Palladium-Chromium Strain Gauges

STATIC STRAIN MEASURABLE AT HIGH TEMPERATURES

By Jih-Fen Lei

Sverdrup Technology Inc., NASA Lewis Research Center Group, Cleveland, Ohio, U.S.A.

In order to meet urgent needs in aerospace research, an electrical resistance strain gauge of palladium-13 weight per cent chromium alloy is being developed both in fine wire and thin film forms at the NASA Lewis Research Center. The wire strain gauge has platinum wire wound around the gauge grid to serve as the temperature compensator, and is coated with a special alumina-based overcoat. This gauge has a sufficiently small apparent strain, with good reproducibility between thermal cycles to 800°C. The apparent strain of the gauge can therefore be corrected within a reasonable error up to this temperature. The thin film gauge, which provides a means for non-intrusive strain measurements, demonstrates the possibility of extending the use of this palladium alloy to approximately 1000°C.

In the work to design and develop hypersonic aerospace vehicles or advanced gas turbine engines, there is an urgent requirement for a high temperature strain gauge that can be used to provide accurate static strain measurements on various hot structures, in order to validate the design codes. The temperatures on the leading edges of hypersonic vehicles or gas turbine blades may exceed 1000°C, but existing static strain gauges are not capable of satisfying the need for high accuracy at these temperatures.

An ideal resistance static strain gauge should have two basic properties: first, its resistance change must be due mainly to the strain. Any other effects which cause resistance changes, for example temperature or time, should be avoided or minimised. Secondly, it should have a stable and reproducible resistance at all temperatures up to the maximum operating temperature. Phenomena which affect the structural stability, and therefore the electrical stability, have to be avoided. Based on these requirements the material used for a static strain gauge must be structurally and chemically stable, and oxidation resistant. In addition, it should have a relatively low temperature coefficient of resistance. The use of presently available commercial resistance static strain gauges has generally been limited to a maximum operating temperature of 400°C. At higher temperatures the materials currently used for gauges experience either oxidation or structural changes. As a result the characteristics of the gauges do not remain within acceptable limits over long periods of time, neither do they vary in a predictable way.

The work to develop a high temperature resistance strain gauge has recently centred on three groups of materials: the historically promising iron-chromium-aluminium systems, platinum-tungsten alloys and the recently developed palladium-chromium solid solutions. The first of these has been used in gauges such as Kanthal A-1 (1), BCL3 (2), and Chinese gauges which operate at temperatures up to 700°C and 800°C (3, 4). These iron-chromium-aluminium alloys offer good self-protection against oxidation and low, but not constant, temperature coefficients of resistance. However, they exhibit microstructural instability in the temperature range 375 to 525°C. The apparent strain versus temperature characteristics of these iron-chromium-aluminium based gauges are therefore sensitive to any heat treatment process, as well as to the heating and cooling rates at which the gauges pass through this transition

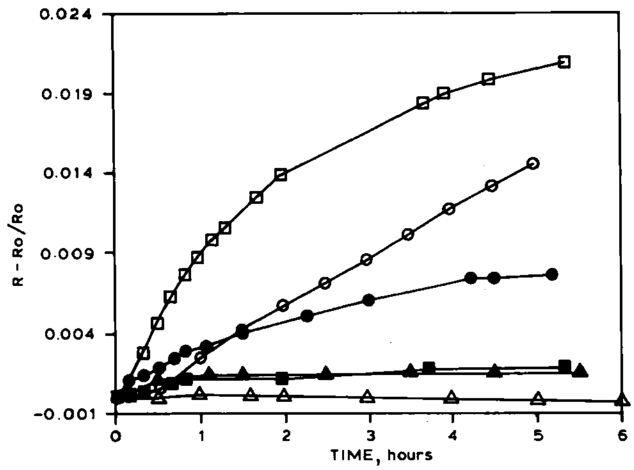


Fig. 1 The resistance drift at 800°C for a 25 μm diameter palladium-chromium wire, bare and after coating with various overcoats:
□ no coating
○ alumina
● alumina-2 wt.%CeO_2
■ alumina-4 wt.%ZrO_2
▲ alumina-1 wt.%Y_2O_3
△ alumina-6 wt.%ZrO_2

temperature range (5, 6). This sensitivity to thermal processing limits the use of these gauges for static strain measurements.

Platinum alloys were extensively investigated for strain gauge application in the 1960s and 1970s. Of all the alloys studied, platinum-tungsten and platinum-palladium-molybdenum appeared to be the most promising (7). These platinum-based alloys have high melting points and are highly sensitive to strain. They are, however, also characterised by low resistivity, excessive sensitivity to trace impurities, and high temperature coefficients of electrical resistance. The performance of these platinum-based gauges for dynamic strain measurements has been shown to be satisfactory at temperatures up to 800°C (8), but the use of these alloys for static strain measurement is generally limited to about 600°C. This is because of possible phase changes and the severe internal oxidation that the materials experience at higher temperatures (9, 10, 11).

Although the use of palladium-chromium alloys as possible high temperature strain gauge materials had been suggested in the early 1960s (12), essentially no work was done until recently. In 1985 after an extensive search, palladium-chromium was identified as the best candidate material for static strain applications at temperatures up to at least 1000°C (11). In this NASA supported contract, a total of thirty-four palladium-chromium alloys were studied and palladium-13 weight per cent chromium was chosen as the optimum composition. An alloy of this composition has a lower temperature coefficient of resistance than alloys containing less

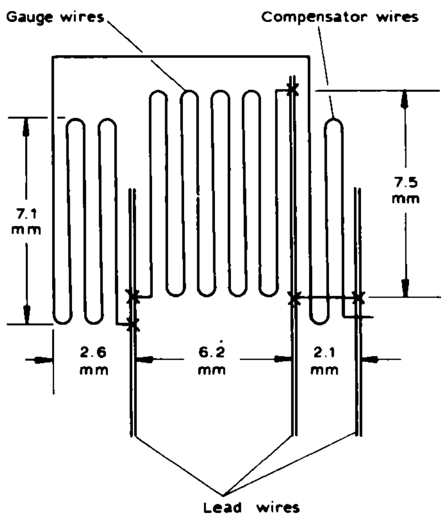


Fig. 2 The configuration of a palladium-chromium temperature-compensated wire strain gauge, using 25 μm diameter palladium-13 wt.% chromium wire for the strain gauge wires, 25 μm diameter platinum wire for the compensator wires and 76 μm diameter palladium-13 wt.% chromium for the lead wires

than 13 weight per cent chromium, while alloys with more than 13 weight per cent chromium have poorer resistance to oxidation (13).

Work at NASA Lewis Research Center to develop a high temperature static strain gauge has therefore concentrated on palladium-13 weight per cent chromium, with the objective of developing both a fine wire and a thin film high temperature static strain gauge system. As the self-protecting oxidised scale on palladium-13 weight per cent chromium has been found to be insufficient to provide the required stability when this alloy is prepared as fine wire or as a thin film (14), an additional overcoat system is needed to protect the gauge against oxidation. In addition, the temperature coefficient of resistance of this alloy is still higher than desired, approximately 175 μohm/ohm°C, so temperature compensation is necessary in order to minimise the temperature effect on the resistance change of the gauge.

Several overcoat systems have been studied, including alumina and alumina with an addition of zirconia, yttria, ceria or hafnia. Coatings consisting of mixtures of alumina and zirconia, or alumina and yttria, have been shown to provide a better diffusion barrier for oxygen, and result in a significant reduction in the drift rate of palladium-13 weight per cent chromium fine wires (14), as shown in Figure 1. As the amount of the zirconia or yttria increases the oxidation rate decreases, and therefore the electrical resistance drift rate of the wire also decreases. However, the amount of the zirconia and yttria additions should be less than 6 weight per cent and 1 weight per cent, respectively, in order to prevent any possible interaction between the palladium-chromium and the overcoat.

Temperature compensation of the gauge is achieved by the use of a Wheatstone bridge circuit, with a compensator element connected to the adjacent arm of the bridge. The configuration of a compensated palladium-chromium wire gauge is shown in Figure 2. The gauge is fabricated from 25 μm diameter wire, and the compensating resistor is 25 μm diameter platinum wire. Platinum is used as the compensator element because it has a much higher temperature coefficient of resistance than

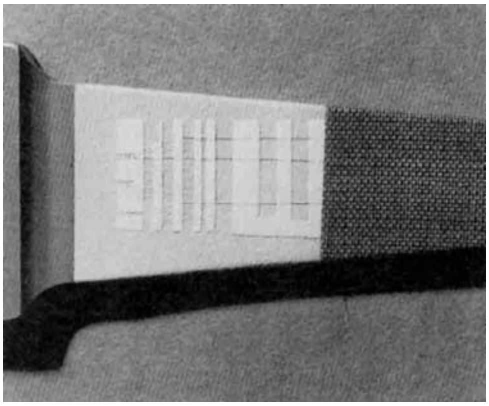


Fig. 3 After the application of an alumina precoat, the compensated wire gauge is taped down with high temperature adhesive strips. Here the substrate is an IN-718 test bar

palladium-13 weight per cent chromium, and because it has good structural and chemical stability at high temperatures. Platinum is wound around the gauge grid to minimise the temperature gradient effect. The lead wires are also palladium-13 weight per cent chromium, but of 76 μm diameter. The lead wires are spot welded to the gauge and to the compensator wires.

The compensated palladium-13 per cent chromium wire gauge has been tested on a Hastelloy-X coupon and an IN-718 cantilever beam. The gauges are mounted with either high temperature ceramic cements or flame-sprayed powders. A layer of alumina is first applied to the substrate as the precoat, and the gauge is then taped down on this precoat by means of high temperature adhesive strips, see Figure 3. A layer of alumina and zirconia, or alumina and yttria mixture is applied, to the open areas between the strips. The strips are then removed and the final alumina mixture overcoat is applied. The cemented gauge can be used satisfactorily up to approximately 600°C (15). At higher temperatures, the porous cement is insufficient to protect the gauge system from oxidation and prevent electrical leakage to ground. The flame-sprayed gauge has been demonstrated to work reasonably well at temperatures up to 800°C, since the flame-sprayed technique usually produces a denser film (16). The change in apparent strain of a prestabilised gauge from

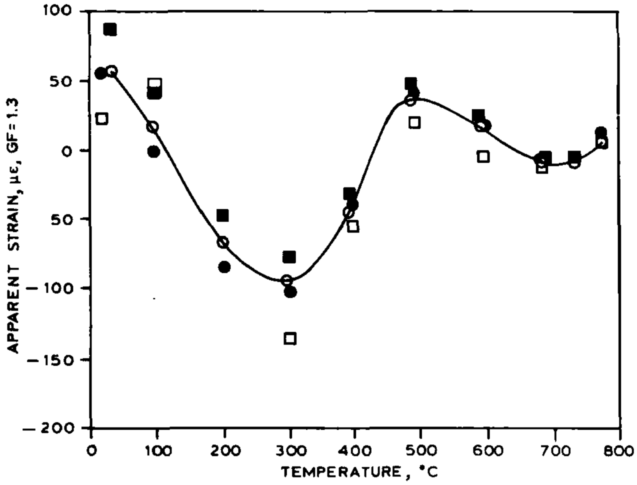


Fig. 4 For two thermal cycles to 800°C the plot of apparent strain versus temperature for a palladium-chromium compensated wire strain gauge, after prestabilising at 780°C for 50 h, shows reproducibility to be within 50 microstrain; with strain sensitivity (Gauge Factor, GF = (δR/R)/δε) = 1.3:
□ heating cycle 1
○ cooling cycle 1
● heating cycle 2
■ cooling cycle 2

room temperature to 800°C is within 300 microstrain (μ inch/inch), with a reproducibility to within 50 microstrain between thermal cycles to 800°C, see Figure 4. The apparent strain of the gauge can therefore be corrected at temperatures up to 800°C, due to its small value and its repeatibility. This is a significant advance on the previous techniques for existing static strain gauges, as demonstrated by the data in Figure 5.

The strain sensitivity (gauge factor) of this compensated wire gauge, both in tension and in compression, is approximately 1.3 at room temperature. The gauge responds linearly to the imposed strain to at least ± 2000 microstrain. Furthermore, the strain sensitivity of the gauge does not vary significantly with temperature (16).

The development of a palladium-13 weight per cent chromium thin film gauge has commenced. Two sputtered thin film gauges, each with four lead pads on an alumina bar, are shown in Figure 6. Palladium-13 weight per cent chromium wire, 75 μm in diameter is used for the lead wires, which are parallel-gap welded to

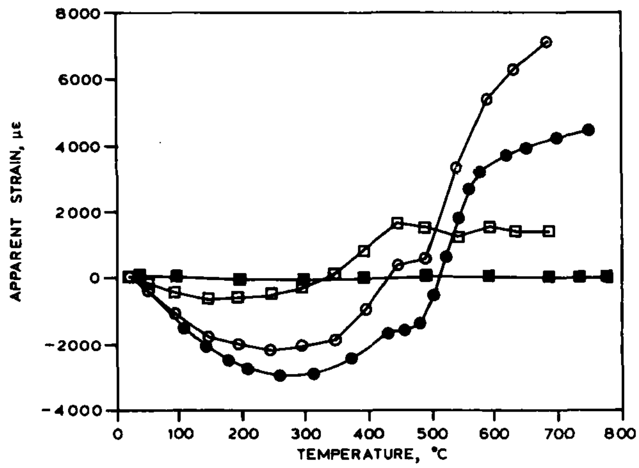


Fig. 5 A comparison of apparent strain versus temperature for four high temperature strain gauges demonstrates the value of the palladium-13 wt.% chromium, for temperatures up to 800°C, and strain sensitivity
(.): Gauge Factor = 2.0;
(+): Gauge Factor = 1.3:
■ Pd-13 wt.% Cr gauge (+)
□ Chinese gauge up to 700°C (.)
○ Kanthal A-1 gauge (.)
● BCL3 gauge (.)

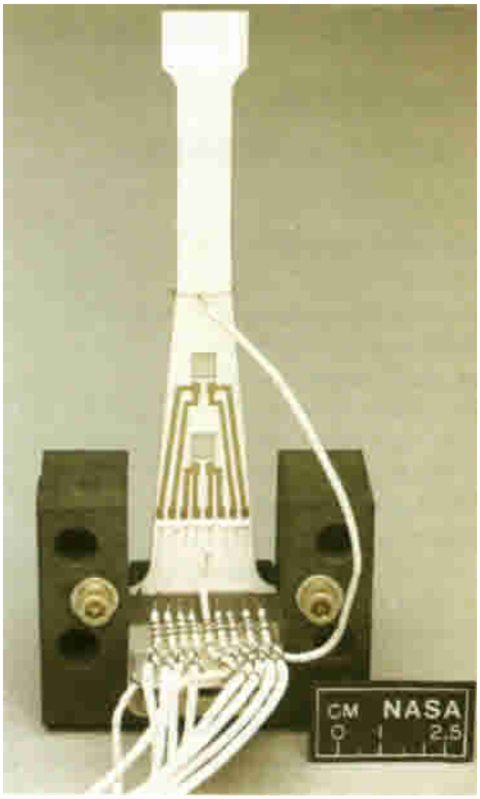
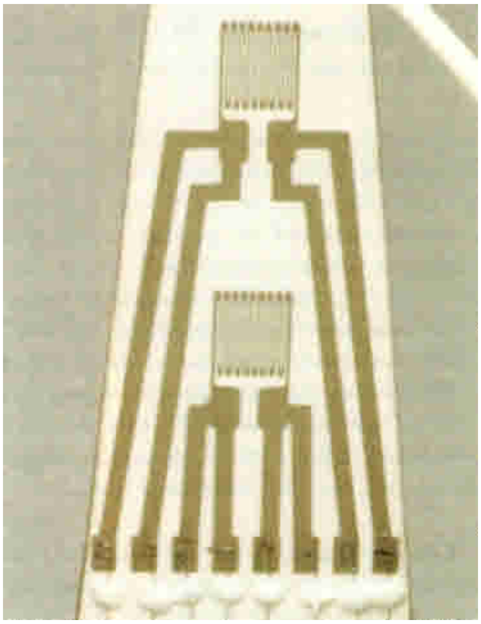


Fig. 6 These two sputtered thin film gauges, on an alumina test beam, were produced as part of a NASA development programme. The enlargement below shows details of the palladium-chromium thin film gauges



the thin film lead pads. The apparent strain change versus temperature characteristics of these sputtered thin film gauges is linear and repeatable at temperatures up to 1000°C. The reproducibility of the apparent strain between repeated thermal cycles to 1000°C can be further improved by prestabilising the gauge before testing, and by coating the gauge with the alumina-based mixture overcoat. This indicates that the maximum temperature at which this thin film gauge can be used can be extended up to at least 1000°C.

Work is currently underway at NASA Lewis Research Center to fabricate palladium-chromium thin film gauges with a compensator element to minimise the apparent strain.

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