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A Flame-Sprayed Resistance Strain Gage for High-Temperature Applications

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The thermal spray technique is often employed for sensor attachments, especially for high-temperature applications, because flame spray techniques usually produce a denser film than ceramic cements. This article introduces a newly developed electrical resistance strain sensor that is installed on the test article by means of a flame spray technique. The gage is made of a specially developed alloy, palladium/13 wt% chromium (Pd13Cr), and is temperature-compensated with a platinum element. A flame-sprayed Pd13Cr-based gage is demonstrated to be a viable sensor candidate for static strain measurement in the temperature range from room temperature to 800 °C (1470 °F). The flame spray technique used for installation of this strain gage is described, and the characteristics of the gage are presented.

1. Introduction

IN THE work to design and test advanced materials and hot structures, there is an urgent need for a high-temperature static strain gage. A gage that can provide accurate static strain measurements on various hot materials/structures is required to validate the design codes as well as to study material/structural durability. An electrical resistance strain gage based on a specially developed alloy, palladium/13 wt% chromium (Pd13Cr), has been demonstrated in the laboratory to be a viable sensor candidate for static strain measurement at high temperatures. Depending on the maximum operating temperature, the gage can be mounted directly on the test article with either ceramic cements or a flame-spray technique. A flame-sprayed Pd13Cr-based gage can be used at temperatures up to 800 °C (1470 °F), compared to 600 °C (1110 °F) for a cemented gage. In addition, a flame-sprayed weldable gage has been developed for field applications where flame-spraying installation cannot be applied. The flame spray technique used for gage installation will be described in detail, and the characteristics of the Pd13Cr-based strain gage will be presented.

2. Basic Operation Principle of a Resistance Strain Gage

An electrical resistance strain gage is a strain-sensing element that changes its electrical resistance with the strain (ε) applied to the substrate on which the gage is bonded. The strain sensitivity, also called the *Gage factor* (G), of a resistance strain gage is defined as:

$$G = \frac{1}{R_0}\left(\frac{\Delta R}{\Delta \varepsilon}\right)$$

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where R_0 is the initial electrical resistance of the strain gage and ΔR is the change in gage resistance due to the change in applied strain ($\Delta\varepsilon$). Ideally, the value of the strain applied to the gage can be determined by knowing the gage factor and by detecting the change in resistance of the gage due to the change in strain.

However, in general, the change in the resistance of a gage system is a function not only of strain, but also of temperature and time. For a resistance strain gage to be usable for static strain measurements over long periods of time during which the temperature and strain may vary, the thermally induced apparent strain and the drift strain of the gage should be either small enough to be neglected or repeatable enough to be correctable within acceptable tolerances. The apparent strain is the "strain" induced by the change in temperature, and the drift strain is the "strain" that changes with time while there is no real strain applied to the test article. For example, if the required accuracy is ±10% for static strain measurements in the range of ±2000 units of microstrain (μin./in. or $\mu\varepsilon$), the apparent strain and the drift strain must be known to within better than ±200 $\mu\varepsilon$ for correction. Because the apparent strain correction also relies on an accurate temperature measurement of the strain gage, cases involving large temperature gradients would require the apparent strain of the gage to be temperature-insensitive in the entire temperature range. These requirements, accuracy and maximum use temperature, exceed the present capability of the resistance strain gage. The use of presently available commercial static strain gages has generally been limited to a maximum operating temperature of 400 °C (750 °F). At higher temperatures, the materials currently used for gages experience either oxidation or structural changes. As a result, the characteristics of the gages do not remain within acceptable limits over long periods of time, nor do they vary in a predictable way.

3. New Strain Gage Design

A Pd13Cr alloy was identified as the best candidate material for static strain applications at high temperatures after an extensive search under a NASA-supported contract (Ref 1). A resistance strain gage based on this Pd13Cr alloy has since been developed at NASA Lewis Research Center to measure static strain at elevated temperatures. The gage is temperature-compensated with a compensator element, platinum. The platinum compensator is in the same form as the Pd13Cr gage element, both being 25 µm (1 mil) in diameter, and is around the periphery of the gage to cancel the effects of the temperature gradients across the gage. The compensator therefore experiences the same strain and temperature as the gage. Figure 1 is a sketch of a free-filament Pd13Cr/Pt dual-element gage with the high-temperature tape frame used for flame spray mounting. The gage is designed so that it is temperature-compensated on any substrate material. The effect of temperature change on the resistance change of the Pd13Cr gage is minimized by connecting the platinum compensator to the adjacent arm of a Wheatstone bridge circuit (Ref 2). The resistance change due to the change in temperature of each arm is designed to be the same and is, therefore, cancelled.

There are three gage lead wires extended from the gage system, with a common lead wire shared by the gage and the compensator. These gage lead wires are 76 µm (3 mil) diameter Pd13Cr wire. The lead routes are designed to minimize stresses on the weld junction and prevent rotation of the leads during bonding.

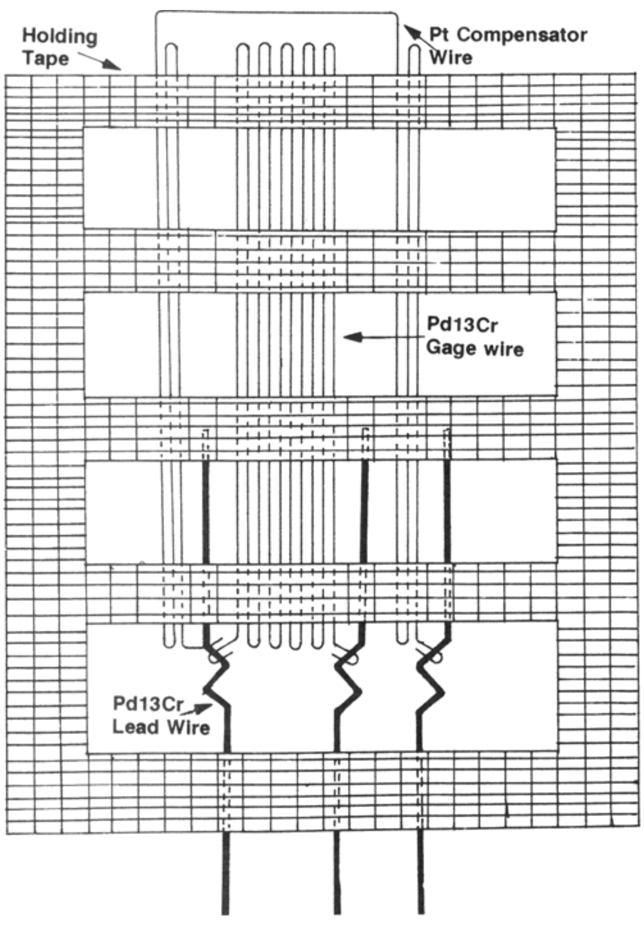

Fig. 1 Sketch of a free-filament Pd13Cr/Pt dual-element strain gage with a tape frame used for flame spray mounting. The platinum compensating element is around the periphery of the Pd13Cr gage element to cancel the effects of the temperature gradients across the gage.

4. Gage Installation Technique

The free-filament wire gage is mounted on the test article with either high-temperature ceramic cements or flame-sprayed materials. The cemented gage can be used at temperatures up to approximately 600 °C (1110 °F) (Ref 3). At higher temperatures, the porous cement is insufficient to protect the gage system from oxidation and prevent electrical leakage to ground. Because flame-sprayed techniques usually produce a denser film, a flame-sprayed gage can be used for a higher-temperature application.

The gage installation procedures using a flame-spray technique are as follows. A detailed description of the installation technique for this gage can be found in Ref 4.

1. *Surface preparation*: Lightly grit blast the gage bonding area to remove the existing surface oxide, and then clean with solvent.
2. *Bond coat application*: Mask the gage bonding area perimeter using flame spray masking tape. Tape must be well bonded to the surface to prevent heat from the flame spraying process from lifting the tape. Apply a 50 to 76 µm (2 to 3 mil) thick nickel aluminide coating to the substrate as the bondcoat. If the substrate is less than 3.2 mm (1/8 in.) thick, cooling air should be used during the coating process to prevent the parts from becoming hot and causing undesirable distortion. The cooling air must be desiccant-filtered to remove all oil; otherwise, an oil-less air compressor should be used. Remove masking tape and gently run an industrial razor over the coating to remove any loose particles. A clean wire brush may also be used to gently remove any loose particles.
3. *Precoat application*: Remask using flame spray masking tape. Place the tape exactly at the edge of the nickel aluminide bond coat. Apply a 50 to 76 µm (2 to 3 mil) alumina precoat over the bond coat. Examine the coating under a microscope to be sure it is continuous.
4. *Gage mounting*: Holding the gage in position with tweezers, press down the gage onto the precoat with the tape carrier as shown in Fig. 2.
5. *Tack coat*: The next step is to apply a coating mixture of alumina and zirconia to the open area between the strips, to provide oxidation protection for the gage (Ref 5). Hold the spraying gun perpendicular to the gage surface at about 25 cm (10 in.) distance and apply a tack coat with rapid passes. The gage grid temperature should not exceed 200 °C (390

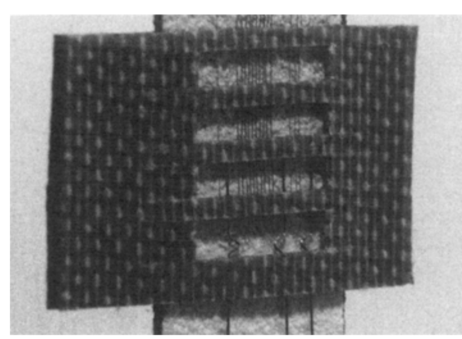

Fig. 2 Photo of a gage taped onto the precoat with the tape carrier

°F) and should return to room temperature before the next pass is made.

6. *Tape removal*: Remove all perimeter tape with sharp tweezers. Examine the gage carefully and remove any debris using an artist's brush.
7. *Remask and final overcoat*: Remask with a single layer of the tape, as shown in Fig. 3. A final alumina mixture overcoat is then applied. Remove all the tape and dress any sharp corners using an aluminum oxide stone. Figure 4 shows two completed gages installed on a 3.2 mm (0.125 in.) thick IN100 coupon. Because both Pd13Cr and platinum have been found to be very sensitive to impurities such as aluminum and silicon, care must be taken during handling and each step of installation to protect the gage from contamination.

A weldable flame-sprayed gage has also been developed for field testing where the conventional flame-spraying installation cannot be applied. The gage is first mounted on a 76 μm (0.003 in.) thick Hastelloy-X shim carrier using the flame spray technique described above. The gage is then mounted on the test article simply by spot welding along the edge of the metal carrier. Figure 5 shows an example of two such gages welded on a 3.2 mm (0.125 in.) thick titanium matrix composite (TMC) coupon with a fiber layup of [0,90,0]. The gages are spot welded along the top fiber direction. Weldable wire gages have been tested on IN100 and IN718, and the characteristics are similar to those of a flame-sprayed gage (Ref 6).

5. Measurement Technique and Procedure

The Pd13Cr-based gage is unique in allowing the user to compensate for temperature effects on materials with a wide range of thermal expansion coefficients by simply varying the resistors of an external circuit (Ref 2). However, in order to perfectly compensate for the unwanted temperature-induced errors, a precalibration process is needed to determine the best value for the ballast resistor in the circuit. This precalibration process is best done on the test article if a thermal cycle to the maximum use temperature is allowed. Otherwise, it can be duplicated on a coupon only if the coupon material is the same as that of the test article. Also, the lead wire material and its length used in the hot zone must be the same as in the real test. The procedures for this precalibration test are described in Ref 2.

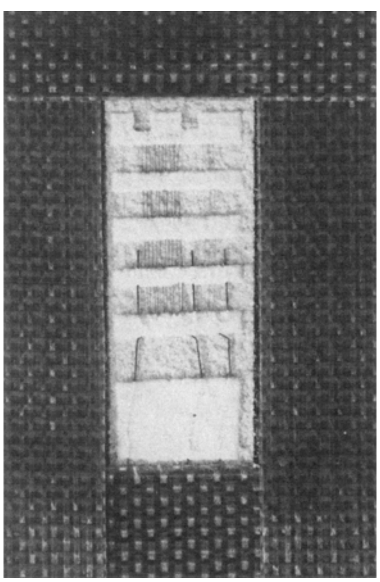

Fig. 3 Gage perimeter masked in preparation for final overcoat spraying

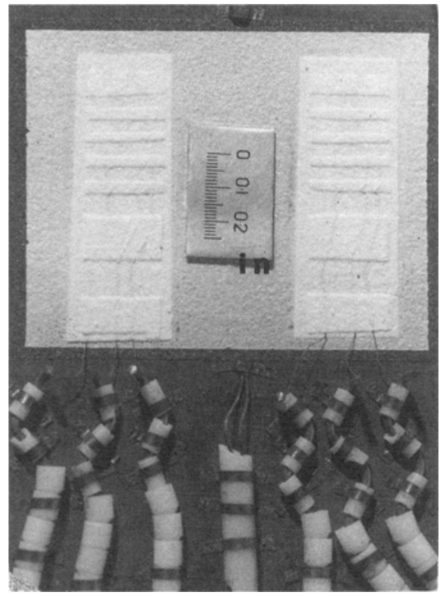

Fig. 4 Two completed gages installed on an IN100 test coupon. Also installed are the thermocouple and extended lead wires to the measurement system.

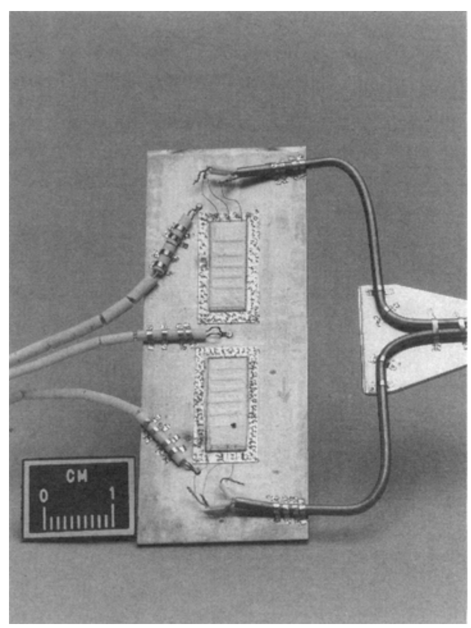

Fig. 5 Two weldable flame spray gages welded on a titanium matrix composite coupon along the top fiber direction

6. Characteristics of the Gage

6.1 *Gage Factor*

The gage factor of the Pd13Cr-compensated wire gage, both in tension and in compression, is approximately 1.35 ± 0.05 at room temperature. It does not vary significantly with temperature, as shown in Fig. 6. The gage responds linearly to the imposed strain to at least ±2000 με.

6.2 *Apparent Strain*

The compensated wire gage has been tested on Hastelloy-X, IN718, IN100, and TMC materials. The residual apparent strain of a flame-sprayed Pd13Cr-based gage is generally within 1200 με, with a reproducibility within ±200 με between thermal cycles to 800 °C (1470 °F). This indicates that the Pd13Cr-based gage is well temperature-compensated on all these materials. Figure 7 presents the apparent strain characteristics of the gage. In this case, the gage is mounted on an IN100 coupon. The apparent strain of the gage is repeatable from the first thermal cycle, with a repeatability within ±100 με between thermal cycles. The apparent strain sensitivity of the gage is less than 3 με/°C (1.7 με/°F) in the entire temperature range. It can therefore be corrected to within ±200 με at temperatures up to 800 °C (1470 °F) if the uncertainty in the temperature measurement is within 67 °C (121 °F). This is a significant advance beyond existing static strain gages, which have generally been limited to a maximum operating temperature of 400 °C (750 °F).

Figure 8 shows the apparent strain characteristics of a weldable flame-sprayed gage during two thermal cycles to 780 °C (1440 °F). The gage is welded on a 3.2 mm (0.125 in.) thick IN100 coupon. As can be seen, the apparent strain characteristics of this weldable gage are similar to those of the gage directly installed on the IN100 (Fig. 7). These two types of gages have comparable reproducibility of apparent strain, although the weldable gage has a slightly larger change in apparent strain over the temperature range. This may have resulted from the difference in the coefficients of thermal expansion between the gage, the Hastelloy-X shim, and the IN100 coupon. No delamination of the weldable gage from the substrate is observed after several thermal cycles.

The critical compressive strain for a weldable gage to start buckling depends strongly on the width of the gage. The narrower the gage is, the higher its critical strain for buckling (Ref 7). Furthermore, the difference in coefficients of thermal expansion between the metal shim and the test article may either increase or decrease the critical buckling strain. When the thermal expansion coefficient of the shim material is greater than that of the substrate material to which it is welded, an increase in temperature will produce a compressive strain in the shim. This will effectively reduce the critical strain limit for the imposed me-

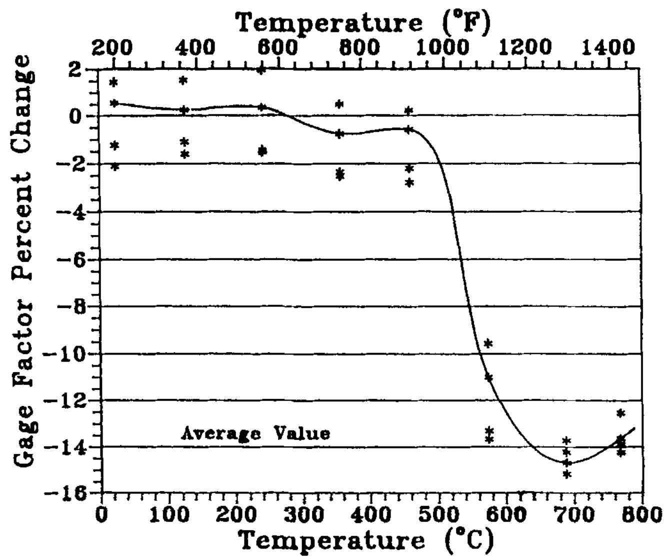

Fig. 6 Gage factor vs. temperature characteristics of a Pd13Cr-based strain gage

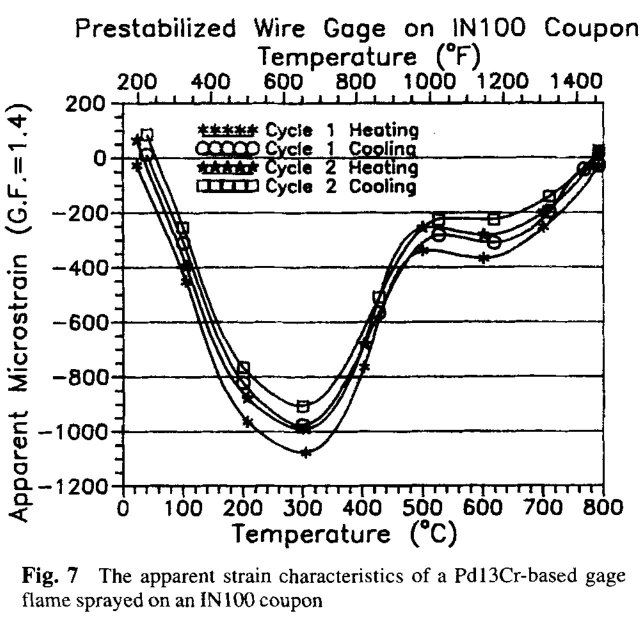

Fig. 7 The apparent strain characteristics of a Pd13Cr-based gage flame sprayed on an IN100 coupon

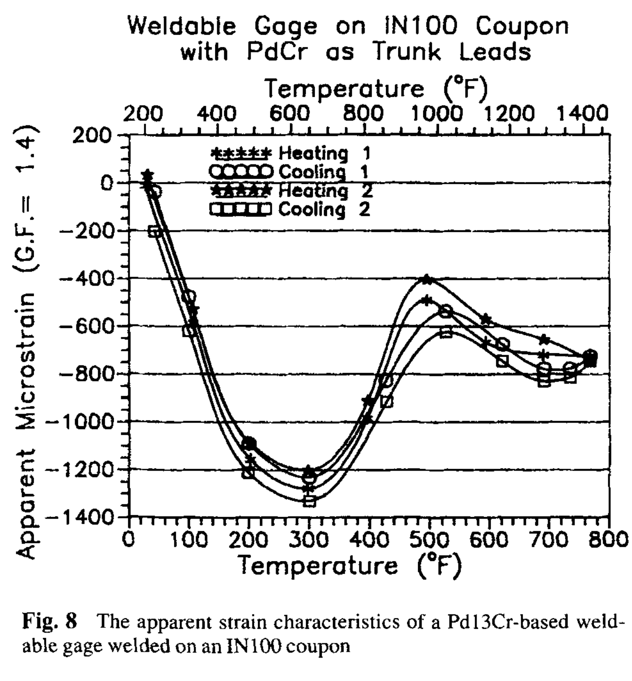

Fig. 8 The apparent strain characteristics of a Pd13Cr-based weldable gage welded on an IN100 coupon

chanical strain. For example, the difference in thermal expansion coefficient between the Hastelloy-X and the TMC produces a compressive mechanical strain of 3600 $\mu\varepsilon$ when they are heated to 650 °C (1200 °F). This Pd13Cr-based weldable gage with a width of 4 mm (0.16 in.) has a critical strain for buckling of approximately 8000 $\mu\varepsilon$ and therefore can survive to a much higher temperature without delamination.

7. Conclusions

A Pd13Cr/Pt temperature-compensated strain gage has been developed for high temperature static strain measurements. It is unique in that its apparent strain and drift strain can be corrected to within a reasonable error on all substrate materials. The flame-sprayed wire gage, both free-filament gage and weldable gage, is usable for static strain measurements up to 800 °C (1470 °F). The weldable gage is suitable for field applications where the flame-spraying installation cannot be directly applied. The performance of this gage, however, depends strongly on the installation technique. Care must be taken during each step of the installation process to ensure an optimal strain gage assembly. A statistical database for the Pd13Cr-based resistance strain gage will be established in the near future.

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