

OPEN ACCESS

Novel polymer derived ceramic-high temperature heat flux sensor for gas turbine environment

To cite this article: N R Nagaiah *et al* 2006 *J. Phys.: Conf. Ser.* **34** 458

View the [article online](#) for updates and enhancements.

You may also like

- [Temperature-mediated structural evolution of vapor-phase deposited cyclosiloxane polymer thin films for enhanced mechanical properties and thermal conductivity](#)
Weiwei Du, Jing Tu, Mingjun Qiu et al.
- [Autoregressive Planet Search: Application to the Kepler Mission](#)
Gabriel A. Caceres, Eric D. Feigelson, G. Jogesh Babu et al.
- [Kepler Presearch Data Conditioning I—Architecture and Algorithms for Error Correction in Kepler Light Curves](#)
Martin C. Stumpe, Jeffrey C. Smith, Jeffrey E. Van Cleve et al.



ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

Novel Polymer Derived Ceramic-High Temperature Heat Flux Sensor for Gas Turbine Environment

N. R. NAGAI AH¹

Mechanical Materials and Aerospace Engineering Department, University of Central Florida, Orlando, Florida 32816, USA
E-mail: na282834@ucf.edu

J. S. KAPAT

Mechanical Materials and Aerospace Engineering Department, University of Central Florida, Orlando, Florida 32816, USA
E-mail: jkapat@mail.ucf.edu

L. AN

Advanced Materials Processing and Analysis Center (AMPAC), Orlando, Florida 32816, USA
E-mail: lan@mail.ucf.edu

L. CHOW

Mechanical Materials and Aerospace Engineering Department, University of Central Florida, Orlando, Florida 32816, USA
E-mail: lchow@mail.ucf.edu

Abstract. This paper attempts to prove the feasibility of a novel High Temperature Heat Flux (HTHF) sensor for gas turbine environment. Based on the latest improvement in a new type of Polymer-Derived Ceramic (PDC) material, the authors present the design and development of a HTHF sensor based on PDC material, and show that such a sensor is indeed feasible. The PDC-HTHF sensor is fabricated using newly developed polymer derived SiCN, whose conductivity is controlled by proper composition and treatment condition. Direct measurements and characterization of the relevant material properties are presented. Electrical conductivity can be varied from 0 (insulator) to $100 \text{ (ohm.cm)}^{-1}$; in addition a value of 4000 ppm/°C (at 600 K) is obtained for temperature coefficient of resistance. This novel sensor is found to perform quite satisfactorily at about 1400 °C for long term as compared to conventional heat flux sensors available commercially. This type of PDC-HTHF sensor can be used in harsh environments due to its high temperature resistance and resistance to oxidation. This paper also discusses lithography as a microfabrication technique to manufacture the proposed PDC-HTHF sensor. In our current design, the sensor dimensions are 2.5mm in diameter and 250 μm thickness.

¹Contact author: N. R. Nagaiah, Ph.: +1 407 823 6072; Fax: +1 407 823 0208.
E-mail: na282834@ucf.edu

1. Introduction

Heat flux is one of the important parameters, together with pressure, temperature, flow, etc., of interest to Gas turbine engine designers. There is need for heat flux sensor that can measure high heat fluxes at high surface temperature especially inner walls of combustion chamber in gas turbines. Standard heat flux sensors do not perform well under these conditions because of high temperature and oxidation environment. Wrbanek et al. investigated the feasibility of ceramics as thin film thermocouples for extremely high temperature applications thus taking advantages of both the stability and robustness of ceramics and the non-intrusiveness of thin films.¹

The need to consider Polymer Derived Ceramics (PDC) sensing elements is brought about by the temperature limits of metal thin film sensors in propulsion system applications. Longer-term stability of thin film sensors made of noble metals has been demonstrated at 1100 °C for 25 hrs.² The maximum temperature of noble metal thin film thermocouples of 1100 °C and their duration of operation may not be adequate for the increasingly harsh conditions of gas turbine engine. The introduction of PDC sensing element shown a feasibility of withstanding high temperature upto 1500 °C and operate under highly oxidation environment for long duration.

2. Working Principle:

Heat flux sensors are classified into three categories according to their measurement principles: the gradient method, the transient method, and the balanced method.³ In our design of HF sensor, the gradient method is preferred for its most frequent use, and is based on Fourier's conduction law in which heat flux is proportional to the thermal conductivity and the temperature gradient.

$$Q \propto K(T) \frac{T_1 - T_2}{\delta} \quad (\text{W/m}^2) \quad (1)$$

Where Q is the incident heat flux, K is the thermal conductivity of thermal resistance layer, δ is the thickness of the thermal resistance layer and $\delta T = T_1 - T_2$ is a temperature difference measured across thermal resistance layer by RTDs.

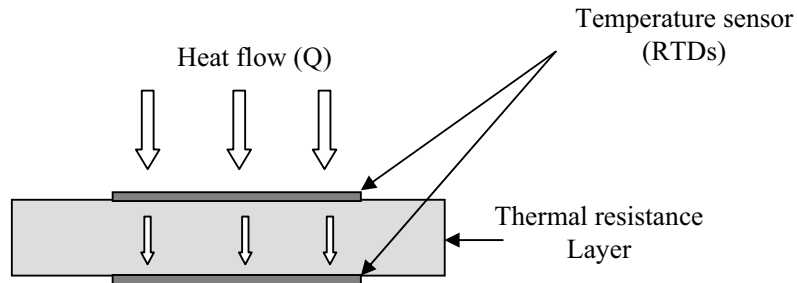


Figure 1. Principle of the layered heat flux measuring gage.

Figure 1. Shows the schematic of conventional layered gage in which heat flows parallel to the direction of the thermal resistance.

3. Need for PDC-HTHF sensor:

The efficiency and performance of gas turbine engines are limited by the materials used and the need for internal cooling. Internal cooling is necessary because temperatures may exceed the melting point of the materials used in some engine components. In almost all the gas turbines the internal cooling of the components is achieved by extracting (typically 20%) of the air from the compressor of the engine. However, the cooling air supply is penalty to the thermal efficiency. Therefore, a balance is sought between raising turbine inlet temperatures and increasing cooling air requirements. This is achieved by an understanding of the various flows and associated heat transfer, and requires instrumentation which can directly measure heat transfer with minimal disruption. Research is being done to quantify the temperatures and heat flux seen by the turbine section of an engine in order to better understand the thermal loads contributing to thermal fatigue.

Commercially available layered heat flux gages pose significant problems in harsh conditions like gas turbine environment where ultra high temperature and high level oxidation are common. Therefore these are not suitable for hostile environments, such as combustion. Our research on micromachined PDC-HTHF sensor is motivated by the needs of heat transfer measurement in gas turbine environment. None of the commercially available heat flux sensors can withstand the thermal and/or chemical environment that exists at the inner surface of a gas turbine combustor liner.

Figure 2. Shows sectional view of industrial gas turbine, the exploded view shows the location where the heat flux to the walls needs to be measured; the measure of heat flux at this location not only helps in design of efficient combustor but also made to control combustion in order to avoid failure of blades due to ultra high temperature.

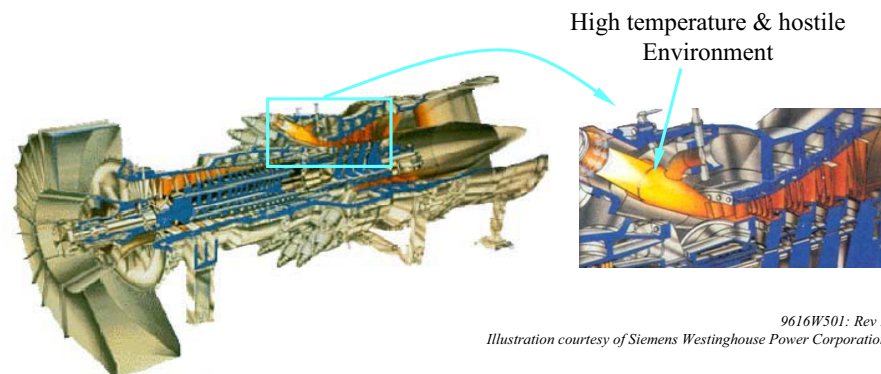


Figure 2. Sectional view of industrial gas turbine

4. Polymer Derived Ceramics (PDC) materials:

Polymer-derived ceramics (PDCs) are a new class of materials synthesized by thermal decomposition of polymeric precursors. The basic processing steps are shown in Figure 3. it involves the following steps: (i) Synthesizing and modifying the polymer precursors, (ii) shaping and cross-linking the precursor to form infusible polymer components with desired structures, and (iii) converting the polymer component to a ceramic by pyrolysis at about 1000 °C.

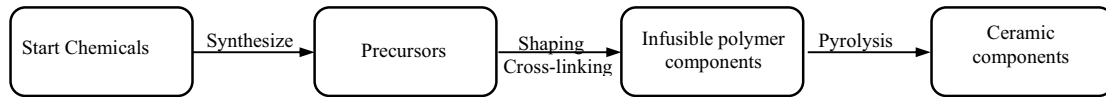


Figure 3. Processing of polymer-derived ceramics.

The polymer-derived ceramics (PDCs) thus obtained are based on amorphous alloys of silicon, carbon and nitrogen. While synthesized at relatively low temperatures, the polymer derived ceramics exhibit excellent thermo-mechanical properties at high temperatures.⁴ Other elements can be incorporated into the PDC materials for the modification of their properties. The electric conductivity of PDCs can be tailored in a large range: from insulator ($10^{-8} (\Omega \cdot \text{cm})^{-1}$) to semi-metallic ($10^4 (\Omega \cdot \text{cm})^{-1}$). Figure 4. shows the conductivity of polymer-derived SiAlCN as a function of temperature. It can be seen immediately that the conductivity of this material is perfectly repeatable during heating/cooling cycles up to 1000 °C, suggesting that the sensors made from the material can be repeatedly used to high temperatures when conductivity is used as sensing mechanism. Figure 4. also suggests that the SiAlCN material shows typical amorphous semiconductor behavior. The characterization of PDC material shown excellent electrical and thermal properties suited to fabricate heat flux sensor⁵.

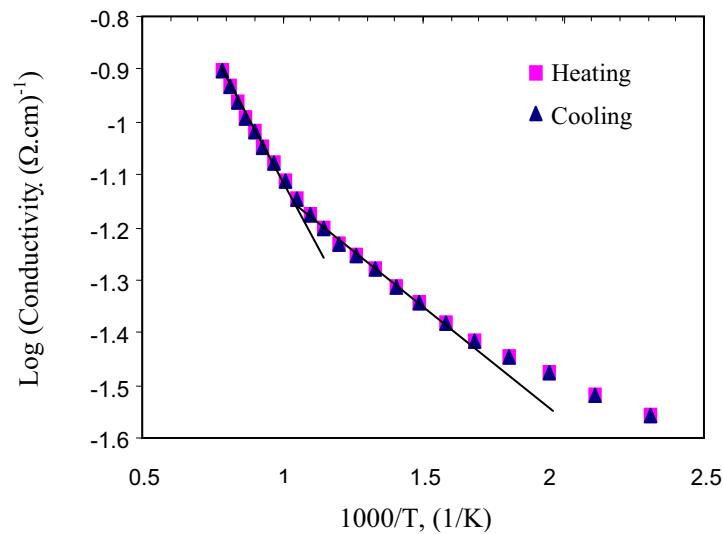


Figure 4. Electric conductivity of SiAlCN as a function of temperature, suggesting amorphous semiconductor behavior of SiAlCN.

5. Design and Fabrication process:

The proposed HTHF sensor consists of two Resistance Temperature Detectors (RTDs) made of SiAlCN, resistive layer made of SiCN (insulator-lightly doped) and electrical leads made of SiCN (conductor-heavily doped). The PDC materials used in our design of Heat Flux sensor not only can withstand ultra high temperature of gas turbine flow field, but also can resist contamination and oxidation (up to 1400 °C). The specifications of the sensor mainly depend on the thermal conductivity of the resistive layer. Based on thermal conductivity and required temperature gradient, the geometry

of the proposed sensors, such as length, width and thickness of the sensing elements and thickness of insulating layer are shown in Figure 5 and 7.



Figure 5. sectional view of proposed heat flux sensor

The direct chemical-to-ceramic processing route of PDCs enables the employment of many well-developed microfabrication technologies. MEMS components and devices can be first made in organic form and then converted to ceramics. Recently, the microfabrication techniques, such as micro-casting, lithography and polymer-based bonding, have been developed for the fabrication of ceramic MEMS with these novel materials⁶⁻¹⁰. Figure 6. shows some representative PDC-MEMS structures.



Figure 6. (a) SEM image of SiCN micro-gear fabricated by microinjection molding; (b) optical image of SiCN atomizer fabricated by lithography.

The overall fabrication process of PDC-HTHF sensor can be carried out by using the cost effective photolithographic technique. The liquid precursors of SiAlCN and SiCN are used in this fabrication process to obtain polymeric structure, from which we directly get ceramic component after pyrolysis.

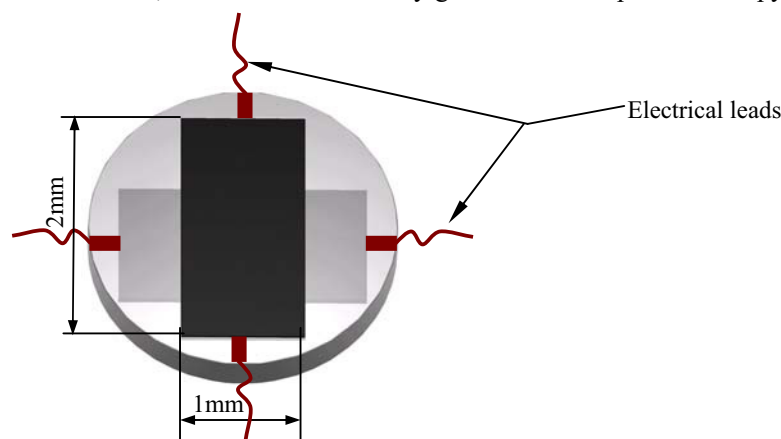


Figure 7. Schematic showing the structure of proposed temperature/heat-flux sensor.

RTD's films are deposited on each side of resistive layer perpendicular to each other to avoid interference of leads. Figure 7. Shows schematic of final form of heat flux sensor.

6. Conclusion:

Comprehensive optimization of design, materials and associated fabrication methods are quite involved and are to be exhaustively addressed in the future work. Such issues will be systematically explored to improve the performance, ease of fabrication, and reliability.

References:

- [1] J.D. Wrbanek, G.C. Fralick, and S.C. Farmer "Development of Thin Film Ceramic Thermocouples for High Temperature Environments". NASA/TM—2004-213211.
- [2] J.F. Lei, L.C. Martin and H.A. Will, "Advances in Thin Film Sensor Technologies for Engine Applications," NASA TM-107418, Turbo Expo '97, Orlando, FL, June 2-5, 1997.
- [3] S.H. Oh, K.C. Lee, J. Chun, M. Kim and S.S. Lee. "Micro heat flux sensor using copper electroplating in SU-8 microstructures". Journal of Micromechanics and Microengineering, Vol. 11, pp. 221-225 (2005).
- [4] L. Bharadwaj, A. Dhamne, L. An, J.S. Kapat and L. Chow, "Polymer-derived Si-Al-C-N-O ceramics for high temperature applications". The proceedings of ASME Turbo Expo-2003.
- [5] N.R. Nagaiah, V. Krishnan, J.S. Kapat and L. An, "A Conceptual Design of a Polymer-Derived Ceramic Hot-Wire Anemometer for Gas Turbine Environment". The proceedings of ASME Turbo Expo-2005.
- [6] L. Liew, W. Zhang, V.M. Bright, L. An, M.L. Dunn and R. Raj, "Fabrication of SiCN Ceramic MEMS Using Injectable Polymer-Precursor Technique," Sensors and Actuators": A. Physical, vol. 89, no. 1-2, 64-70, 2001.
- [7] L. Liew, W. Zhang, L. An, S. Shah, R. Lou, Y. Liu, T. Cross, K. Anseth, V. Bright and R. Raj, "Ceramic MEMS – New Materials, Innovative Processing and Futuristic Applications," Am. Ceram. Soc. Bull., 80(5), 25-30 (2001).
- [8] L. Liew, Y. Liu, R. Luo, T. Cross, L. An, V.M. Bright, M.L. Dunn, J.W. Daily, R. Raj, "Fabrication of SiCN MEMS by photopolymerization of pre-ceramic polymer," Sensors and Actuators: A. Physical, 95 (2-3): 120-134 (2002).
- [9] Y. Liu, L. Liew, R. Lou, L. An, V.M. Bright, M.L. Dunn, J.W. Daily and R. Raj, "Application of Microforging in SiCN MEMS Structure Fabrication," Sensors and Actuators: A. Physical, 95 (2-3): 143-151 (2002).
- [10] C. Walsh, L. An, J.S. Kapat and L.C. Chow, "Feasibility of a High-Temperature Polymer-Derived-Ceramic Turbine Fabricated Through Micro-Stereolithography," Proceeding of IGTI ASME Turbo Expo, Jun 2002, Amsterdam.
- [11] P. Freymuth, "Engineering estimate of heat Conduction loss in constant temperature thermal sensors", TSI Incorporated, Volume V, Issue 3 (1979).