High Temperature Strain Measurements Using Fiber Optic Sensors

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ABSTRACT

Strain gage measurements at elevated temperatures (> 350 C) is a complicated problem. In particular, the effects of temperature on gage electrical properties and the ability to monitor static and dynamic strains simultaneously while compensating for thermal apparent strain have posed great difficulty. In this paper, a fiber optic strain gage sensor is used to measure both the static and dynamic strain on a test sample in excess of 400 C. Issues regarding experimental set-up, fiber optic gage bonding and signal conditioning are addressed.

INTRODUCTION

In many applications, strain measurements are to be performed at high temperatures. Conventional gages are typically rated to 350 C and are limited to bonding methods as well as thermally induced errors. In many cases, the desired temperature range can be in excess of 500 C. Alternate methods do exist for capturing strain at such high temperatures, but each has its own limitations.

The operation of conventional electric resistance strain gages is well established for temperatures below 350 C. Although thermal effects can significantly alter performance in this temperature range, methods for compensation are well known. These will be described in more detail later in this paper. The main problem with conventional gages lies at temperatures above 350 C. At these temperatures, problems associated with bonding, gage backing durability, and changes of electrical properties with temperature become very significant.

Free filament gages, which are effectively an un-backed gage bonded with a ceramic-based cement, have been used to overcome many of the high temperature strain issues [1]. They have been used in many applications at temperatures above 650 C. Although this type of gage can capture dynamic strains very well at high temperatures, difficulties exist for measurement of steady state strains.

Optical methods have also been utilized to measure strain at high temperatures [2-4]. The optical methods offer the advantage of being a non-contact method and in some cases, show the whole strain field rather than the strain at a single point. A primary disadvantage for most of the non-contact optical methods however, is poor dynamic performance and a lack of ruggedness. Typically, methods such as ESPI and Digital Image Correlation use CCD image capturing and processing, so dynamic performance is usually dictated by the frame rate of the acquisition system. Furthermore, they require a direct line of sight and are often not rugged enough for industrial environments.

Fiber optic based sensors offer an alternative to the methods mentioned above. Commercially available fiber optic strain gages are small and quite durable. The sensor signals are transmitted via a fiber optic line, therefore they are immune to electro-magnetic noise. Additionally, since the strain measurement is based on the modulation of an optical signal, the physical properties of the gage are unaffected by temperature - as the case of the electric resistance gage.

In this paper, the use of fiber optic gages to capture both dynamic and static strain at temperatures above 300 C is shown. The first part of the paper will address thermal issues associated with conventional strain gages. Then an explanation of the operating principal of an Extrinsic Fabry-Perot Interferometer (EFPI) fiber optic gage is presented followed by the experimental work that was performed for this paper. Finally, conclusions are discussed as well as potential future work.
HIGH TEMPERATURE STRAIN MEASUREMENTS WITH CONVENTIONAL STRAIN GAGES

It is commonly known that conventional, electrical resistance-based strain gages are susceptible to errors associated with thermal effects[1,5]. The two primary factors that cause this error in the strain reading are the temperature-induced apparent strain and the gage factor variation that occurs with temperature. If not accounted for, both of these phenomena can create vary large errors in the actual strain reading. Great efforts have been made in compensating for these effects over typical operating ranges. At higher temperatures however, these effects are more pronounced and more difficult to correct.

Temperature-Induced Apparent Strain
This apparent strain produced by a strain gage is caused by two factors. The first is the fact that the electrical resistance of the gage is temperature dependent. Secondly, differences in the thermal expansion coefficients between the gage grid and the substrate material creates a thermal expansion mismatch. A change in temperature will cause the specimen and gage grid to expand or contract differently and thus create a strain reading that is independent of the mechanically induced strain. The combination of these two strain effects can be expressed as the resistance change as:

\[
\frac{\Delta R}{R_0} = \beta_G \Delta T + \left[ F_G \left(1 + \frac{K_t}{1 - \zeta_o K_t}\right) \alpha_S - \alpha_G \right] \Delta T
\]  

(1)

\( R \) refers to resistance of the gage, \( K \) is the sensitivity of the gage, \( F \) is the gage factor, \( T \) is temperature, and subscripts \( S \) and \( G \) refer to the substrate and the gage respectively. The first term of the equation represents the change in resistance due to temperature and the second term is the resistance change due to CTE mismatch.

Gage Factor Variation with Temperature
The gage factor that is given with a conventional resistance strain gage is used to convert the electrical signal from the gage to strain units. In a quarter bridge configuration, for example, the strain is related to the bridge output as:

\[
\varepsilon = \frac{4V_{\text{signal}}}{FV_{\text{supply}}}
\]

(2)

where \( \varepsilon \) is the strain, \( V_{\text{signal}} \) are the bridge voltages and \( F \) is the gage factor.

The various metallic alloys used in strain gages typically show some variation of the gage factor with temperature. The variations for the various alloys have been well documented at standard temperatures (-100 to 500 F) and in many cases, are small enough to be ignored. At high temperatures however, these factors can become significant.

Correction of Temperature Induced Errors
A variety of methods have been developed to correct for the temperature induced apparent strain and the gage factor variation with temperature [1,5]. One particular method is the use of a compensating or "dummy" gage in the Wheatstone bridge circuit. The compensating gage is placed in an unstrained region and subjected to the same temperatures as the active gage. The compensating gage then sees the same thermal effects as the active gage, but they are subtracted by the Wheatstone bridge circuit. The disadvantages lie primarily in maintaining identical temperature conditions between the gages and ensuring that the compensation gage experiences no mechanical strain. In practice this can be difficult to achieve.

Self-Temperature-Compensated strain gages are metallurgically matched to the specimen material. Over a particular temperature range these gages will exhibit very little thermal output variation. At high temperatures however, the self-temperature-compensation relation is not valid and the thermal output can be very large.

Finally, another method of handling the thermal output is to use thermal calibration data. This data is usually provided by the gage supplier and gives the relationship between the apparent strain due to thermal effects and the temperature. If the temperature of the gage is known, then the corresponding apparent strain is subtracted from the strain reading. Again, this is usually only given for particular temperature ranges which do not include the high temperatures ranges that we are interested in.
OPERATING PRINCIPLE OF EFPI FIBER OPTIC STRAIN GAGES
A Fabry-Perot based sensor consists of a glass capillary that contains two partially reflective mirrors that form a Fabry-Perot cavity (Figure 1). When a broadband light source is brought into the cavity via an optical fiber, the resulting frequency spectrum is given by

\[ I(\lambda) = \frac{(1 - R)^2}{(1 - R)^2 + 4R \sin^2\left(\frac{\delta}{2}\right)} \]  

(3)

Where

\[ \frac{\delta}{2} = \lambda d \cos(\theta) \]  

(4)

In Equation (1), \( D \) is the mirror separation, \( R \) is the mirror reflectivity and \( \theta \) is the angle between the mirrors. For the case of the fiber optic strain gage, the ends of the fibers act as the mirrors and the angle approaches zero.

Equation 1 shows that the frequency spectrum is dependent on the gap between the two mirrors. Therefore the separation of the mirrors can be determined from the frequency spectrum of the light coming from the Fabry-Perot cavity. Several methods for determining the frequency of the content of the output light are available. One method is spectral interrogation which analyzes the spectral power as a function of wavelength. Using signal processing methods, the cavity length can be determined absolutely [ref XX].

An alternate method involves passing the frequency modulated light through a low angle prism that is mounted to a linear CCD detector. The prism acts as a cross-correlator on the frequency modulated light. This creates a maximum transmission onto the CCD that occurs at a prism thickness that corresponds to the cavity length \([\] \). This is the method used for the research in this paper.

![Figure 1. Typical geometry of a Fabry-Perot based strain gage (Used with permission of Fiso Technologies, Inc).](image)
EXPERIMENT

To perform the testing of the components at high temperature (up to 315 °C), steel tensile test specimens were created and a single EFPI fiber optic strain gage was mounted to the specimen as shown in Figure 3. The active axis of the fiber was placed in the direction of the tensile load. The fiber optic gage was mounted to the specimen using high temperature ceramic adhesives in a manner similar to that used in free-filament gages. Although fiber optic gages are available with temperature compensation options that are material dependent, temperature compensation was not used. This was chosen so that the thermally induced strain could be detected in the specimen. Effectively, this is monitoring the apparent temperature-induced strain. Since the sensor is glass, the gage thermal expansion is very small (~0.5 x 10^-6 per °C). Temperature monitoring was accomplished by a thermocouple welded to the specimen next to the fiber optic gage.

It was desired to provide both a mechanical load and a thermal load to the specimen simultaneously. Mechanical load was provided by a 98 KN MTS load frame utilizing load control. A focused infrared heater was used to provide localized heat to the strain gaged specimen. For the size and mass of the specimen, the heater was able to heat the specimen to temperatures of 450 °C.

Two tests were performed on the specimens. The first test was to evaluate the performance of the fiber optic strain gage for temperature induced strain alone. The specimen was placed under a slight tensile load and heat was applied. Strain data was acquired and monitored while the temperature of the specimen increased from an ambient temperature of 27 °C to 413 °C. Results of this test are shown in Figure 4.

As indicated in the plot, the strain of the fiber optic gage follows the first order response that is typical for heating. The strain values represent the specimen strain due purely to thermal effects. The maximum strain indicated by the fiber optic gage at 417 °C was 3937 microstrain. To calculate the theoretical thermally induced strain, the equation for thermal expansion was used.
\[ \frac{\Delta l}{L} = \varepsilon = \alpha \Delta T \]  

(5)

For this relation, \( \alpha \) is the coefficient of thermal expansion, \( \Delta T \) is the change in temperature and \( \varepsilon \) is the strain.

Assuming a thermal expansion coefficient for steel of 10 x 10^{-6} per C Equation 5 gives a theoretical thermal strain of 4130 microstrain. This 5% difference from the experimental value can be attributed to the expansion of the glass in the strain gage.

A second experiment was conducted to evaluate the performance of the fiber optic gage to record both the static, high temperature strain component as well as the dynamic mechanical component. Many practical applications exhibit this type of behavior and it is often desired to capture both components simultaneously. To simulate this behavior, the same specimen was again loaded in the MTS load frame. A 6000 lb static load was applied to the specimen and the fiber optic strain gage was zeroed. The specimen was heated and allowed to reach a steady state temperature of 343 C. An alternating mechanical load of ±4448 Newtons at 2 Hz was then applied and the data was recorded. Figure 5 shows these results.

Figure 3. Photograph of tensile test specimen fixture, fiber optic strain gage location and thermocouple location.

Figure 4. Plot showing thermal strain for a fiber optic strain gage mounted to steel specimen during heating from 27 C to 413 C. The red line indicates the theoretical thermal strain for the specimen at 413 C.
The theoretical strain value was calculated by combining the theoretical thermal strain with the theoretical mechanical strain. The thermal strain was expressed by Equation (5). The amplitude of the mechanically induced strain component for a flat bar specimen under tensile load is

\[ \varepsilon = \frac{P}{AE} \]  

(6)

where \( P \) is the applied load, \( A \) is the cross sectional area and \( E \) is Young’s modulus.

For a sinusoidal loading of the bar, the mechanical strain is

\[ \varepsilon_M = \frac{P}{AE} \sin(2\pi f) \]  

(7)

Where \( P \) is the load amplitude and \( f \) is the frequency. Thus the total strain from both the mechanical loading and the thermal loading is

\[ \varepsilon_{M+T} = \frac{P}{AE} \sin(2\pi f) + \alpha \Delta T \]  

(8)

For the results shown in Figure 5, the experimental peak-to-peak strain amplitude of 250 microstrain matches the theoretical strain amplitude of 254 microstrain very well. The DC offset of both plots represent the thermally induced strain. As in the static test, a 5% offset is present. Again, this is most likely due a mismatch of the coefficients of thermal expansion between the gage and the specimen.

**CONCLUSIONS**

Many applications require the simultaneous measurement of steady state thermally induced strain and dynamic mechanical strain at extreme temperatures. In this paper, a fiber optic strain gage was used to measure both static and dynamic strains in a tensile test specimen at 345 F. This temperature range is beyond the capability of commercial strain gages. Measured strain values compared very well to theoretical results for both the thermal components as well as the mechanical. The primary discrepancy that was noted was a 5% offset in static values that can be attributed to the assumed coefficient of thermal expansion value.
The primary advantage of the fiber optic gage in this case was the simplicity of use and correction of thermal output errors. The strain that was recorded reflected the strain components in the part due to thermal and mechanical inputs. Compensation of the thermal mismatch between the materials was very straightforward and there were no errors due to electrical effects. Further investigations are necessary however, at temperatures that are above the temperatures used in these tests. Additionally, further testing is planned in applications that reflect real world applications.

REFERENCES


