temperature change, and the two signals are readily separable. If, however, there is combined static/dynamic strain, and the static component must also be measured, or if the frequency of temperature change is of the same order as the strain frequency, thermal output effects must again be considered.

2.1 Compensation for Thermal Output

2.1.1 Compensating (Dummy) Gage

In theory, at least, the error due to thermal output can be completely eliminated by employing, in conjunction with the "active" strain gage, but connected in an adjacent arm of the Wheatstone bridge circuit, an identical compensating or "dummy" gage — mounted on an unstrained specimen made from the identical material as the test part, and subjected always to the same temperature as the active gage. Under these hypothetical conditions, the thermal outputs of the two gages should be identical. And, since identical resistance changes in adjacent arms of the Wheatstone bridge do not unbalance the circuit, the thermal outputs of the active and dummy strain gages should cancel exactly — leaving only the stress-induced strain in the active strain gage to be registered by the strain indicator. For this to be precisely true requires additionally that the leadwires to the active and dummy gages be of the same length and be routed together so that their temperature-induced resistance changes also match identically.

The principal problems encountered in this method of temperature compensation are those of establishing and maintaining the three sets of identical conditions postulated above. To begin with, it is sometimes very difficult to arrange for the placement of an unstrained specimen of the test material in the test environment; and even more difficult to make certain that the specimen remains unstrained under all test conditions. There is a further difficulty in ensuring that the temperature of the compensating gage on the unstrained specimen is always identical to the temperature of the active gage. This problem becomes particularly severe whenever there are temperature gradients or transients in the test environment. And, as indicated in the preceding paragraph, the same considerations apply to the leadwires. Finally, it must be recognized that no two strain gages — even from the same lot or package — are precisely identical. For most static strain measurement tasks in the general neighborhood of room temperature, the difference in thermal output between two gages of the same type from the same lot is negligible; but the difference may become evident (and significant) when measuring strains at temperature extremes such as those involved in high-temperature or cryogenic work. In these instances, point-by-point correction for thermal output will usually be necessary. With non-self-temperature-compensated gages, the gage-to-gage differences in thermal output may be so great as to preclude dummy compensation for temperatures which are remote from room temperature.

In general, when the three identity criteria already mentioned can be well satisfied, the method of compensating with a dummy gage is a very effective technique for controlling the thermal output error. There is, moreover, a special class of strain measurement applications which is particularly adaptable to compensation of thermal output with a second gage. This class consists of those applications in which the ratio of the strains at two different but closely adjacent (or at least thermally adjacent) points on the test object are known a priori. Included in this class are bars in pure torsion, beams in bending, columns, diaphragms, etc., all stressed within their respective proportional limits. In these applications, the compensating gage can often be located strategically on the test member itself so as to provide two active gages which undergo the same temperature variations while sensing strains that are preferably opposite in sign and of known ratio. The two gages in adjacent arms of the Wheatstone bridge circuit then function as an active half bridge.

For example, when strain measurements are to be made on a beam which is thin enough so that under test conditions the temperatures on the two opposite surfaces normal to the plane of bending are the same, the two strain gages can be installed directly opposite each other on these surfaces (Figure 2a). The active half bridge thus formed will give effective temperature compensation over a reasonable range of temperatures and, since the strains sensed by the gages are equal in magnitude and opposite in sign, will double the output signal from the Wheatstone bridge. Similarly, for a bar in pure torsion (Figure 2b), the two gages can be installed adjacent to each other and aligned along the principal axes of the bar (at 45° to the longitudinal axis). As in the case of the beam, excellent temperature compensation can be achieved, along with a doubled output signal.

When making strain measurements along the axis of a column or tension link, the compensating gage can be mounted on the test member adjacent to the axial gage and aligned transversely to the longitudinal axis to sense the

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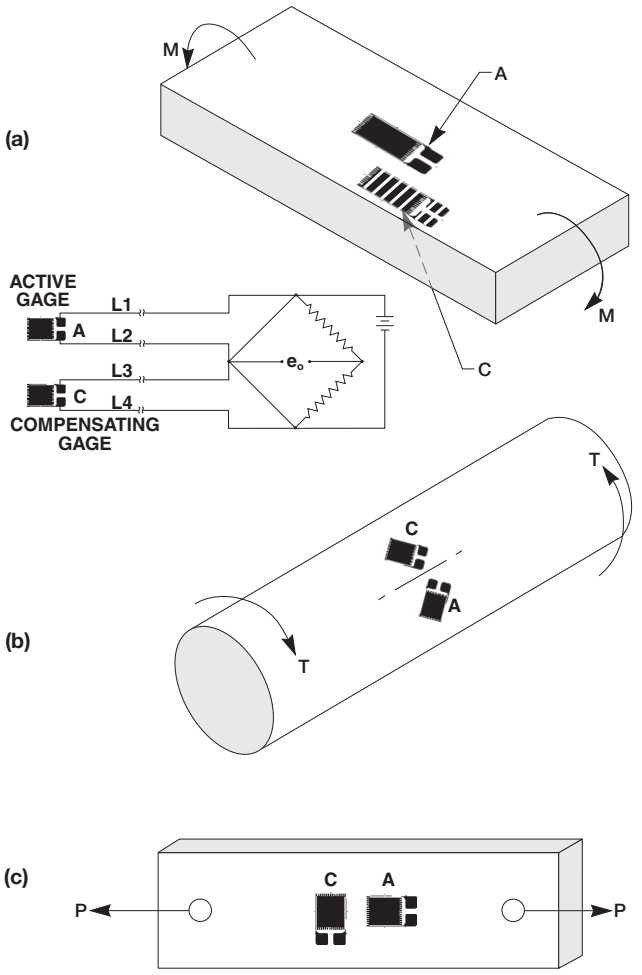

Figure 2. Examples illustrating the use of a second (compensating) strain gage in an adjacent Wheatstone bridge arm to cancel the effect of thermal output.

Poisson strain (Figure 2c). The result, again, is compensation of the thermal output, accompanied by an augmented output signal [by the factor $(1 + \nu)$ in this case]. It should be borne in mind in this application, however, that the accuracy of the strain measurement is somewhat dependent upon the accuracy with which the Poisson's ratio of the test material is known. The percent error in strain measurement is approximately equal to $\nu/(1 + \nu)$ times the percent error in Poisson's ratio. A further caution is necessary when strain gages are mounted transversely on small-diameter rods (or, for that matter, in small-radius fillets or holes). Hines has shown (see Appendix) that under these conditions the thermal output characteristics of a strain gage are different than when the gage is mounted on a flat surface of the same material.

In all strain-measurement applications which involve mounting the compensating gage on the test object itself, *the relationship between the strains at the two locations must be known with certainty.* In a beam, for example, there must be no indeterminate axial or torsional loading; and the bar in torsion must not be subject to indeterminate axial or bending loads. This requirement for a priori knowledge of the strain distribution actually places these and most similar applications in the class of transducers. The same method of compensation is universally employed in commercial strain gage transducers; such transducers, however, ordinarily employ full-bridge circuits and special arrangements of the strain gages to eliminate the effects of extraneous forces or moments.

2.1.2 Self-Temperature-Compensated Strain Gages

The metallurgical properties of certain strain gage alloys — in particular, constantan and modified Karma (Micro-Measurements A and K alloys, respectively) — are such that these alloys can be processed to minimize the thermal output over a wide temperature range when bonded to test materials with thermal expansion coefficients for which they are intended. Strain gages employing these specially processed alloys are referred to as *self-temperature-compensated.*

Since the advent of the self-temperature-compensated strain gage, the requirement for a matching unstrained dummy gage in the adjacent arm of the Wheatstone bridge has been relaxed considerably. It is now normal practice when making strain measurements at or near room temperature to use a single self-temperature-compensated gage in a quarter-bridge arrangement (with a three-wire hookup), completing the bridge circuit with a stable fixed resistor in the adjacent arm (Figure 3). Such "bridge-completion" resistors, with very low temperature coefficients of resistance, are supplied by Micro-Measurements and are incorporated in most modern strain indicators.

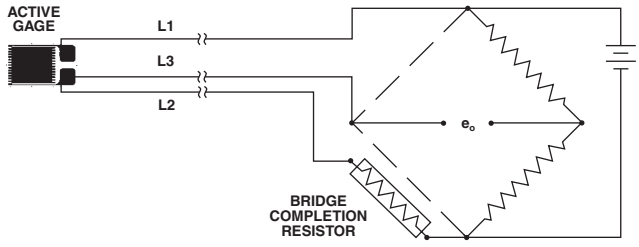

Figure 3. A single self-temperature-compensated strain gage in a three-wire quarter-bridge circuit exemplifies modern strain gage practice for stress analysis measurements.

Figure 4 illustrates the thermal output characteristics of typical A- and K-alloy self-temperature-compensated strain gages. As demonstrated by the figure, the gages are designed to minimize the thermal output over the temperature range from about 0° to +400°F [–20° to +205°C]. When the self-temperature-compensated strain gage is bonded to material

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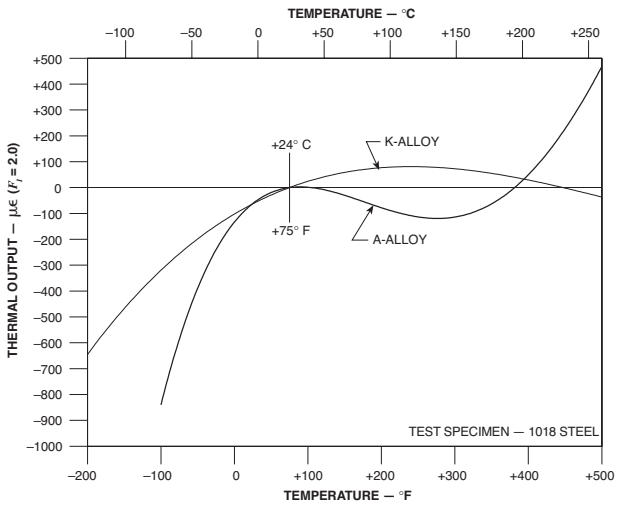

Figure 4. Typical thermal output variation with temperature for self-temperature-compensated constantan (A-alloy) and modified Karma (K-alloy) strain gages.

having the thermal expansion coefficient for which the gage is intended, and when operated within the temperature range of effective compensation, strain measurements can often be made without the necessity of correcting for thermal output. If correction for thermal output is needed, it can be made as shown in the following sections.

Self-temperature-compensated strain gages can also be used in the manner described in Section 2.1.1. That is, when circumstances are such that a pair of matched gages can be used in adjacent arms of the bridge circuit, with both gages maintained at the same temperature, and with one of the gages unstrained (or strained at a determinate ratio to the other gage), excellent temperature compensation can be achieved over a wide temperature range.

The designations of Micro-Measurements self-temperature-compensated strain gages include a two-digit S-T-C number identifying the nominal thermal expansion coefficient (in ppm/°F) of the material on which the gage will exhibit optimum thermal output characteristics as shown in Figure 4. Micro-Measurements constantan alloy gages are available in the following S-T-C numbers: 00, 03, 05, 06, 09, 13, 15, 18, 30, 40, and 50. S-T-C numbers of 30 and higher are intended primarily for use on plastics. In K alloy, the range of S-T-C numbers is more limited, and consists of 00, 03, 05, 06, 09, 13, and 15. For reference convenience, Table 1 lists a number of engineering materials, and gives nominal values of the Fahrenheit and Celsius expansion coefficients for each, along with the S-T-C number which would normally be selected for strain measurements on that material. The table also identifies those test materials used in determining the published thermal output curves for Micro-Measurements self-temperature-compensated strain gages.

TABLE 1—NOMINAL THERMAL EXPANSION COEFFICIENTS OF ENGINEERING MATERIALS

MATERIAL DESCRIPTION	EXPANSION COEFFICIENTS**		RECOMMENDED S-T-C NUMBER
	Per °F	[Per °C]	
ALUMINA, fired	3.0	[5.4]	03
ALUMINUM Alloy, 2024-T4*, 7075-T6	12.9	[23.2]	13*
BERYLLIUM, pure	6.4	[11.5]	06
BERYLLIUM COPPER, Cu 75, Be 25	9.3	[16.7]	09
BRASS, Cartridge, Cu 70, Zn 30	11.1	[20.0]	13
BRONZE, Phosphor, Cu 90, Sn 10	10.2	[18.4]	09
CAST IRON, gray	6.0	[10.8]	06
COPPER, pure	9.2	[16.5]	09
GLASS, Soda, Lime, Silica	5.1	[9.2]	05
INCONEL, Ni-Cr-Fe alloy	7.0	[12.6]	06
INCONEL X, Ni-Cr-Fe alloy	6.7	[12.1]	06
INVAR, Fe-Ni alloy	0.8	[1.4]	00
MAGNESIUM Alloy*, AZ-31B	14.5	[26.1]	15*
MOLYBDENUM*, pure	2.7	[4.9]	03*
MONEL, Ni-Cu alloy	7.5	[13.5]	06
NICKEL-A, Cu-Zn-Ni alloy	6.6	[11.9]	06
QUARTZ, fused	0.3	[0.5]	00
STEEL Alloy, 4340	6.3	[11.3]	06
STEEL, Carbon, 1008, 1018*	6.7	[12.1]	06*
STEEL, Stainless, Age Hardenable (17-4PH)	6.0	[10.8]	06
STEEL, Stainless, Age Hardenable (17-7PH)	5.7	[10.3]	06
STEEL, Stainless, Age Hardenable (PH15-7Mo)	5.0	[9.0]	05
STEEL, Stainless, Austenitic (304*)	9.6	[17.3]	09*
STEEL, Stainless, Austenitic (310)	8.0	[14.4]	09
STEEL, Stainless, Austenitic (316)	8.9	[16.0]	09
STEEL, Stainless, Ferritic (410)	5.5	[9.9]	05
TIN, pure	13.0	[23.4]	13
TITANIUM, pure	4.8	[8.6]	05
TITANIUM Alloy, 6AL-4V*	4.9	[8.8]	05*
TITANIUM SILICATE*, polycrystalline	0.017	0.03	00*
TUNGSTEN, pure	2.4	[4.3]	03
ZIRCONIUM, pure	**3.1**	**[5.6]**	**03**

* Indicates type of material used in determining thermal output data supplied with Micro-Measurements strain gages.
** Nominal values at or near room temperature for temperature coefficient of expansion values.

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If a strain gage with a particular S-T-C number is installed on a material with a nonmatching coefficient of expansion, the thermal output characteristics will be altered from those shown in Figure 4 by a general rotation of the curve about the room-temperature reference point (see Section 2.2.5). When the S-T-C number is lower than the material expansion coefficient, the rotation is counterclockwise; and when higher, clockwise. Rotation of the thermal output curve by intentionally mismatching the S-T-C number and expansion coefficient can be used to bias the thermal output characteristics so as to favor a particular working temperature range.

2.2 Correction for Thermal Output

Depending upon the test temperature and the degree of accuracy required in the strain measurement, it will sometimes be necessary to make corrections for thermal output, even though self-temperature-compensated gages are used. In any case, when making strain measurements at a temperature different from the instrument balance temperature, the indicated strain is equal to the sum of the stress-induced strain in the test object and the thermal output of the gage (plus the strain equivalent of any other resistance changes in the gage circuit). With the thermal output expressed in strain units, as in Equation (2), correction for this effect is made by simply subtracting (algebraically, with sign) the thermal output from the indicated strain.

As an aid to the user in correcting for temperature-dependent properties, the Engineering Data Sheet in each package of Micro-Measurements A- and K-alloy strain gages includes a graph showing the thermal output and gage-factor variation with temperature. Figure 5 is typical (for A alloy) of the graphs supplied with the gages. In addition to plots of thermal output and gage factor variation, polynomial equations are provided (in both Fahrenheit and Celsius units) for the thermal output curve. Also given on the graph are two other important items of information: (1) the lot number of the strain gages, and (2) the test material used in measuring the thermal output characteristics. It should be noted that the thermal output data are specifically applicable to only gages of the designated lot number, applied to the same test material.

2.2.1 Simple Procedure

Approximate correction for thermal output can be accomplished most directly and easily using the formula (Figure 5) on the gage package data label. This simple method of correction is based on the fact that the gage factors of A- and K-alloy gages are close to 2.0, which is the standardized gage-factor setting employed in calibrating the gages for thermal output. Adjustment of the thermal output data for a different instrument gage-factor setting is described in Section 2.2.2.

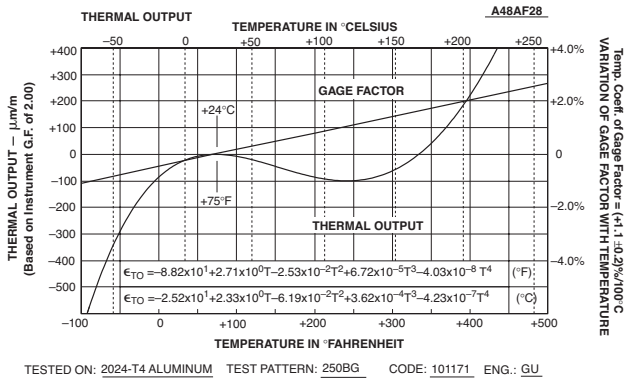

Figure 5. Graph showing typical thermal output and gage factor variation with temperature.

The first step in the correction procedure is to refer to the graph and read the thermal output corresponding to the test temperature. Then, assuming that the strain indicator was balanced for zero strain at room temperature (the reference temperature with respect to which the thermal output data were measured), subtract the thermal output given on the graph from the strain measurements at the test temperature, *carrying all signs*. This procedure can be expressed analytically as follows:

$$\hat{\epsilon} = \hat{\hat{\epsilon}} - \epsilon_{T/O} \tag{3}$$

where:

$\hat{\hat{\epsilon}}$ = uncorrected strain measurement, as registered by the strain indicator.

$\hat{\epsilon}$ = partially corrected strain indication—that is, corrected for thermal output, but not for gage factor variation with temperature (see Sections 3.0 and 4.0).

$\varepsilon_{T/O}$ = thermal output, in strain units, from the gage package data label.

As an example, assume that, with the test part under no load and at room temperature, the strain indicator was balanced for zero strain. At the test temperature of +250°F [+121°C], the indicated strain is +2300$\mu\varepsilon$. Referring to Figure 5, assuming that the graph was the one in the gage package, the thermal output at test temperature is –100$\mu\varepsilon$. From Equation (3), the corrected strain is thus 2300 – (–100) = 2400$\mu\varepsilon$. Had the indicated strain been negative, the corrected strain would be: –2300 – (–100) = –2200$\mu\varepsilon$. If the instrument were balanced for zero strain at some temperature other than +75°F [+24°C], the value of $\varepsilon_{T/O}$ for use in Equation (3) is the net change in thermal output in going from the balance temperature to the test temperature. That is, $\varepsilon_{T/O} = \varepsilon_{T/O}(T_2) - \varepsilon_{T/O}(T_1)$, carrying the sign of the thermal output in each case.

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2.2.2 Adjusting Thermal Output for Gage Factor

It should be noted that the instrument gage factor setting employed in recording thermal output data is standardized at 2.0 for all Micro-Measurements A- and K-alloy gages. If, during strain measurement, the user's instrument is set at a gage factor different from 2.0, the thermal output component of the indicated strain will differ accordingly from that given in Figure 5. This difference is usually no more than several percent when the instrument gage factor is set to that of an A- or K-alloy gage. A modest improvement in the accuracy of the thermal output correction can thus be made by adjusting the data from Figure 5 (taken at $F_I = 2.0$) to the current gage factor setting of the instrument. This is done as follows:

$$\epsilon'_{T/O} = \epsilon_{T/O} \frac{2.0}{F_I} \tag{4}$$

where: $\varepsilon'_{T/O}$ = thermal output adjusted for instrument gage factor setting.

$\varepsilon_{T/O}$ = thermal output from gage package data sheet ($F_I = 2.0$).

F_I = instrument gage factor setting during strain measurement.

Continuing the numerical example, and assuming that the data sheet gives a room-temperature gage factor of 2.10 for the gage, and that the instrument is set at this same gage factor, the adjusted thermal output is calculated from Equation (4):

$$\epsilon'_{T/O} = -100 \text{ x } \frac{2.0}{2.1} = -95\mu\epsilon$$

And the corrected strain measurements become:

$$2300 - (-95) = 2395\mu\varepsilon$$

and,

$$-2300 - (-95) = -2205\mu\varepsilon$$

As shown in Figure 5, the gage factor of the strain gage varies slightly with temperature. When this effect is significant relative to the required accuracy in strain measurement, the gage factor of the strain gage can be corrected to its test-temperature value (Section 3.1), and the gage factor of the instrument set accordingly. The resulting instrument gage factor is substituted into Equation (4) to obtain the adjusted thermal output, which is then subtracted algebraically from the indicated strain to yield the stress-induced strain.

2.2.3 Extensive Data Acquisition

If desired, for extensive strain measurement programs, the thermal output curve in Figure 5 can be replotted with the gage factor adjustment — either room-temperature or test-temperature — already incorporated. Upon completion, the thermal output read from the replotted curve can be used directly to correct the indicated strain. This procedure may be found worth the effort if many strain readings are to be taken with one gage or a group of gages from the same lot.

For convenience in computerized correction for thermal output, Micro-Measurements supplies, for each lot of A-alloy and K-alloy gages, a regression-fitted (least-squares) polynomial equation representing the thermal output curve for that lot. The polynomial is of the following form:

$$\varepsilon_{T/O} = A_0 + A_1T + A_2T^2 + A_3T^3 + A_4T^4 \tag{5}$$

where: T = temperature.

If not included directly on the graph, as shown in Figure 5, the coefficients A_i for Equation (5) can be obtained from Micro-Measurements on request by specifying the lot number.

It should be borne in mind that the regression-fitted equations, like the data from which they are derived, are based on an instrument gage factor of 2.0; and, for greatest accuracy, the thermal output values calculated from the equations must be adjusted to the gage factor setting of the instrument if other than 2.0. As an alternative, the A_i coefficients in Equation (5) can be multiplied by the ratio $2.0/F_I$, where F_I is the instrument gage factor used for strain measurement. Another consideration which should not be overlooked is that the supplied thermal output data and equations are applicable *only* to the specified lot of gages, bonded to the identical material used by Micro-Measurements in performing the thermal output tests.

2.2.4 Accuracy and Practicality — First-Hand Measurement of Thermal Output

There is a limit as to just how far it is practical to go in adjusting the manufacturer's thermal output data in an attempt to obtain greater accuracy. In the first place, the thermal output curve provided on the gage package data label (or by the polynomial equation) represents an average, since there is some variation in thermal output characteristics from gage to gage within a lot. And the width of the scatterband increases as the test temperature departs further and further from the room-temperature reference.

Furthermore, the thermal output data given in the gage package were necessarily measured on a particular lot of a particular test material (see Table 1). Different materials with the same or closely similar nominal expansion coefficients, and even different lots and forms of the same material, may have significantly different thermal expansion characteristics.

From the above considerations, it should be evident that in order to achieve the most accurate correction for thermal output it is generally necessary to obtain the thermal output data with the actual test gage installed on the actual test part. For this purpose, a thermocouple or resistance temperature

sensor is installed immediately adjacent to the strain gage. The gage is then connected to the strain indicator and, with no loads applied to the test part, the instrument is balanced for zero strain. Subsequently, the test part is subjected to the test temperature(s), again with no loads applied, and the temperature and indicated strain are recorded under *equilibrium* conditions. If, throughout this process, the part is completely free of mechanical *and thermal* stresses, the resulting strain indication at any temperature is the thermal output at that temperature. If the instrument gage factor setting during subsequent strain measurement is the same as that used for thermal output calibration, the observed thermal output at any test temperature can be subtracted algebraically from the indicated strain to arrive at the corrected strain. Otherwise, the thermal output data should be adjusted for the difference in gage factor settings, as described in Section 2.2.2, prior to subtraction.

In order to correct for thermal output in the manner described here, it is necessary, of course, to measure the temperature at the strain gage installation each time a strain measurement is made. The principal disadvantage of this procedure is that two channels of instrumentation are preempted for each strain gage — one for the strain gage proper, and one for the thermocouple or resistance temperature sensor.

2.2.5 S-T-C Mismatch

When a strain gage is employed on a material other than that used in obtaining the manufacturer's thermal output data for that lot of gages, an S-T-C mismatch occurs. In such cases, the thermal output of the gage will differ from the curve supplied in the gage package. Consider, for example, strain measurements made at an elevated temperature on Monel with a strain gage of 06 S-T-C number, calibrated for thermal output on 1018 steel (Table 1). The thermal expansion characteristics of Monel are somewhat different from 1018 steel, and the strain gage will produce a correspondingly different thermal output. Thus, if accurate strain measurement is required, the thermal output characteristics of the gage bonded to Monel must be measured over the test temperature range as described in Section 2.2.4. For small temperature excursions from room temperature, the effect of the difference in expansion properties between Monel and 1018 steel is not very significant, and would commonly be ignored.

On the other hand, when the difference in thermal expansion properties between the thermal output calibration material and the material to which the gage is bonded for stress analysis is great, the published thermal output curve cannot be used directly for making corrections. Examples of this occur in constantan strain gages with S-T-C numbers of 30, 40, and 50. The principal application of these gages would normally be strain measurement on high-expansion-coefficient plastics. But the thermal (and other) properties of plastics vary significantly from lot to lot and, because of formulation differences, even more seriously from manufacturer to manufacturer of nominally the same plastic. This fact, along with the general instability of plastics properties with time, temperature, humidity, etc., creates a situation in which there are no suitable plastic materials for use in directly measuring the thermal output characteristics of gages with S-T-C numbers of 30 and above. As an admittedly less-than-satisfactory alternative, the thermal output data provided with these gages are measured on 1018 steel specimens because of the stability and repeatability of this material.

As a result of the foregoing, it is always preferable when measuring strains on plastics or other materials with 30, 40 or 50 S-T-C gages (at temperatures different from the instrument balance temperature) to first experimentally determine the thermal output of the gage on the test material as described in Section 2.2.4. Using these data, corrections are then made as usual by subtracting algebraically the thermal output from the measured strain.

For use as a quick first approximation, the thermal output characteristics of 30, 40, or 50 S-T-C gages on a plastic (or on any other material) of known coefficient of expansion can be estimated by reversing the clockwise rotation of the thermal output curve which occurred when measuring the characteristics on a steel specimen. Assume, for example, that a 30 S-T-C gage is to be used for strain measurements on a plastic with a constant expansion coefficient of 35 x 10^{-6}/°F (63 x 10^{-6}/°C) over the test temperature range. Assume also that the expansion coefficient of 1018 steel is constant at 6.7 x 10^{-6}/°F (12.1 x 10^{-6}/°C) over the same temperature range. With the strain indicator set at the gage factor of the strain gage, so that $F_I = F_G$, and noting that the ratio $(1 + K_t)/(1 - \nu_0 K_t)$ is normally close to unity for A-alloy gages, Eq. (2) can be rewritten in simplified (and approximate) form as follows:

$$\epsilon_{T/O} = \left(\frac{\beta_G}{F_G} - \alpha_G \right) \Delta T + \alpha_S \Delta T \tag{6}$$

(Note: Although the remainder of this example is carried through in only the Fahrenheit system to avoid overcomplicating the notation, the same procedure produces the equivalent result in the Celsius system.)

When specifically applied to 6.7 and 35 x 10^{-6}/°F materials, Equation (6) becomes:

$$\epsilon_{T/O\,(6.7)} = \left(\frac{\beta_G}{F_G} - \alpha_G \right) \Delta T + 6.7 \Delta T \tag{7a}$$

and,

$$\epsilon_{T/O\,(35)} = \left(\frac{\beta_G}{F_G} - \alpha_G \right) \Delta T + 35 \Delta T \tag{7b}$$

Strain Gage Thermal Output and Gage Factor Variation with Temperature

Solving Eq. (7a) for: $\left(\frac{\beta_G}{F_G} - \alpha_G\right) \Delta T$, and substituting into Equation (7b),

$$\varepsilon_{T/O(35)} = \varepsilon_{T/O(6.7)} + (35 - 6.7)\Delta T \qquad (8)$$

In words, Equation (8) states that the thermal output curve for the 30 S-T-C gage mounted on 1018 steel can be converted to that for the same gage mounted on a 35 x 10^{-6}/°F plastic by adding to the original curve the product of the difference in expansion coefficients and the temperature deviation from room temperature *(always carrying the proper sign for the temperature deviation)*. Figure 6 shows the thermal output curve for a 30 S-T-C gage as originally measured on a 1018 steel specimen, and as rotated counterclockwise to approximate the response on a plastic with an expansion coefficient of 35 x 10^{-6}/°F.

The procedure just demonstrated is quite general, and can be used to predict the approximate effect of any mismatch between the expansion coefficient used for obtaining the thermal output curve on the gage package data sheet and the expansion coefficient of some other material on which the gage is to be installed. Although generally applicable, the procedure is also limited in accuracy because the expansion coefficients in Equation (6) are themselves functions of temperature for most materials. A further limitation in accuracy can occur when measuring strains on plastics or other materials with poor heat transfer characteristics. If, due to self-heating, the temperature of the strain gage is significantly higher than that of the test part, the thermal output data supplied in the gage package cannot be applied meaningfully.

It should be borne in mind that the foregoing procedure gives, at best, a rough approximation to the actual thermal output when there is a mismatch between the expansion coefficient of the test material and the selected S-T-C number of the strain gage. When accurate correction for thermal output is required, direct measurement, as described in Section 2.2.4, is highly recommended.

3.0 Gage Factor Variation with Temperature

The alloys used in resistance strain gages typically exhibit a change in gage factor with temperature. In some cases, the error due to this effect is small and can be ignored. In others, depending upon the alloy involved, the test temperature, and the required accuracy in strain measurement, correction for the gage factor variation may be necessary.

It can be seen from Figure 7 that the effect in the A alloy is essentially linear, and quite small at any temperature, typically being in the order of 1% or less per 100°F [2% or less per 100°C]. Thus, for a temperature range of, say, ±100°F [±50°C], about room temperature, correction may not be necessary. At more extreme temperatures, when justified by accuracy requirements, the correction can be made as shown in Section 3.1, or combined with the thermal output correction as in Section 4.0.

The variation of gage factor in the D alloy, while very modest and flat between room temperature and +200°F [+95°C], steepens noticeably outside of this range. However, even for temperatures where the gage factor deviation is several percent, correction may not be practical. This is because D alloy is used primarily for purely dynamic strain measurement, under which conditions other errors in the measurement system may greatly overshadow the gage factor effect.

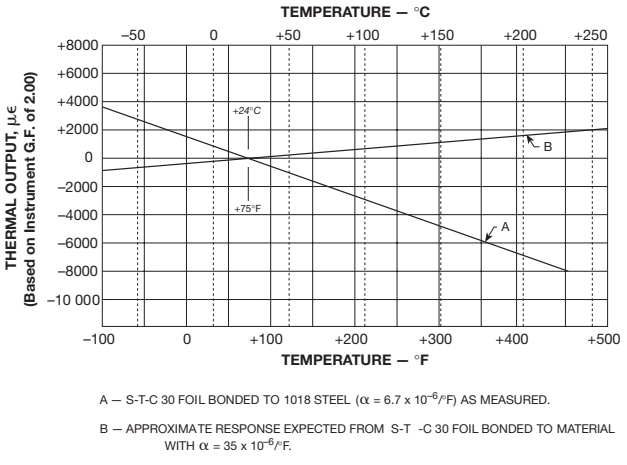

Figure 6. Rotation of the thermal output function [from (A) to (B)] when a strain gage is installed on a material of higher thermal expansion coefficient than that used by the manufacturer in S-T-C calibration.

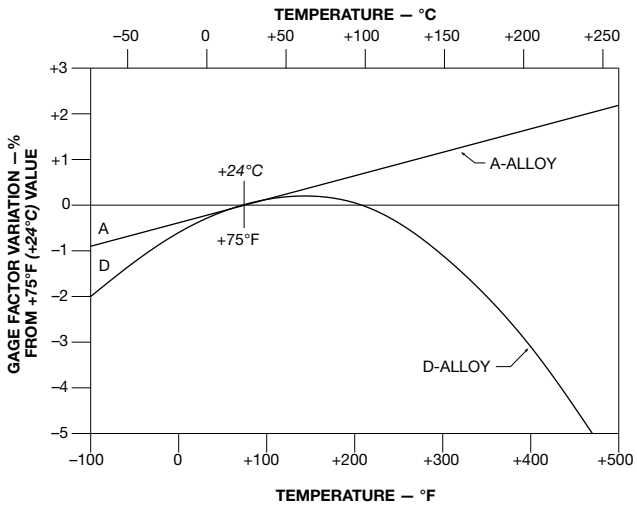

Figure 7. Gage factor variation with temperature for constantan (A-alloy) and isoelastic (D-alloy) strain gages.

Strain Gage Thermal Output and Gage Factor Variation with Temperature

As shown in Figure 8, the gage factor variation with temperature for modified Karma (K alloy) is distinctly different from that of the A and D alloys. The gage factor variation is nearly linear with temperature, as it is for A alloy, but the slope is negative and is a function of the S-T-C number, becoming steeper with higher numbers.

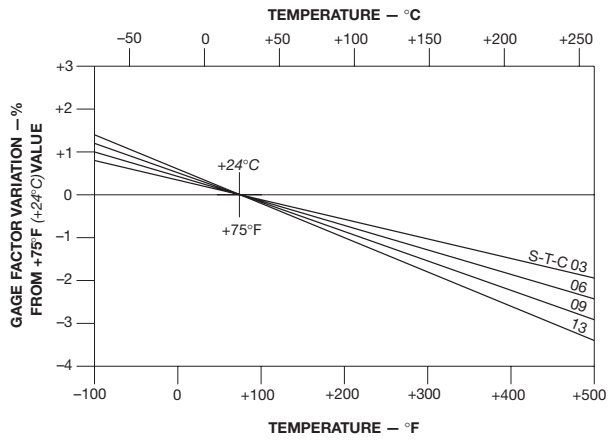

Figure 8. Variation of K-alloy gage factor with temperature and S-T-C number.

3.1 Correcting Strain Measurements for Gage Factor Variation with Temperature

The standard procedure for measuring the gage factor of a lot of any particular type of strain gage is performed at room temperature. It is this value of the gage factor, along with its tolerance, which is given on the gage package data label of Micro-Measurements strain gages. Thus, at any temperature other than room temperature the gage factor is different, and a correction may be needed, according to the circumstances. Also given on each data sheet is the applicable graph of gage factor variation with temperature, such as those in Figures 7 and 8. This information is all that is required to make the correction.

In general, any strain measurement data can be corrected (or adjusted) from one gage factor to another with a very simple relationship. Assume, for instance, that a strain, ϵ_1, was registered with the gage factor setting of the strain indicator at F_1, and it is desired to correct the data to a gage factor of F_2. The corrected strain, ϵ_2, is calculated from:

$$\epsilon_2 = \epsilon_1 \times \frac{F_1}{F_2} \tag{9}$$

When correcting for gage factor variation with temperature, F_1 can be taken as the package-data room-temperature gage factor at which the strain indicator may have been set, and F_2 the gage factor at the test temperature. Of course, when the test temperature is known with reasonable accuracy in advance, the gage factor control of the strain indicator can be set at F_2, initially, and no correction is necessary. It should be noted in this case, however, that if thermal output corrections are to be made from the graph (or polynomial equation) on the gage package data label, the thermal output data must be adjusted from a gage factor of 2.0 (at which the thermal output was measured) to the test temperature gage factor, F_2, being used for strain measurement.

The following relationship is used to determine the gage factor at the test temperature from the tabular and graphical data supplied in the gage package:

$$F_2 = F_1 \left(1 + \frac{\Delta F(\%)}{100}\right) \tag{10}$$

where: $\Delta F(\%)$ = percent variation in gage factor with temperature as shown in Figures 7 and 8. (Note: The sign of the variation must always be included.)

As a numerical example, using Equations (9) and (10), assume that the room-temperature gage factor of a 13 S-T-C, K-alloy gage is 2.05 and, with the instrument set at this value, the strain indication at +450°F [+230°C] is 1820$\mu\epsilon$. Referring to Figure 8, $\Delta F(\%)$ for this case is –3, and, from Equation (10),

$$F_2 = 2.05\ (1 - 0.03) = 1.99$$

Substituting into Eq. (9),

$$\epsilon_2 = 1820 \times \frac{2.05}{1.99} = 1875\mu\epsilon$$

Since gage factor variation with temperature affects both the thermal output and the stress-induced strain, and because confusion may arise in making the corrections individually and then combining them, the following section gives equations for performing both corrections simultaneously.

4.0 Simultaneous Correction of Thermal Output and Gage Factor Errors

Relationships are given in this section for correcting indicated strains for thermal output and gage factor variation with temperature. The forms these relationships can take depend upon the measuring circumstances — primarily upon the strain indicator gage factor setting and the temperature at which the instrument was balanced for zero strain.

The strain indicator gage factor can be set at any value within its control range, but one of the following three is most likely:†

1. Gage factor, F^*, used by Micro-Measurements in determining thermal output data ($F^* = 2.0$).

† The instrument gage factor setting should not be changed during a test (after zero-balance), since this may introduce a zero shift.

Strain Gage Thermal Output and Gage Factor Variation with Temperature

2. Room-temperature gage factor as given on the gage package data label.
3. Gage factor of gage at test temperature or at any arbitrary temperature other than room or test temperature.

No single gage factor is uniquely correct for this situation; but, of the foregoing, it will be found that selecting the first alternative generally leads to the simplest form of correction expression. Because of this, the procedure developed here requires that the gage factor of the instrument be set at $F_I = F^* = 2.0$, the gage factor at which the thermal output data were recorded.

Similarly, the strain indicator can be balanced for zero strain at any one of several strain gage temperatures:

1. Room temperature
2. Test temperature
3. Arbitrary temperature other than room or test temperature

The second and third of the above choices can be used for meaningful strain measurements only when the test object is known to be completely free of mechanical and thermal stresses at the balancing temperature. Because this requirement is usually difficult or impossible to satisfy, the first alternative is generally preferable, and is thus selected for the following procedure.

As an example, assume that the strain indicator is balanced with the gage at room temperature, and with the gage factor control set at F^*, the value used by Micro-Measurements in recording the thermal output data. Assume also that a strain $\hat{\hat{\epsilon}}_1$ is subsequently indicated at a temperature T_1 which is different from room temperature. The indicated strain $\hat{\hat{\epsilon}}_1$ is generally in error due both to thermal output and to variation of the gage factor with temperature — and hence the double caret over the strain symbol.

Consider first the correction for thermal output. Since the gage factor setting of the strain indicator coincides with that used in measuring the thermal output, this correction can be made by direct subtraction of the thermal output (as given on the gage package data label) from the indicated strain. That is,

$$\hat{\epsilon}_1 = \hat{\hat{\epsilon}}_1 - \epsilon_{T/O}(T_1)$$

where: $\hat{\hat{\epsilon}}_1$ = indicated strain, uncorrected for either thermal output or gage factor variation with temperature.

$\hat{\epsilon}_1$ = semi-corrected strain; i.e., corrected for thermal output only.

$\epsilon_{T/O}(T_1)$ = thermal output at temperature T_1 (functional notation is used to avoid double and triple subscripts).

Next, correction is made for the gage factor variation with temperature. Because the strain measurement was made at a gage factor setting of F^*, the correction to the gage factor at the test temperature is performed with Equation (9) as follows:

$$\epsilon_1 = \hat{\epsilon}_1 \frac{F^*}{F(T_1)}$$

where: ϵ_1 = strain magnitude corrected for both thermal output and gage factor variation with temperature.

$F(T_1)$ = gage factor at test temperature.

Combining the two corrections,

$$\epsilon_1 = \left[\hat{\hat{\epsilon}}_1 - \epsilon_{T/O}(T_1)\right] \frac{F^*}{F(T_1)} \qquad (11)$$

When the prescribed conditions on the gage factor setting and the zero-balance temperature have been met, the strain ϵ_1 from Equation. (11) is the actual strain induced by mechanical and/or thermal stresses in the test object at the test temperature. As a numerical example of the application of Equation (11), assume the following:

Strain gage	WK-06-250BG-350
Test material	Steel
†Room-temperature gage factor, F_0	2.07
Test temperature	–50°F [–45°C]
$\hat{\hat{\epsilon}}_1$, indicated strain at test temperature (with instrument gage factor set at F^*)	$-1850\mu\epsilon$
†$\epsilon_{T/O}(T_1)$, thermal output at test temperature	$-200\mu\epsilon$
†$\Delta F(T_1)$, deviation at test temperature from room-temperature gage factor	+0.6%

Using Equation (10) to obtain $F(T_1)$, the gage factor of the gage at test temperature,

$$F(T_1) = F_0\left(1 + \frac{0.6}{100}\right) = 2.07 \text{ x } 1.006$$

$$F(T_1) = 2.08$$

Substituting into Eq. (11), with $F^* = 2.0$,

$$\epsilon_1 = \left[-1850 - (-200)\right] \frac{2.0}{2.08} = -1587\mu\epsilon$$

† From engineering data on gage package.

Strain Gage Thermal Output and Gage Factor Variation with Temperature

For what might appear to be a more complex case, consider a strain-gage-instrumented centrifugal compressor, operating first at speed N_1, with the temperature of the gage installation at T_1. Under these conditions, the indicated strain is $\hat{\epsilon}_1$. The compressor speed is then increased to N_2, with a resulting gage installation temperature of T_2, and an indicated strain $\hat{\epsilon}_2$. The engineer wishes to determine the change in stress-induced strain caused by the speed increase from N_1 to N_2.

This problem is actually no more difficult than the previous example. Applying Equation (11) to each condition:

$$\epsilon_1 = \left[\hat{\epsilon}_1 - \epsilon_{T/O}(T_1)\right] \frac{F^*}{F(T_1)}$$

$$\epsilon_2 = \left[\hat{\epsilon}_2 - \epsilon_{T/O}(T_2)\right] \frac{F^*}{F(T_2)}$$

The same numerical substitution procedure is followed as before, and the results subtracted to give $(\epsilon_2 - \epsilon_1)$, the change in stress-induced strain caused by the speed increase. The subtraction can also be done algebraically to yield a single equation for the strain change:

$$\epsilon_2 - \epsilon_1 = F^* \left[\frac{\hat{\epsilon}_2 - \epsilon_{T/O}(T_2)}{F(T_2)} - \frac{\hat{\epsilon}_1 - \epsilon_{T/O}(T_1)}{F(T_1)} \right]$$

When computerized data reduction is used, analytical expressions for the functions $\epsilon_{T/O}(T)$ and $F(T)$ can be introduced into the program to permit direct calculation of corrected strains from indicated strains.

Appendix
Surface Curvature Effects on Thermal Output

Frank F. Hines has demonstrated† that when a strain gage is installed on a sharply curved surface, the thermal output manifested by such an installation is different than for the same gage mounted on a flat surface. The curvature-indicated *change* in thermal output, referred to here as the *incremental* thermal output, is due to the fact that the strain-sensitive grid of the gage is above the surface of the test member by the thickness of the gage backing and adhesive layer. It can be shown that under these conditions a temperature change causes a different strain in the grid than would occur with the grid bonded to a plane surface. The result is an altered thermal output from the data provided in the gage package.

The curvature-induced incremental thermal output is a second-order effect which can ordinarily be ignored; but it can become significant when the radius of curvature is very small. As a rule of thumb, the incremental thermal output can be neglected when the radius of curvature is 0.5 in (13 mm) or greater. With smaller radii, correction may be necessary, depending upon the required strain-measurement accuracy.

Employing the same basic approach and approximations used by Hines in his derivation, but generalizing the treatment to allow for any combination of adhesive and backing properties, an expression for estimating the incremental thermal output can be written as follows:

$$\Delta\epsilon_{T/O} = \frac{1}{R}\left[(1+2\nu_{A-B})(h_A\alpha_A + h_B\alpha_B) - 2\nu_{A-B}\alpha_S(h_A + h_B)\right]\Delta T \qquad \text{(A-1)}$$

where, in consistent units,

$\Delta\epsilon_{T/O}$ = curvature-induced incremental thermal output.

R = radius of curvature of test surface at gage site.

ν_{A-B} = average Poisson's ratio of adhesive and backing.

h_A, h_B = adhesive and backing thickness, respectively.

α_A, α_B = thermal expansion coefficients of adhesive and backing, respectively.

α_S = thermal expansion coefficient of substrate (specimen material).

ΔT = temperature change from reference temperature.

Approximate values for the adhesive and backing parameters in Equation (A-1) are given in Table A-1 for representative Micro-Measurements adhesives and gage series. The sign of the incremental thermal output is obtained from Equation (A-1) when the signs of ΔT and R are properly accounted for — that is, an increase in temperature from the reference temperature is taken as positive, and a decrease negative; and correspondingly, a convex curvature is positive, while a concave curvature is negative. The calculated result from Equation (A-1) is then added algebraically to the thermal output data supplied in the gage package to give the curvature-corrected thermal output for use in making thermal output corrections as shown in this Tech Note.

TABLE A-1
Adhesive and Backing Parameters for Use with Equation (A-1)

Adhesive Type	h_A, h_B		α_A, α_B	
	in	[mm]	per °F	[per °C]
M-Bond 200	0.0006	[0.015]	45 x 10^{-6}	[81 x 10^{-6}]
M-Bond AE-10/15	0.001	[0.025]	45	[81]
M-Bond 600/610	0.0002	[0.005]	45	[81]
Gage Series (Backings)				
EA, CEA, EP, ED	0.0012	[0.030]	50 x 10^{-6}	[90 x 10^{-6}]
SA, SK, SD, S2K	0.001	[0.025]	10	[18]
WA, WK, WD	0.0015	[0.038]	10	[18]
ν_{A-B} = 0.35 for all combinations				

† Proceedings, Western Regional Strain Gage Committee, Nov. 9, 1960, pp. 39-44.

Strain Gage Thermal Output and Gage Factor Variation with Temperature

Because the adhesive and backing parameters given in Table A-1 are approximate, and are affected by gage installation tech-nique and other variables, the curvature correction defined by Equation (A-1) is limited in accuracy. When the surface curvature is severe enough so that the curvature-induced incremental thermal output may be important, the actual thermal output should be measured as described in Section 2.2.4 of the text. In other words, the strain gage should be bonded to the test part as for strain measurement, a thermocouple or resistance temperature sensor should be installed adjacent to the gage, and the test part then subjected to test temperatures (while free of mechanical and thermal stresses) to record the "true" thermal output.

As an aid in judging the approximate magnitude of the curvature-induced thermal output, Equation (A-1) has been evaluated for several representative combinations of Micro-Measurements adhesives and gage series. Parameters from Table A-1 were substituted into the equation, along with α_S = 6.0 x 10^{-6} (assuming a steel test material), and the results plotted in Figure A-1. Note, in the figure, that the ordinate gives the incremental thermal output *per unit of temperature change* from the initial reference temperature — that is, $\Delta\epsilon_{T/O}/\Delta T$.

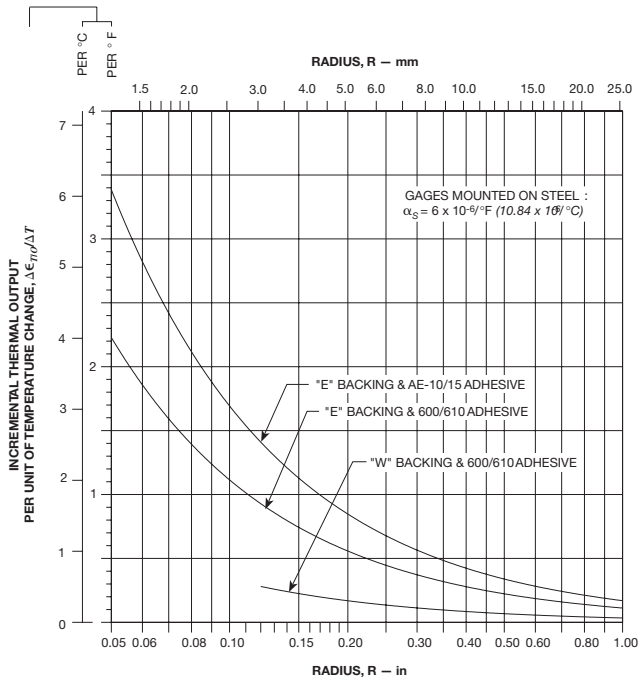

Figure A-1. Equation (A-1) evaluated and plotted for various standard Micro-Measurements strain gage backing materials when bonded to a steel substrate.