Preparation and evaluation of PdCr thin film resistive strain gauges

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Abstract. Thin film resistive strain gauges using PdCr alloy as sensing material were fabricated on nickel-based alloy substrate, and evaluated for strain response, apparent strain and drift strain over a temperature range to 800 °C. The results indicated that the PdCr thin film strain gauge showed an excellent linear response to applied strain and stable gauge factor at different temperatures. The apparent strain can be estimated and compensated due to its repeatability and low value. The drift strain can be neglected until 600 °C. Even at 800 °C the drift strain can also be corrected since it drifted slightly and linearly. The repeatability of PdCr thin film strain gauge was also evaluated. It showed that the repeatable measurement error was 6.4%.

1. Introduction

The engine blades which work in harsh environment of high temperature, heat stress and strong vibration will appear fatigue cracks, lost blocks and other phenomena with the use of time, and thus cause engine failure. In order to meet the needs of the growing demand, the research on more performance of equipment, such as stress, strain, vibration and other mechanical parameters, is urgently needed.

Advanced thin film sensors, which are sputter deposited directly onto the surface of heating components, have thickness on the order of a few micrometers; therefore, they leave intact the surface structural integrity and add negligible mass to the surface and create minimal disturbance of the gas flow over the surface[1]. Thin film strain gauge can provide more effective method of accurate strain and other mechanical parameter measurement at high temperature environment for engine turbine blades and other heating components.

PdCr[2,3] is structurally stable, undergoes no phase transformation or order-disorder transition over temperature range up to 1100 °C, and it forms an adherent, self-protective Cr2O3 scale in air[4]. All these properties of PdCr result in repeatable, stable resistance versus temperature relationship which is independent of heating and the cooling rates. As sensing material of thin film strain gauge, the
palladium-13w/o chromium alloy (Pd-13Cr) was regarded to be the optimum composition. The alloy of this composition has a lower temperature coefficient of resistance (TCR) than alloys containing less than 13% weight Cr, while alloys with more than 13% weight Cr have poorer resistance to oxidation [5].

2. Experimental

PdCr thin film strain gauges were fabricated on Nickel-alloy (GH3536) flat bar specimens. The test bars were polished with an appropriate degreaser, and then were cleaned by ultrasonic agitation in a bath of acetone, alcohol and deionized (DI) water until the polished surfaces passed the water break test. A NiCrAlY layer was then deposited by sputtering with a thickness of approximately 15 μm. By heating treatment in vacuum and following oxygen atmosphere, on surface of this coating a “graded buffer layer” formed a stable and adherent electrically insulating Al₂O₃ layer. Next, YSZ and Al₂O₃ were deposited as “composite insulation layer” with a thickness of 1μm and 5μm to obtain the required insulation resistance, respectively. The PdCr sensitive thin film was sputtered onto the insulating layer with a controlled resistance and thickness. Finally, the gauges were covered with an Al₂O₃ overcoat to reduce the possible oxidation, followed by vacuum heating treatment for stabilization at 800 °C for 2 hours. The leadwires of platinum (Pt) wire with 100 μm in diameter were connected to each of the two gauge lead pads by high temperature conductive silver paste for tests. Figure 1 shows a sample of PdCr thin film resistive strain gauge on flat bar specimen.

![Figure 1](image)

**Figure 1.** A sample of PdCr thin film resistive strain gauge on flat bar specimen.

The strain-resistance response tests of prepared gauges were performed in Zwick/Roell-Z050 material testing system by step-by-step loading at different temperatures. The applied strain to flat bar was determined by laser extensometer with a resolution of 0.11 μm; and the resistance and temperature of the thin film gauges were acquired through a HBM QuantumX MX840B amplifier. Four-wire measurement of resistance was used to minimize the lead wires effect. During test, all parameters were recorded by a computer, simultaneously.

The gauge factor (GF) of PdCr thin film resistive strain gauge, which is determined by measuring the fractional change in resistance at applied strain, can be expressed as [1]

\[ GF = \frac{\Delta R}{\varepsilon R_0} \]  \hspace{1cm} (1)

where, \( \Delta R \) is the change in gauge resistance; \( R_0 \) is unstrained resistance of strain-sensing element; and \( \varepsilon \) is applied strain.

For elevated temperatures, the gauge resistance changes with temperature \( T \) and with time \( \tau \) at high temperature, and the measured strain \( \varepsilon_m \) results from true strain, apparent strain, and drift strain, expressed as

\[ \varepsilon_m = \varepsilon_t + \varepsilon_a + \varepsilon_d \]  \hspace{1cm} (2)

where \( \varepsilon_t \) is true strain, \( \varepsilon_a \) apparent strain, and \( \varepsilon_d \) drift strain.
The apparent strain, due to temperature change and thermal mismatch rather than applied strain is described by the following equation:

\[ \varepsilon_a = \frac{\Delta R_T / R_0}{G_{FT}} \]  

(3)

And drift strain, caused by the resistance change of the sensing material during holding time at elevated temperature, is defined by:

\[ \varepsilon_d = \frac{\Delta R_{T,T} / R_T}{G_{FT}} \]  

(4)

In the equations, \( R_0 \) and \( R_T \) are unstrained resistance of gauge resistance at room temperature and temperature \( T \), respectively, and \( \Delta R_T \) is their difference as \( R_T - R_0 \); \( \Delta R_{T,T} \) is the drift of unstrained resistance during holding time at temperature \( T \), and \( G_{FT} \) is the gauge factor at temperature \( T \).

For strain gauge system, careful attention must be given to minimize or compensate the apparent strain and drift strain to obtain applied true strain. In this work, the apparent strain and drift strain of PdCr thin film resistive gauge was experimentally evaluated.

3. Results and Discussion

The strain-resistance response for PdCr thin film strain gauge at room temperature is presented in figure 2. Figure 2(a) shows the applied strain and the corresponding resistance value versus loading time. Note that the trends of the two curves were exactly the same. The step-by-step applied strain results in the step change of gauge resistance. Figure 2(b) presents the change in relative resistance versus applied strain during the test. As can we seen, the relationship between the variation of resistance and strain was linear and positive, from which the gauge factor can be obtained to be 1.41 according to formula (1).

![Figure 2](image-url)

Figure 2. The strain-resistance response for PdCr thin film strain gauge at room temperature. (a) The strain and corresponding resistance versus loading time; (b) The relative change in resistance versus applied strain.

After the room temperature test, the PdCr thin film strain gauge was subjected to elevated temperature tests at 600 °C and 800 °C, respectively. For each circle of tests, the specimen was first cooled down to room temperature to evaluate repeatability, then raised to next target temperature for test.

The test results for 600 °C were shown in figure 3. Although the obvious fluctuations of resistance, the step change can be clearly observed. Resistance variations were less than 0.02 \( \Omega \), resulting in a
error of ±50 με. The linear curve of the resistance change with applied strain was presented in figure 3 (b), the gauge factor is fitted to be 1.55.

Figure 3. The strain-resistance response for PdCr thin film strain gauge at 600 °C. (a) The strain and corresponding resistance versus loading time; (b) The relative change in resistance versus applied strain.

The apparent strain and drift strain of PdCr thin film strain gauge can be determined by heating and soaking the gauge in high temperature environment. The curve of the resistance with heating and holding time for 600 °C was presented in figure 4, as well as the resistance as a function of temperature showed in the inset, from which we can see that the resistance increased linearly with temperature. The apparent strain sensitivity, defined as \( \frac{\Delta \varepsilon}{\Delta T} \), was 115 με/°C. The drift strain of PdCr thin film gauge at 400 °C can be neglected since the resistance remained almost unchanged at holding stage.

Figure 4. The resistance changes of the PdCr gauge heating up to and soaking at 600 °C.

Figure 5 presented the results of the PdCr thin film strain gauge tested at 800 °C. It was observed from figure 5(a) that the variation in resistance was significantly increased to 0.05 Ω, about an error of ±100 με. This error is believed to be acceptable in 800 °C harsh environment. The increased fluctuations of resistance might be attributed to the thermal noise of the electronic motion in high temperature environment. From figure 5(b), the gauge factor of PdCr strain gauge at 800 °C was determined to be 1.41.
Figure 5. The strain-resistance response for PdCr thin film strain gauge at 800 °C. (a) The strain and corresponding resistance versus loading time; (b) The relative change in resistance versus applied strain.

The heating and holding curve of PdCr thin film strain gauge for 800 °C was presented in figure 6. The linear resistance change with temperature at heating phase suggested that the apparent strain sensitivity remained constant, which was found to be 127με/°C. The resistance drift of the gauge at 800 °C during 4 hours soak was recorded to decrease about 1.1 Ω. Notice that the resistance drifts slightly and linearly, indicating no serious oxidation in PdCr thin film at 800 °C. The results show that PdCr thin film remains stable at high temperature. According to equation (4), the drift strain is 1800 με/hr at 800 °C. Since the resistance of PdCr thin film strain gauge decrease linearly with time, the drift strain can be easily corrected.

Figure 6. The resistance change of the PdCr gauge heating up to and soaking at 800 °C.

The repeatability of prepared PdCr thin film strain gauges was evaluated simultaneously. The room temperature test results after cooling down from 600 °C and 800 °C, respectively, were presented in figure 7. The results indicated that the resistance change of the PdCr thin film gauge remains linear under applied strain after several high temperature tests. However, the calculated gauge factor was decreased from original 1.41 at room temperature to 1.34 and 1.32, respectively. That is, the repeatable error after several high temperature tests was 6.4%. And the total lifetime of the PdCr gauge was more than 10 hours.
Figure 7. The repeatability of PdCr thin film strain gauge.

(a) cooled down from 600°C; (b) cooled down from 800°C.

4. Conclusion

High temperature thin film resistive strain gauges using PdCr alloy as sensing material were fabricated on nickel-based alloy substrate. The test results showed that the PdCr thin film strain gauge had an excellent linear response to applied strain and stable gauge factor at different temperatures, as well as repeatable low apparent strain and neglectable, correctable drift strain. The repeatability and lifetime of PdCr thin film strain gauge were also evaluated by several thermal circles at different temperatures. It showed that the repeatable measurement error was 6.4% at different circles, and lifetime was over 10 hours.

Reference

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