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DEVELOPMENT OF HIGH TEMPERATURE SEMICONDUCOR STRAIN GAGES FOR THERMAL POWER PLANT APPLICATIONS

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ABSTRACT

This paper discusses a specially developed semiconductor strain cell that allows sensitive measurement of surface strain in environments with temperatures up to 1050F (566C). There is an unmet industry-wide need in the manufacturing and power generation fields for monitoring material mechanics and component degradation at temperatures exceeding the maximum working temperature of traditional strain gage technologies. This technology advances attachment methodology of the semiconductor gage to allow field deployment and a physically reliable interface with structural strain. Measuring strain at these temperatures is useful both in the laboratory and in practical monitoring applications. The technology provides a way to monitor changes in materials exposed to heat and stress and give plant engineers tools to predict and avoid critical failures.

INTRODUCTION

Most traditional strain gage technologies are only useful below 500F (260C). Even in moderate temperature regimes below 300F (149C) they progressively lose sensitivity and suffer creep related measurement errors with increased temperature. While there are some current methods of measuring strain at higher temperatures, these methods are limited in how well they are able to measure strain in harsh environmental conditions. Contemporary high temperature strain measurement such as capacitive or wire gage is also physically large and can be too delicate for long term field measurements. The proposed strain cell in this research incorporates reinforced ceramics and specially fabricated semiconductor strain gages to allow operation at temperatures as high as 1050F (566C) while maintaining continuity with the substrate material. The resulting strain cell is a mechanically continuous block which can resist abusive conditions better than alternate gage technologies. This novel approach has performed well in early tests and theoretical material limits show very compelling evidence to further develop this new technology up to temperatures in excess of 1500F (815C).

Areas that could benefit from this technology include critical assets containing weldments or load bearing elements in high temperature locations. Examples include power generation boilers and steam pipe systems. The absence of continual monitoring in these structures presents a risk of considerable facility loss and personnel hazard. Several historical incidents resulting in complete or partial facility loss highlight the urgency of this area of research. High temperature surface strain monitoring applications have been limited to traditional capacitive or wire gages which suffer from limited mechanical bandwidth, a low sensitivity, and installation challenges. The lack of sensitivity severely limits traditional gage technologies for early prognosis of structural issues and results in late stage detection of events. Furthermore, contemporary gage technologies have issues surviving field environments, preventing the application of online nondestructive evaluation (NDE) and strain monitoring implementations.

Initial experiments initiated by EPRI have shown stable strain measurement performance and were able to measure strain and withstand elevated temperatures without degradation in excess of 3000 hours.

STRAIN CELL DESIGN

The high temperature strain cell discussed in this paper has several features that are specifically designed to accommodate installation, environmental survival, and online monitoring. The first feature is a new ceramic-metal interface approach. The interface approach is a transitional matrix from isotropic metal to aggregate ceramic. This is achieved through a transition into a porous sintered metal medium that uptakes ceramic material and provides a mechanical interlock with the ceramic. Due to the quasi-random mechanical interlock, this interface is observed to be superior to ceramic-metal oxide bonding alone and has demonstrated the ability to withstand temperature changes while maintaining stable measurements. The mechanical design discussed in this work is built from sintered stainless steel laser welded to a solid stainless steel platform (e.g. shim, carrier). The sintered porous metal is infused with a ceramic aggregate material. Cast within the metal-bound ceramic is a bridge of P-doped (boron) silicon semiconductor strain gages.

The second feature of the strain cell is modular construction of the cell that allows lead wire interconnects to be made reliably to larger breakout studs embedded in a structural ceramic. These breakouts are appropriate for signal line attachment and relieve the sensor of cable related strains that may otherwise distort measurements.

A third feature addresses field installation practicality with the assembly construction of the cell upon a carrier shim of parent material. This shim is weldable by common techniques such as TIG or stick welding, which are appropriate and accessible methods for boiler site work.

A fourth feature is the fabrication process of the semiconductor strain gage itself. The plate-up process for the gage is unique as well as lead wire bonding techniques that prevent the use of gold in contact with the silicon metal. This is required for survival of the gage at temperatures above the eutectic point of Si-Au binary phase system.

Materials for High Temperature Strain Cell

Potassium Silicate is a family of inorganic compounds. The most common potassium silicate has the formula K_2SiO_3, samples of which contain varying amounts of molecularly bound water [1].

Potassium silicate solutions are industrially synthesized by treating silica with potassium hydroxide, as shown in Eq. 1.

$$n\,SiO_2 + 2\,KOH \rightarrow K_2O \cdot n\,SiO_2 + H_2O \qquad (1)$$

These solutions are highly alkaline liquids which are useful on their own as coatings and adhesives. For this development, they are mixed with metal oxide fillers (e.g. aluminum oxide) to give strength to the resultant material as an aggregate. The silicate solution loses a large portion of its water through evaporation to form fragile and hydrophilic films. Water molecules remain bound to the molecular structure after this initial evaporation and must be driven off through the use of heat (>500F [260C]) to form hard, pH neutral and water resistant ceramic films. The basic monomer of these films is K_2SiO_3 which adopts a chain or cyclic structures with interlinked SiO_3 monomers, as shown in Fig.1.

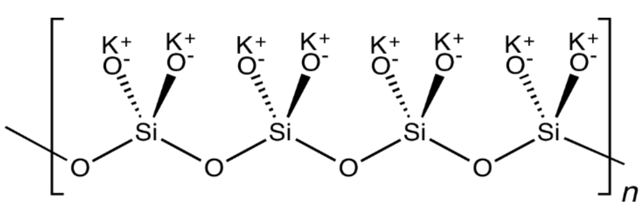

FIGURE 1. CERAMIC FILM STRUCTURE

The interlinking of these long chains surrounding hard oxide aggregate form a hard porcelain-like material that is excellent for strain transfer. The resulting aggregate is resistant to crack propagation due to the aggregate particles interrupting crack formation and evolution in the material. Potassium silicate also has good adhesive properties to metals and metal oxides. Specifically, the silicate compound joins ionically to metal oxide layers.

Porous Sintered Stainless Steel is used in a unique approach and is introduced as a material for the purpose of making a distributed joint with the ceramic aggregate. Partial density stainless is known as a filtration medium which is manufactured by powdered metallurgy techniques.

For this application, the thermal expansion difference between the ceramic and the base metal (stainless steels) is sufficiently large that simple adhesive bonding between silicate and flat solid metal surface is at risk for shear failure. To overcome this risk, the choice was made to not rely on adhesion. Instead, mechanical interlocking of the silicate around parts is used to transfer strain. Because of the distributed mechanical interlocking, chemical adhesion between the ceramic and sintered metal is not required to ensure the transfer of strain. The potassium silicate is drawn into a porous matrix of stainless steel and hardens around the metal filaments. The strain propagates through the disc and physically deforms the ceramic mortar in which the gages are cast. The gages also have a “dog bone” shape conducive to this mechanical transfer of strain that does not rely on adhesion as is the case with traditional gaging practices. Although SiO2 coating the gage surface does bond to silicate, this again is not a dependency for continuity of the strain.

As temperature increases the volumetric expansion of the metals (both porous stainless and silicon gages) is greater than the expected thermal expansion from the mortar. This puts the mortar within the porous metal into a desirable state of mechanical compression.

In addition to being a good material for strain transfer, the potassium silicate mortar has other properties necessary for our purpose. It is electrically insulating which is mandatory for the gage bridge to work since it functions by changes in resistance. The silicate mortar also has a high operating temperature (>1400F [760C]) and does not go through a progressive softening as the temperature rises. Rather, it retains its hardness until it reaches the point of liquefication (the transition happens in a narrow temperature range). After proper curing it is chemically stable and exhibits no changes related to heat aging, oxidation, or other forms of temperature related degradation.

Manufacturing Process

The process begins with a stainless steel shim with three machined holes as demonstrated in Fig. 2. One hole is in the center and is a slip fit for a sintered disc. Two small holes are tapped for machine screws. The thickness of this shim is chosen to be structurally capable of field welding and handling. This shim is the carrier for the gage cell assembly.

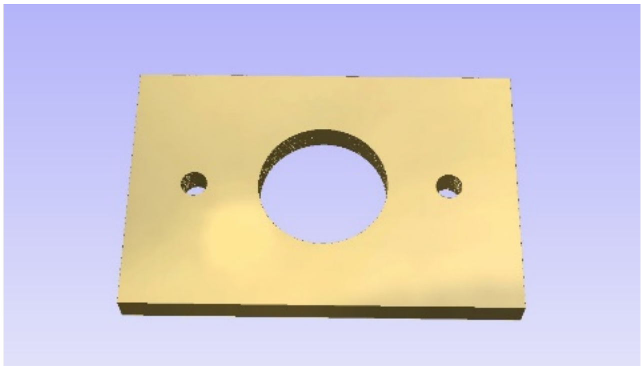

FIGURE 2. STAINLESS STEEL SHIM

The sintered disk is welded into the center hole in the shim. The preferred method of welding is with a laser welder due to the porosity of the sintered disk. Filler rod is introduced to the weld to take up volume in the disk. While other welding methods may work, laser welding introduces less heat to the metal and, as a result, has less of a chance of damaging the sintered disk. The disk is welded around its circumference to provide symmetrical strain transfer. In order to create an electrical insulating layer for gage mounting in later steps, the sintered disc is recessed below the surface of the shim. This is demonstrated in Fig. 3. The unit is heated to 1000F (538C) to grow an oxide layer on the stainless steel to enhance silicate bonding. It is allowed to cool to room temperature.

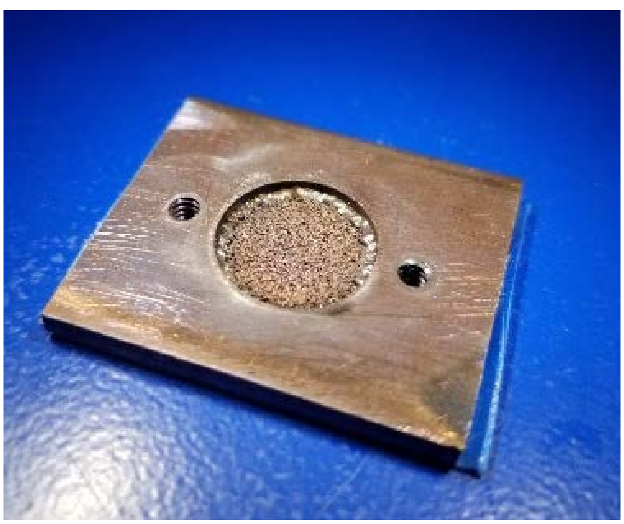

FIGURE 3. STAINLESS STEEL SHIM WITH WELDED SINTERED DISC

Silicate mortar is drawn through the sintered disc using a vacuum applied to the rear side of the shim. The ceramic aggregate is distributed into and through the sintered disk. An excess of mortar is applied to the part so there is a small mound that protrudes above the surface of the shim. This excess ensures that there is a flat surface across the porous area once the unit is lapped. The silicate is cured in stages to reject water from the silicate matrix. This initial cure stage occurs below 500F (260C) so that the ceramic is hardened, but remains “green” and can accept secondary bonding to the strain gages. The green ceramic is planed flat on a diamond lapping plate to remove excess mortar and create a flat surface upon which the strain gages can be mounted.

Gages are mounted with a small amount of the same silicate mortar used to infuse the sintered disc. This forms a Wheatstone bridge on the surface of the structure with lead wires exposed for subsequent connection.

The mortar used to apply the strain gages bonds to the ceramic that has infused the porous metal disk. Chemical continuity of the silicate joins the planed surface to the new silicate surrounding the gages. The gages are mechanically entombed in the mortar, making a continuous structure. The resulting gage is shown in Fig. 4. The mounted gages and cell is allowed to dry at room temperature then cured to 1000F (538C) in a series of water rejection steps and slowly cooled to room temperature.

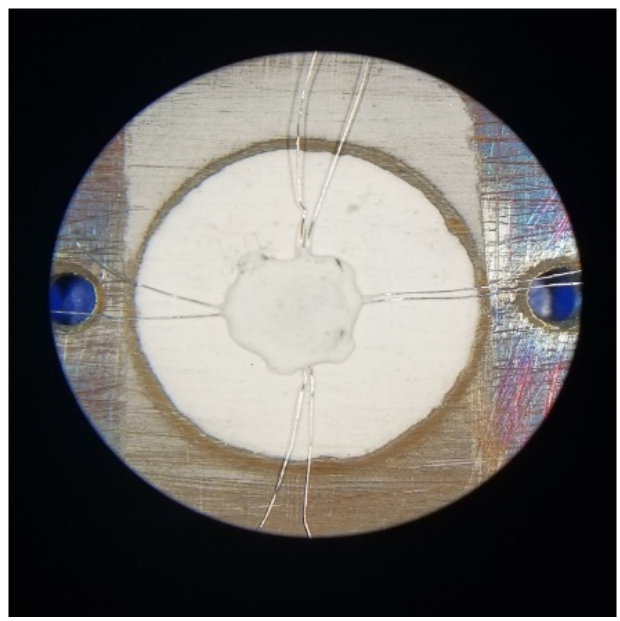

FIGURE 4. ASSEMBLED STRAIN GAGE

The shape of the gages creates a mechanical lock with the mortar to transfer strain independent of adhesion. For comparison, the mechanical shape of a common semiconductor bar style strain gage is shown in Fig. 5. The ends of the gage contain the pad and interconnect. Adhesive bonding of this type of semiconductor gage generally does not perform well at elevated temperatures.

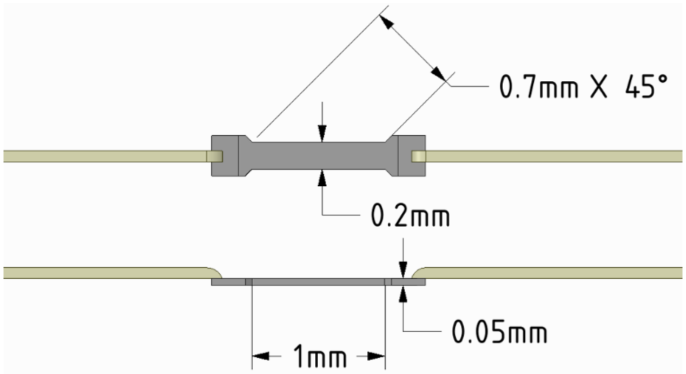

FIGURE 5. COMMON SEMICONDUCTOR BAR STYLE STRAIN GAGE

Breakout Terminal Block

To attach signal leads to the strain cell structure, a terminal block is fabricated from machinable ceramic. The ceramic circuit terminal block is mounted to the cell with small machine screws. The strain gage lead wires are laser welded to the terminals of the ceramic board.

The breakout board structure allows for larger more rugged conductors to carry the signal to a location of data acquisition. The strain gage lead wires are terminated locally and protected within the ceramic block. The fabricated strain cell is shown in Fig. 6.

FIGURE 6. STRAIN GAGE TERMINAL BLOCK

LABORATORY TESTING

Testing at 1000F (538C)

Two separate long-term isothermal tests were performed on the strain cells to observe longevity and potential measurement drift when subjected to strain. In both cases, the cells showed stable behavior at temperatures up to 1000F (538C). The first test was engineered to study drift and stability and the second test for validating strain response at temperature.

Test 1: Isothermal Block

A 2” x 2” x 4” (5cm x 5cm x 10cm) 17-4 PH stainless steel block was prepared with a cartridge heater to replicate an internal temperature source. A hole was drilled for a thermocouple to regulate this temperature from within the block. On the upper surface of the block, a high temperature strain cell was welded. The assembly was placed into a highly insulated container with a mica window and brought up to 1000F (538C). The strain gage element resistance was recorded for 4 months (3000 hours). The gages exhibited expected temperature coefficient of resistance at the beginning of the test as a result of the assembly coming up to temperature. After the controller reached regulation the resistance settled and became constant with the exception of a very slight variation as the heating cartridges cycled on and off to maintain temperature. This was expected and was an indication throughout the test that the cell was operating and that strain due to thermal differential expansion was being measured. A number of times during the test the blocks were allowed to cool and the resistance returned to the initial resistance measured at the beginning of the test. This showed that the silicate mortar maintains continuity with the porous disk under thermal cycling and extended periods at high temperature. The isothermal block testing assembly is shown in Fig. 7. The data from this test is encouraging since both cycling offset consistency and temperature stability are marked challenges with contemporary strain gage technology.

The data collected shows an expected temperature coefficient of resistance during a step change from room temperature to operating temperature at 1000F (538C). The step change is consistent between multiple gages and scales linearly with temperature. This resistance change is a combination of both linear thermal expansion in the material and the piezo resistive temperature coefficient of resistance. This offset behaves in a way that can be compensated by proportional offset to the temperature reading at the gage site.

Figure 8 shows the resistance change of a strain gage on a shim experiencing a step change in temperature. The resistance of the gage shown in ohms follows the step change in temperature and settles out as the control system stabilizes and maintains a constant temperature in the test block.

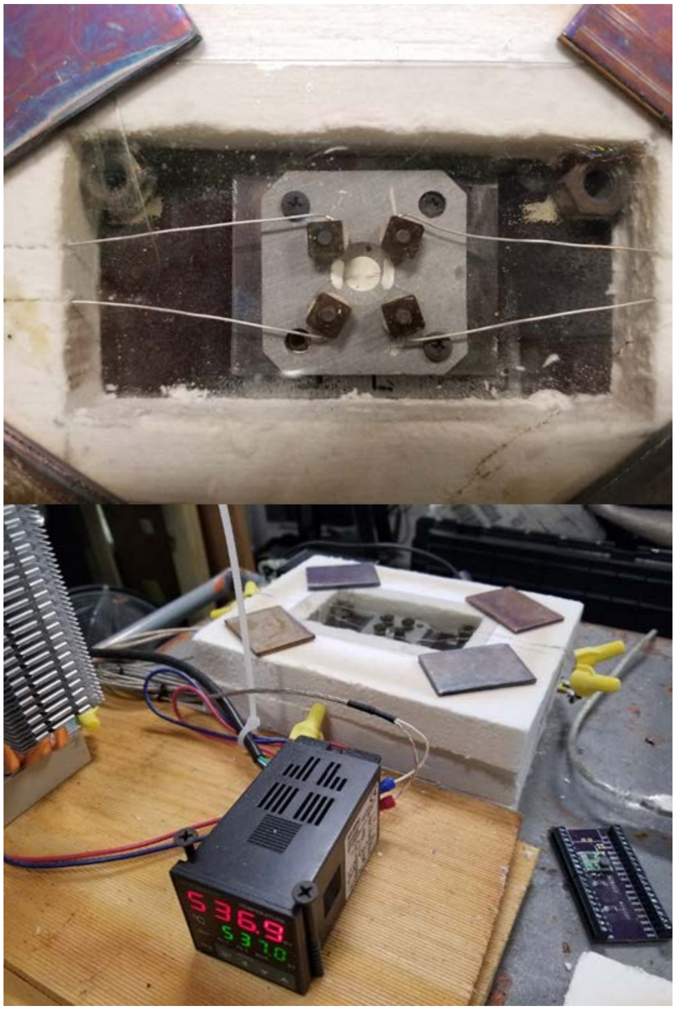

FIGURE 7. ISOTHERMAL BLOCK TESTING

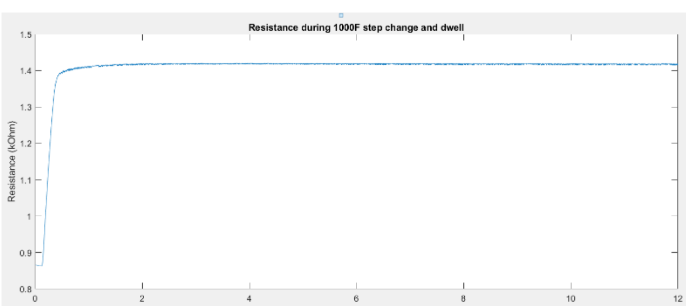

FIGURE 8. RESISTANCE CHANGE OF STRAIN CELL EXPERIENCING STEP CHANGE IN TEMPERATURE

Test 2: Strain Stability and Dynamics Testing

A cantilever beam jig was fabricated from 316 stainless steel and a strain cell was mounted by laser welding to the fixed end of the beam. The cantilever was constructed to demonstrate that the strain cell is stable and does not drift under applied mechanical strains at testing temperatures up to 1050F (566C). The layout of the cantilever beam was designed to mount into an oven for isothermal testing over a period of approximately one month. Figure 9 illustrates the assembled strain cell mounted on a cantilever beam jig.

A weight was placed on the end of the beam and the assembly placed in an oven at the EPRI laboratories in Charlotte, NC. Isothermal testing was conducted at temperatures up to 1050F (566C) for 800 hours. Placement of the cantilever beam jig in the testing furnace is shown in Fig. 10. The insulating structure over the beam prevents direct infrared irradiation of the beam and strain cell by the oven heating elements. Over the duration of the test the initial settling of the gage response held a constant value and the bridge offset was consistent showing offset drift less than 71 PPM (part per million) of full scale.

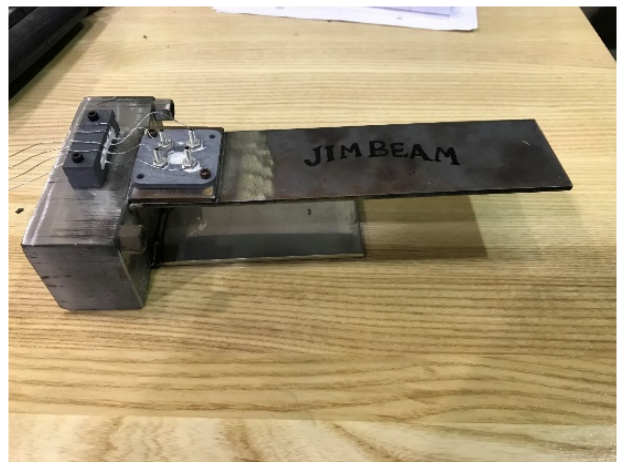

FIGURE 9. CANTILEVER BEAM JIG FOR ISOTHERMAL TESTING

FIGURE 10. CANTILEVER BEAM JIG IN TESTING FURNACE

The intended objective of this isothermal oven test was identifying that the static drift was controlled and the gages continued to respond as expected at the operational temperature. This feature is important for creep related life assessment of high temperature components in fossil power applications. However, an equally interesting outcome was the performance of the dynamic sensing possible with this strain gage cell. The environmental vibration inside the oven was recorded during setup, at which point the technicians were handling the oven controls and the specimen was at room temperature. As shown in Fig. 11, the strain cell did an admirable job recording these spurious inputs and gave an unsolicited yet valuable piece of data regarding dynamic response measurement.

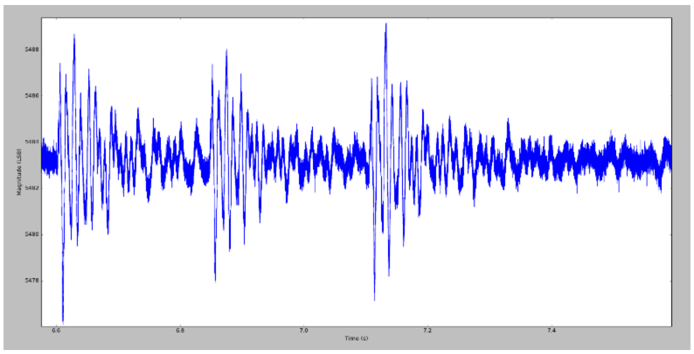

FIGURE 11. EXEMPLAR DYNAMIC RESPONSE FROM STRAIN CELL

At room temperature, the frequency response of the beam shows several modes below 50Hz, which are expected with a simply supported cantilever. Natural frequencies of 16.7Hz, 23.5Hz, 30.5Hz and 43.6Hz were observed from this room temperature data, as captured in Fig. 12. Note that this response is resulting environmental vibration input, without a specified input. This is natural vibration from external movement in the lab.

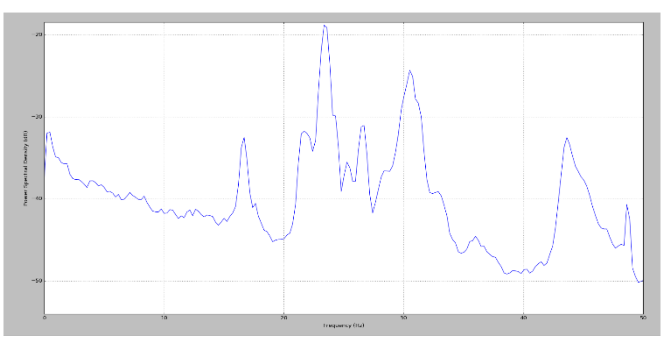

FIGURE 12. NATURAL FREQUENCY RESPONSE ON CANTILEVER BEAM DURING TESTING AT ROOM TEMPERATURE AS MEASURED BY STRAIN CELL

At operating temperature, the same modes were observed when the beam reacted to external stimulus and vibration of the oven rack. This is illustrated in Fig. 13. At the elevated temperatures, frequencies of 12.5, 23.1, 28.5, 43.2 Hz were observed. This is consistent with expected trends of lower material modulus at the higher temperature.

The study of dynamic response from this high temperature gage cell is important moving forward. Tests are planned for applying measured inputs to a cantilever so that repeatable initial conditions excite the modal response and a direct comparison at various temperatures can be conducted.

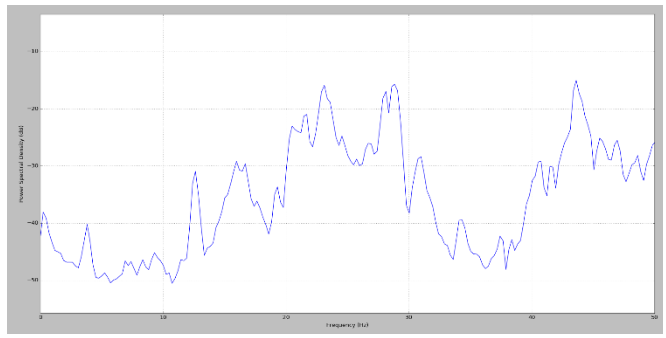

FIGURE 13. NATURAL FREQUENCY RESPONSE ON CANTILEVER BEAM DURING TESTING AT ELEVATED TEMPERATURE AS MEASURED BY STRAIN CELL

FUTURE DEVELOPMENT AND TESTING

Future development will be focused on practical application of this strain cell to measure and quantify structural issues at temperature. Based on the proof of concept, this strain cell design is capable of being used as a source of monitoring data. However, more work should be done in the laboratory to demonstrate the ability to detect changes in a structure. Particularly, more work should be done to explore the potential for dynamic measurements to identify cracks in welds or similar structure damage. It is expected that through the use of frequency analysis that changes in structural stiffness can be estimated through the natural frequency data. Furthermore, multiple strain cells can be used to measure vibration coherence (transfer function) between two gages located on a continuous structure.

The static stability of this gage has potential to be applied for studying creep behavior of high stress components in boiler structures. In particular, EPRI has an interest in quantifying the extent of creep damage from measurements over welds. This data has value to alloys being deployed in ultra-super critical boiler designs.

This gage cell can also be made into an accelerometer, similar to the cantilever behavior observed in the isothermal test experiment. Piezo resistive accelerometers are based on strain gage technology and this strain cell has the potential to be made into an accelerometer design capable of monitoring vibration from high temperature locations.

Another potential application that is being considered is the possible use of this strain cell technology in babbitt casting processes for large journal bearings. The gage cell can survive the temperatures of ~700F (~371C) at which the babbitt is cast into the bearing shell. Such a gage application could be significantly valuable to measure shaft alignment, imbalance, and elastohydrodynamic effects (e.g. whirl, whip, etc) in the oil film of the bearing.

Field monitoring of weldments is a likely next step, beginning with simple structures such as Y-type pipe junctions. The ultimate goal is the monitoring of complex structural weldments such as manifolds and headers. The latter would most likely require a modeling effort or structural failure mode analysis to validate the strain cell placement and monitoring approach.

CONCLUSION

A new type of strain cell technology has been developed and evaluated. The application of semiconductor gages affixed to a metal substrate through the matrix of porous metal and ceramic has overcome technical issues with ceramic to metal adhesion and oxide bonding.

The strain cell technology has been proven to function in the laboratory and exhibits significant potential for use in field data acquisition. Early use of this strain cell technology has validated that it can survive temperatures up to 1050F (566C) while reliably making sensitive measurements. The static and dynamic data this strain cell can produce has many uses in monitoring structural effects that could previously not be measured by practical means.

NOMENCLATURE

EPRI = Electric Power Research Institute
NDE= Nondestructive evaluation

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