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ABSTRACT

Advanced thin film sensors that can provide accurate surface temperature, strain, and heat flux measurements have been developed at NASA Glenn Research Center. These sensors provide minimally intrusive characterization of advanced propulsion materials and components in hostile, high-temperature environments as well as validation of propulsion system design codes. The sensors are designed for applications on different material systems and engine components for testing in engine simulation facilities. Thin film thermocouples and strain gauges for the measurement of surface temperature and strain have been demonstrated on metals, ceramics and advanced ceramic-based composites of various component configurations. Test environments have included both air-breathing and space propulsion-based engine and burner rig environments at surface temperatures up to 1100°C and under high gas flow and pressure conditions.

The technologies developed for these sensors as well as for a thin film heat flux gauge have been integrated into a single multifunctional gauge for the simultaneous real-time measurement of surface temperature, strain, and heat flux. This is the first step toward the development of smart sensors with integrated signal conditioning and high temperature electronics that would have the capability to provide feedback to the operating system in real-time.

A description of the fabrication process for the thin film sensors and multifunctional gauge will be provided. In addition, the material systems on which the sensors have been demonstrated, the test facilities and the results of the tests to-date will be described. Finally, the results will be provided of the current effort to demonstrate the capabilities of the multifunctional gauge.

INTRODUCTION

Sensors developed for aeronautic and aerospace research applications must be able operate in environments where stress and temperature gradients are high and aerodynamic effects need to be minimized. To meet these needs, sensors in thin film form are being developed at NASA Glenn Research Center for surface measurement on various material systems.¹ Thin film sensors provide a minimally intrusive means of

measuring surface parameters in engine systems such as temperature, strain and heat flux that are needed to evaluate advanced materials and components and to provide experimental verification of computational models. Unlike conventional wire sensors, thin films do not require machining the surface and therefore leave intact the structural integrity of the engine component being measured. The thin films are vacuum deposited directly onto the surface and have thicknesses on the order of a few micrometers (μm) which are orders of magnitude less than wire sensors. As a result, thin film sensors add negligible mass to the surface and cause minimal disturbance to the gas flow over the surface. Thin film sensors, therefore, have minimal impact on the thermal, strain, and vibration patterns that exist in the operating environment.

The thin film thermocouple (TFTC) has been developed and demonstrated on several material systems for jet aircraft and space-based engine applications, including superalloys, ceramics, intermetallics, and ceramic matrix composite materials. TFTCs have been tested in laboratory furnaces tests as well as in harsh environments, including gas turbine and hydrogen/oxygen engine environments under both low and high pressure conditions, a high heat flux facility and a diesel engine environment.¹⁻⁷ The test temperatures have ranged from 1000–1500°C.

The strain gauges developed at NASA GRC for high temperature applications are palladium-13 wt% chromium (PdCr). This alloy is structurally stable up to elevated temperatures and its apparent strain versus temperature characteristic is linear, repeatable and not sensitive to heating and cooling rates. PdCr gauges have been demonstrated in both dynamic and static strain testing on superalloy, ceramic, and ceramic matrix composite components of engines and aircraft structures to 1100°C.^{1,8}

A thin film heat flux gauge developed at NASA GRC is based on measurement of temperature differences which in this case is measured across two locations on the substrate surface. Since the temperature drop is small, the differential signal output is increased by placing a number of thermocouple pairs connected in series. This is achieved with a circular thermopile with two thicknesses of a ceramic insulator. The advantages the thin film heat

flux gauge offers over conventional gauges include the capability to measure steady as well as transient heat fluxes, excellent transient response characteristics, minimal obstruction to thermal as well as physical flow, high temperature capability, and good sensitivity due to large output signal.^{9,10}

The technologies developed for the thermocouple, strain gauge, and heat flux sensors are being integrated into a single multifunctional gauge for the simultaneous real-time measurement of surface temperature, strain, and heat flux. This is the first step toward the development of smart sensors with integrated signal conditioning and high temperature electronics that would have the capability to provide feedback to the operating system in real-time.

SENSOR DESIGN

Electrical Insulation

The thin film sensors are fabricated in a Class 1000 Microfabrication Clean Room which contains sputter deposition and evaporation systems, wire bonding systems, etching capabilities, photolithography equipment, and a surface profilometer. The thin film sensor fabrication process must be tailored to the substrate material and intended end application in order to ensure good adhesion as well as no chemical interaction between the sensor and substrate material. Figure 1 is a schematic diagram of the sensor layers on both electrically insulating and electrically conducting substrates. Electrically insulating materials allow the sensor to be deposited directly onto the substrate as long as there is no chemical interaction between the sensor and substrate materials. For applications that require protection from the operating environment, a protective overcoat, typically aluminum oxide, is sputter deposited or evaporated onto the sensor to a thickness of approximately 2-3 μm .

In the case of electrically conductive ceramic materials such as silicon carbide, the substrate is thermally

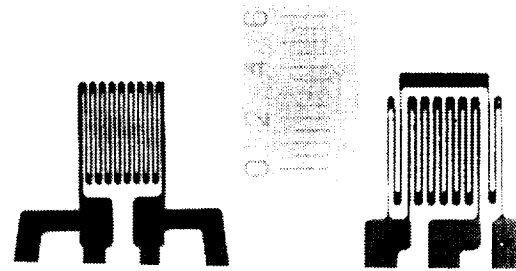


Figure 2. PdCr thin film strain gauges: dynamic strain gauge (left) and static strain gauge (right).

oxidized to form a stable, adherent silicon dioxide layer. An additional layer of alumina is sputter deposited or electron beam evaporated onto the surface to fill any pinholes or cracks that are present in the grown oxide which then enables the film to reach the required insulation resistance. The thickness of the thermally grown silicon dioxide and sputter deposited aluminum oxide are approximately 2-3 μm and 5-8 μm , respectively. The sensor elements are then fabricated on the oxide layer followed by a protective overcoat, if needed.

In the case of electrically conductive metal substrates such as superalloy materials, an MCrAlY bond coat is deposited via electron beam deposition or sputter deposition. M may be Fe, Co, Ni, or a combination of Co and Ni. This coating forms a stable, adherent, electrically insulating alumina layer when heat treated. Again, an additional layer of alumina is deposited to complete the insulation layer and the sensor and protective overcoat can then be deposited.

Sensor Elements

The thin film thermocouples are standard Type R thermocouples (platinum-13% rhodium vs. platinum) and are typically patterned with stenciled shadow masks and sputter deposited to approximately 5 μm thickness. A process has also been developed using photolithography methods involving a lift-off process.

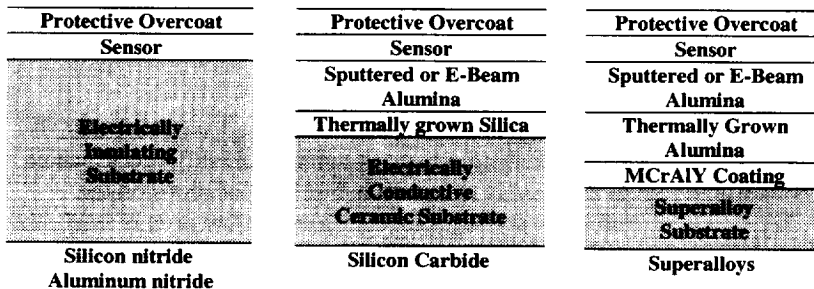


Figure 1. Schematic diagram of thin film sensors on various substrate materials.

The PdCr strain gauge is prepared by sputter deposition of approximately 8 μm of PdCr which is then patterned via photolithography and chemical etching. The dynamic strain gauge is presented in Figure 2. For static strain applications, a temperature compensator element of platinum is used to minimize the temperature effect on the PdCr resistance change. PdCr has a higher, but constant, temperature coefficient of resistance than that permitted for a static strain gauge. The sputter-deposited platinum element is

5 μm thick and is patterned with a stenciled shadow mask. It is located around the PdCr gauge grid and connected to the adjacent arm of a Wheatstone bridge circuit to minimize the temperature effect (Figure 2).¹¹

The thin film heat flux gauge is a planar thermopile arranged in a circular pattern consisting of 40 thermocouples in series (Figure 3). The thermopile is used to measure temperature difference between the inside and outside junctions.^{9,10} The use of a thermopile allows the output signal to be multiplied by the number of thermocouple pairs. Since a thin film insulator produces a small temperature difference, the thermopile is effective in boosting the output signal. The elements are platinum and platinum-10% rhodium. To create a temperature difference, dielectric films (either silicon dioxide or aluminum oxide) of two thicknesses are deposited on the two thermopile junctions (Figure 4).

The incident heat flux (\dot{Q}) is determined with the equation:

$$\dot{Q} = K \frac{T_1 - T_2}{x_1 - x_2}$$

where K is the coefficient of thermal conductivity, ($T_1 - T_2$) is the temperature difference across the two layers of insulator, and x_1 and x_2 are the thicknesses of the two insulator layers.

The sensor is patterned with microlithography, lift-off, etch processing and sputter deposition.

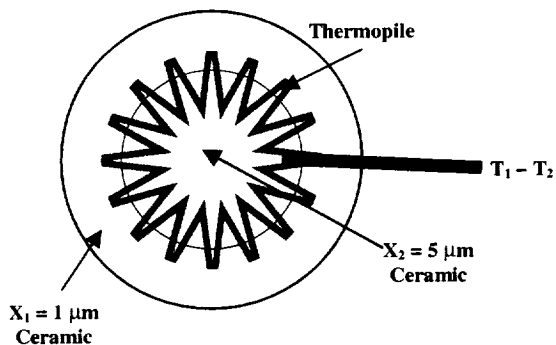


Figure 3. Planar thermopile concept for measuring heat flux.

Lead Wire Attachment

Parallel gap welding is used to attach 75 μm lead wires to the thin film sensors. Platinum and platinum-rhodium wires are used for the Pt and Pt-Rh elements of

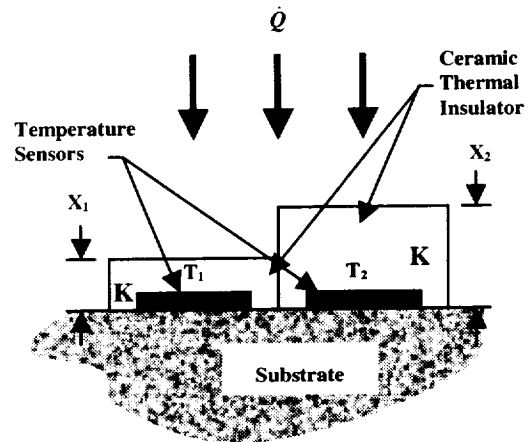


Figure 4. Concept for heat flux measurement

the thermocouples and heat flux gauges and Pt wires are used for both PdCr and Pt strain gauge elements. When needed, high temperature ceramic cement is used to further secure the lead wires to the substrate.

SENSOR APPLICATIONS

Thermocouples

Thin film thermocouples have been fabricated and tested on a number of substrate systems including nickel-based superalloys, silicon carbide, silicon nitride, mullite and aluminum oxide ceramics, ceramic matrix composites (CMC) and intermetallics. The sensors have been demonstrated on various test component configurations and in different test environments.

Thin film thermocouples were demonstrated on Space Shuttle Main Engine (SSME) turbine blades (Figure 5) in a test facility designed to simulate the highly transient temperature and pressure conditions of the SSME high pressure fuel turbopump environment. The blades were Ni-based superalloys as were a series of flat substrates instrumented with thin film thermocouples and tested in hydrogen-fueled burner rigs. The films proved to be highly adherent and durable to the 1000°C test conditions.

Thin film thermocouples have also been used in evaluating advanced ceramic matrix composite materials of various test hardware configurations designed to meet propulsion capability goals of several development programs.¹⁴ A hydridopolysilazane fiber/silicon carbide matrix CMC liner was tested with thin film thermocouples in a jet-fueled burner rig operating under pressures of 0.7 to 2 MPa and gas temperatures of 1500°C. Temperature data up to 1100°C was obtained



Figure 5. Thin film thermocouples on SSME turbine blade.

for over 25 hours of testing. Several SiC fiber/SiC matrix ceramic matrix composites panels, cylinders, and combustor liners have also been instrumented with thin film thermocouples and successfully tested in the same combustor test facility. The typical initial failure mode for the sensors is the detachment of the lead wires from the sensor film. This issue is currently being addressed.

Strain Gauges

Thin film PdCr strain gauges have been fabricated and tested on nickel-based superalloys, silicon nitride and aluminum oxide ceramics, and SiC/SiC ceramic matrix composites. Test environments have included air furnaces, a heat flux arc lamp, spin rig, and jet-fueled combustor test facility.¹

The requirements for a useful strain gauge may be different dependent upon the application for a dynamic or static strain measurement. In the case of dynamic strain measurements during which the strain rate of change is much larger compared with the temperature change rate, the permissible apparent strain sensitivity of the gauge can be high as compared to static strain measurement. The general requirements for a dynamic strain gauge are that its apparent strain sensitivity is less than 100 microstrain $\mu\epsilon/^\circ\text{C}$ and its drift strain rate at the application temperature is less than 500 $\mu\epsilon/\text{hour}$.¹² However, for static strain measurements over long periods of time, both the temperature and strain may vary. Therefore, for a required accuracy of 10% for static strain measurement in the range of 2000 $\mu\epsilon$, the total

apparent strain and drift strain should be smaller than 200 $\mu\epsilon$ so as to be neglected, or repeatable to within 200 $\mu\epsilon$ so it can be corrected.

The apparent strain of a PdCr dynamic strain gauge is stable and repeatable between thermal cycles to 1100 $^\circ\text{C}$ when connected to a Wheatstone bridge circuit in a quarter bridge configuration.⁸ The apparent strain sensitivity is approximately 85 $\mu\epsilon/^\circ\text{C}$ and the drift strain at 1100 $^\circ\text{C}$ is less than the permissible value of 500 $\mu\epsilon/\text{hour}$. The resulting apparent strain characteristic of a PdCr static strain gauge connected to a Wheatstone bridge circuit in a half bridge configuration is stable and repeatable to within $\pm 200 \mu\epsilon$ between thermal cycles to 1100 $^\circ\text{C}$ with a sensitivity less than 3.5 $\mu\epsilon/^\circ\text{C}$ in the entire temperature range. The apparent strain of the PdCr compensated thin film gauge can be corrected to within $\pm 200 \mu\epsilon$ if the temperature measurement uncertainty is within 57 $^\circ\text{C}$. The gauge is stable and responds linearly to mechanical loads up to 1050 $^\circ\text{C}$. This is 500 $^\circ\text{C}$ above the usable temperature for conventional NiCr strain gage technology. The strain sensitivity, or gauge factor, for PdCr decreases approximately 22% from room temperature to 1050 $^\circ\text{C}$.

PdCr thin film strain gauges have been demonstrated in an air furnace up to 1100 $^\circ\text{C}$ and in a heat flux calorimeter with heating rates up to 1100 $^\circ\text{C}/\text{sec}$ and heat flux up to 2 MW/m^2 . The dynamic gauges were also fabricated on an advanced silicon nitride turbine blade and survived tests up to 42,500 rpm and fatigue tests at $\pm 2000 \mu\epsilon$ up to 1000 $^\circ\text{C}$ for a million cycles. The gauges have also been demonstrated on SiC/SiC ceramic matrix composite components in a jet-fueled burner rig operating at surface temperatures of approximately 1100 $^\circ\text{C}$.

A weldable PdCr thin film strain gauge was developed for applications that do not allow a gauge to be sputtered directly on to the component because the component is too large to be accommodated in the deposition rig or when gauge installation must be performed in the test field. The gauge is first deposited on a metal shim that has a similar coefficient of thermal expansion to that of the substrate material. The shim is then welded onto the test article. The mechanical response of the weldable gauge is similar to that of a direct-deposited gauge in that it is linear to the mechanical load and does not cause delay in strain transfer.⁸

Heat Flux Gauges

The thin film heat flux gauges have been demonstrated on silicon, aluminum oxide, silicon nitride, and nickel-based superalloys.¹⁰ Test environments include exposure to radiation from a furnace to 900 $^\circ\text{C}$ providing a low heat flux of 0.1 Mw/m^2 . The output of the sensor was about

30 microvolts. The gauge has also been tested in a heat flux arc lamp calibrator at temperatures up to 900°C and heat flux up to 1.5 Mw/m² with an output of up to almost 4 millivolts.

The sensor has also been fabricated on the curved surface of a SSME turbine blade (Figure 6).¹⁰ Because many of the intended applications are on engine components that have complex shapes, these sensors must be able to be fabricated on curved surfaces. The fine lines and dimensions of these heat flux gauges along with the multistep patterning process makes this effort challenging.

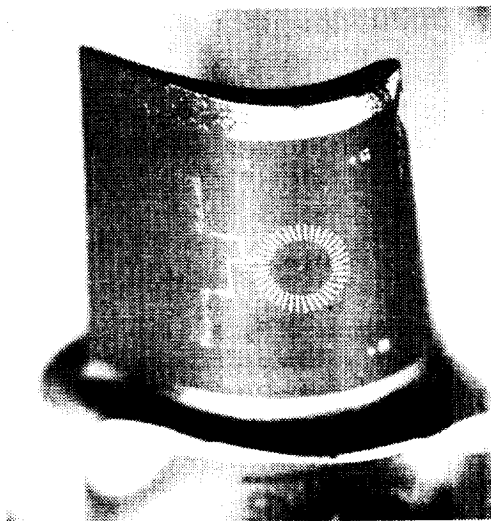


Figure 6. Thin film heat flux gauge on SSME turbine blade.

MULTIFUNCTIONAL SENSOR

Design

In order to address the call for smart sensors that not only track the performance of a component during operation but also provide feedback in real time, the first step has been taken by integrating the technologies discussed thus far into a single, multifunctional gauge. This provides a single array for real-time measurement of temperature, strain, and heat flux with the potential for gas flow measurement as well.

For the magnitude and direction of both strain and flow, a triangular strain gauge has been designed. The patented design modified a rosette pattern strain gauge by linking the three legs of the rosette together and powering them

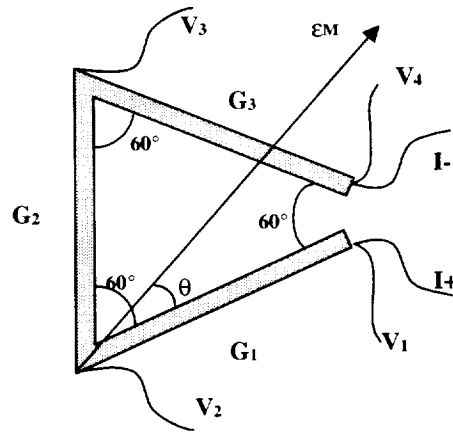


Figure 7. Concept for triangular strain gauge component of Multifunctional Sensor.

under a single constant current source.^{13,14} A schematic of the design is shown in Figure 7.

The strain applied to the triangular gauge is sensed as individual strain components by each of the three legs of the rosette. These strain components are determined by measuring the increase or decrease of the voltage drop along each leg due to the applied strain. The voltage drop on each leg is the sum of the strain component in that direction and the apparent strain with the assumption that the apparent strain is the same for each leg. The three legs provide three equations and three unknowns: strain magnitude, strain direction, and apparent strain. In principal, the apparent strain is eliminated and the main parameters of interest, strain magnitude and direction, are obtained by solving the equations.

This gauge design allows measurement of strain magnitude and direction but with half the lead wires required for a standard rosette gauge. In addition, by measuring the resistance change in the gauge under high current conditions, the sensor can be calibrated for flow measurement as an anemometer.¹³

Both PdCr and platinum are being utilized as gauge materials. PdCr is limited to applications below 1100°C whereas platinum is usable for higher temperature use.

Figure 8 shows the complete gauge design incorporating the triangular strain gauge, heat flux gauge and thermocouple. The heat flux gauge and thermocouple incorporate the design discussed earlier in this paper. The element materials for both the heat flux gauge and

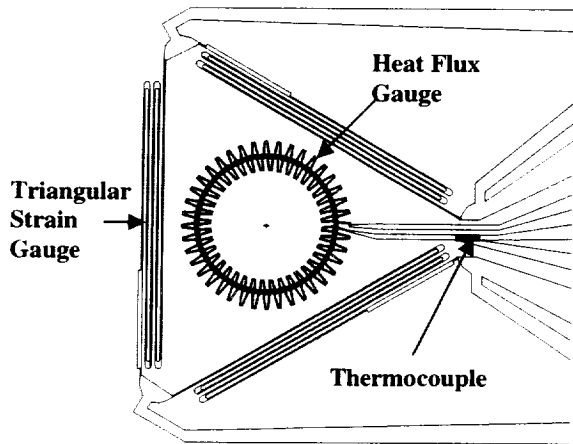


Figure 8. Design of Multifunctional Sensor.

the thermocouple are platinum-13% rhodium and platinum. The entire gauge is enclosed in a triangle approximately 1.5 cm on a side with line widths of 50 μm . The gauges are fabricated with photolithography techniques, lift-off, etching, and metal masking. Figure 9 shows three prototype gauges on constant strain alumina beams. Figure 10 shows a close-up of the most recent prototype of the gauge.

Prototype Testing

Various prototypes of the gauge have been bench tested for all of the parameters except flow.¹³ The gauge was tested for strain response in the Dynamic Load Test Rig. Measurements of both the static and dynamic response of the sensors were made and the strain magnitude was measured to an accuracy of within $\pm 10\%$ of the nominal value. The strain angle was measured to an accuracy of within $\pm 1^\circ$ of the nominal value. The sensor reacted to heat flux as predicted when exposed to a heat gun

flowing perpendicular to the surface. The resulting signal data is shown in Figure 11. Calibration, transient, and frequency response of the heat flux portion of the sensor is described in Reference 15. Longitudinal flows over the sensor produced twice the response of transverse flows, demonstrating the feasibility of measuring flow.

Future testing will include measuring all of the parameters simultaneously from a single prototype sensor. Additionally, the sensor will be fabricated on an engine component and tested in the lab as well as in harsh test environments. Alternate materials for the sensor elements will be explored as the sensor is pushed for use in higher temperature applications. Ceramic thermocouple and strain gauge materials are being investigated and may replace the metals currently being used. An electronics package is to be developed to allow the sensor to become "smart" without the need for PC-based software. Additionally, the sensor is to be developed as a transferable gauge, similar to the weldable strain gauge described earlier.

SUMMARY

The ongoing development of thin film sensors is addressing the need for advanced measurement techniques for propulsion systems. The technology for measuring temperature, dynamic and static strain, and heat flux has been demonstrated on numerous material systems and in several test environments. These technologies are currently being incorporated into a single, multifunctional system that is minimally intrusive and usable in harsh test environments. These systems will be designed to be smart, stand-alone systems with integrated electronics. Additionally, lead wire attachment techniques are being addressed in order to improve durability and reliability. Finally, sensors

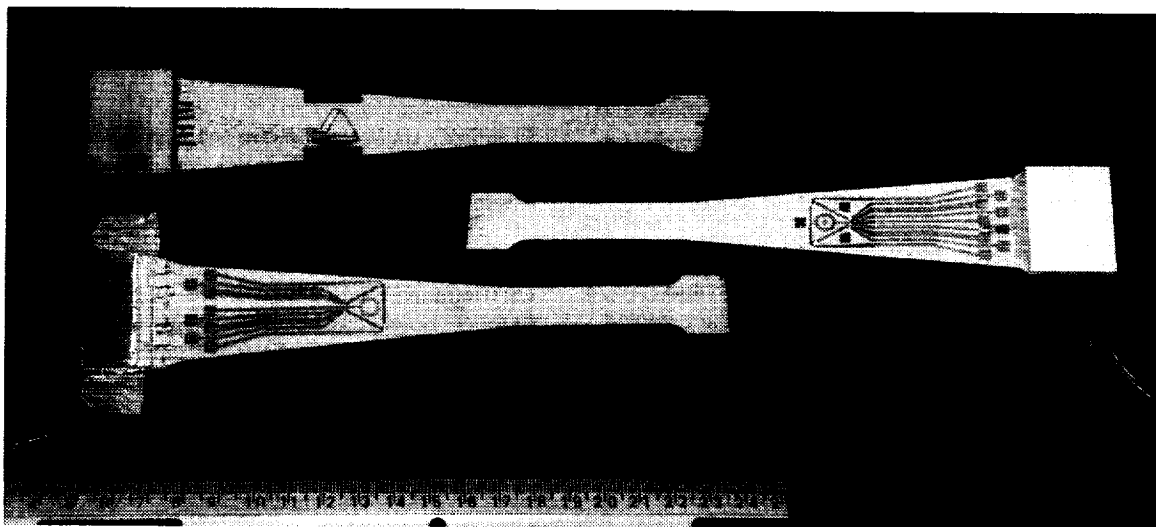


Figure 9. Prototype gauges on constant strain alumina beams.

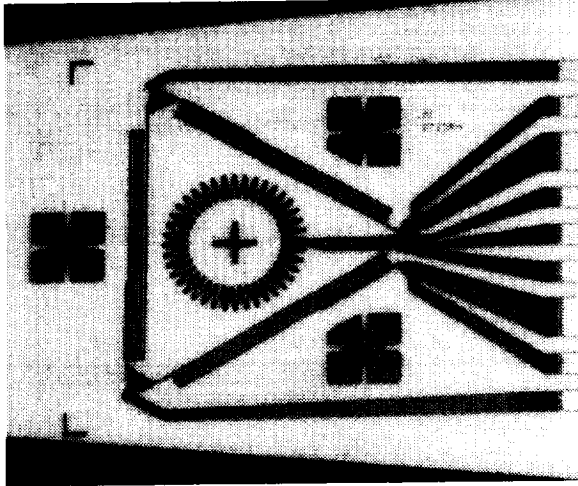


Figure 10. Close-up of most Multifunctional Sensor prototype.

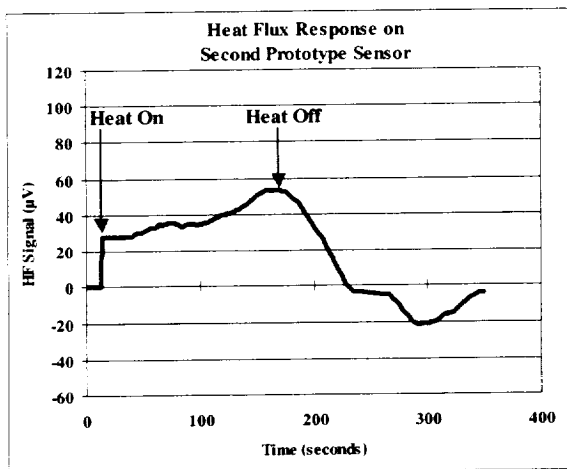


Figure 11. Heat flux response from Multifunctional Sensor prototype.

that can be used to even higher temperatures ($>1200^{\circ}\text{C}$) are being explored to address the demands being made by advanced aeropropulsion research for higher use temperatures.

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