Journal of Physics: Conference Series

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To cite this article: N R Nagaiah *et al* 2006 *J. Phys.: Conf. Ser.* **34** 277

Institute of Physics Publishing Journal of Physics: Conference Series **34** (2006) 277–282
doi:10.1088/1742-6596/34/1/046 International MEMS Conference 2006

A Novel Design and Analysis of a MEMS Ceramic Hot-Wire Anemometer for High temperature Applications

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Abstract. This paper attempts to prove the feasibility of high temperature MEMS hot-wire anemometer for gas turbine environment. No such sensor exists at present. Based on the latest improvement in a new type of Polymer-Derived Ceramic (PDC) material, the authors present a Novel design, structural and thermal analysis of MEMS hot-wire anemometer (HWA) based on PDC material, and show that such a sensor is indeed feasible. This MEMS Sensor is microfabricated by using three types of PDC materials such as SiAlCN, SiCN (lightly doped) and SiCN (heavily doped) for sensing element (hot-wire), support prongs and connecting leads respectively. This novel hot wire anemometer can perform better than a conventional HWA in which the hot wire is made of tungsten or platinum-iridium. This type of PDC-HWA can be used in harsh environment due to its high temperature resistance, tensile strength and resistance to oxidation. This HWA is fabricated using microstereolithography as a novel microfabrication technique to manufacture the proposed MEMS Sensor.

1. Introduction

The hot-wire anemometer (HWA) has been used for many years as a research tool in fluid mechanics. It utilizes a small, electrically heated element exposed to the fluid medium for the purpose of measuring the flow parameters. Normally the parameters being measured are velocity, turbulence levels and flow patterns. The hot-wire anemometer is based on convective heat transfer from a heated element placed in the fluid flow. Any changes in the fluid medium will cause changes in the sensor's heat loss[1]. The thermal anemometer, using the fact that electrical power is proportional to the sensor heat loss, transduces the flow parameters reading into an electrical signal.

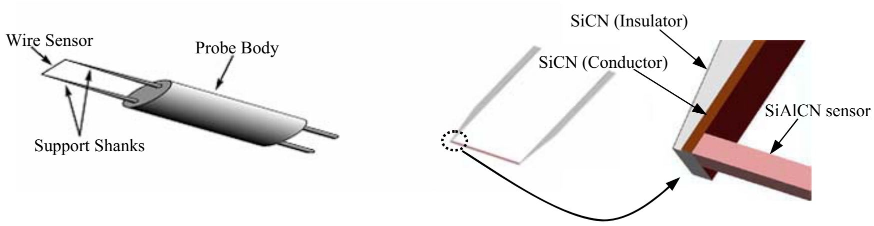


Figure 1. (a) Conventional -HWA (b) Polymer Derived Ceramic-HWA.

The conventional HWA (Figure 1a) is noted for its low cost, fast response, small size and low noise[1]. However these HWAs pose significant problems in harsh conditions like gas turbine environment where the high-speed flow and ultra high temperature are common. Therefore these HWAs are not suitable for hostile environments, such as combustion [2]. Our research on micromachined PDC-HWA is motivated by the needs of fluid flow measurement in gas turbine environment. None of the commercially available HWAs can withstand the thermal and/or chemical environment that exists at the exit of a gas turbine combustor or turbine inlet. Figure 2. Shows sectional view of industrial gas turbine, the exploded view shows the location where the flow parameter needs to be measured; the measure of flow parameters at this location not only helps in design of efficient gas turbines but also made to control combustion in order to avoid failure of blades due to ultra high temperature.

The proposed MEMS ceramic-HWA (Figure 1b) consists of a sensing wire made of SiAlCN, two parallel support prongs made of SiCN (lightly doped) and electrical leads made of SiCN (heavily doped). The PDC materials used in our design of thermal anemometer not only can withstand ultra high temperature of gas turbine flow field, but also can resist contamination and oxidation (up to 1500 0C).

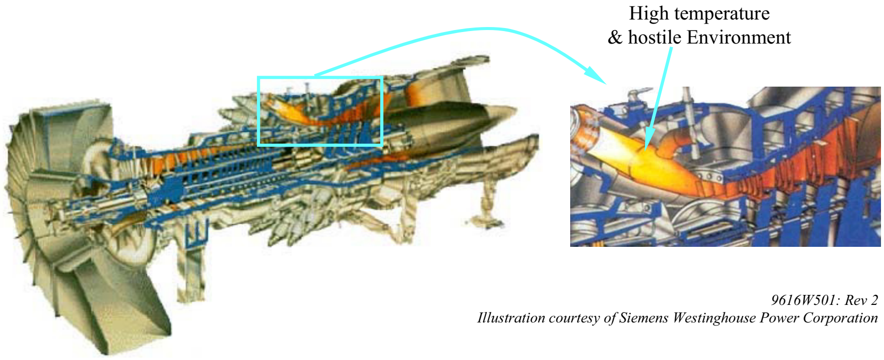


Figure 2. Sectional view of industrial gas turbine

2. 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 ^{0}C.

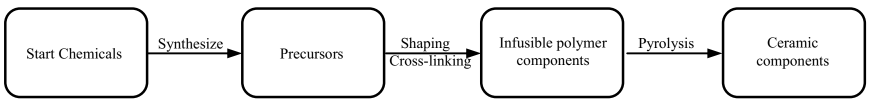
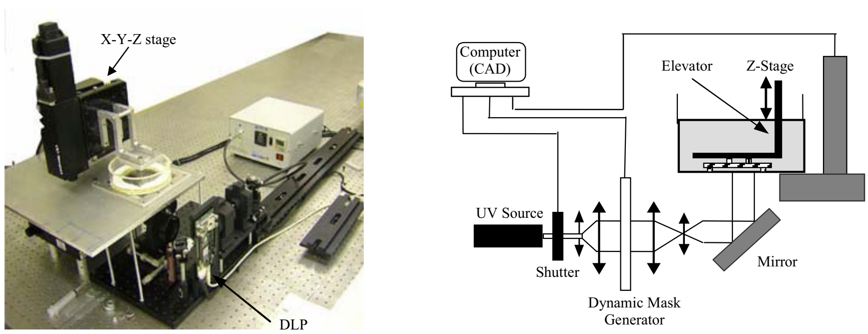


Figure 3. Processing of polymer-derived ceramics.

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[3]. Other elements can be incorporated into the PDC materials for the modification of their properties. Electrical properties of PDC materials are listed and compared with conventional materials [4].

3. Fabrication process

The overall fabrication process of MEMS ceramic-HWA can be carried out by using the cost effective micro stereolithographic (μSL) technique. This technique derived from stereolithography, provides unique opportunity for fabricating complex high-aspect ratio 3D microstructures [5]. Figure 4(a). Shows the photograph of Invert-micro stereolithography (I-μSL) set up. The fabrication principle is illustrated in Fig. 4(b), schematically.



(a) (b)

Figure 4. (a) Photograph of Invert-micro-stereolithography developed at UCF and (b) Principle of Invert - μSL

3.1. Materials preparation:

The commercially available Ceraset™ (from Kion Corp., USA), can be used as a UV sensitive monomer. And 2,2,-dimethoxy-2-phenyl acetophenone (commercially known as Irgacure 651 from Aldrich chemical, Milwaukee, USA), can be used as photo initiator [6].

SiCN Ceramics Precursor preparation: Precursor is prepared by adding $5_{wt}\%$ photo initiator (Irgacure-1300 from Ciba Speciality Chemicals) to liquid Ceraset, after mixing at about $70\text{-}80^0$ C for one hour, the transparent yellow liquid precursor is obtained. Then, this liquid precursor is placed in a vacuum oven at the condition of 30in Hg for 24 hours to remove air bubbles.

Figure 5., is a schematic of the general fabrication process. First, the liquid precursor is spun on to a silicon wafer. The liquid thickness and, thus the final structure thickness can be varied according to the spin speed. The liquid is then subjected to non-contact UV exposure through a Dynamic Mask Generator to solidify regions of the liquid. These regions remain on the substrate while the remaining liquid is then removed by spin-rinsing in acetone solution. The result is a substrate with solid polymer structures attached. These structures are removed from the substrate. The individual structures are then crosslinked and pyrolyzed in a furnace to form PDC MEMS devices [6].

The general Fabrication procedure for anemometer supporting prongs is shown in Figure 5. The same procedure is used to fabricate the PDC sensor wire and connecting leads separately.

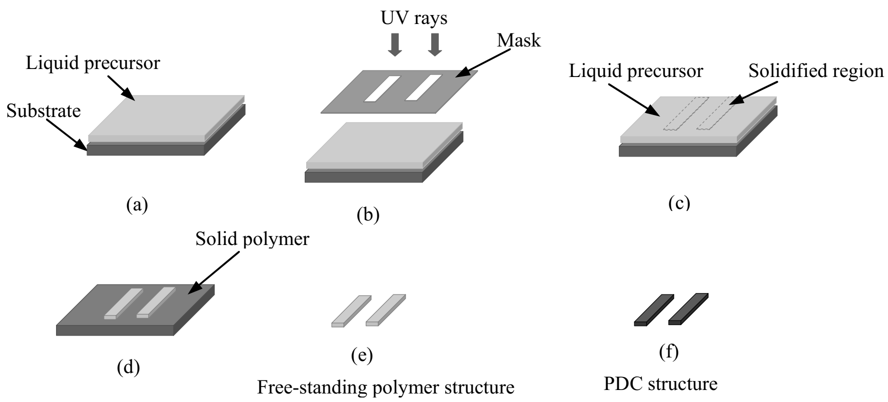


Figure 5. General Fabrication process: (a) spin precursor onto substrate; (b) UV exposure; (c) solidified polymer with remaining liquid; (d) removing non-solidified precursor; (e) remove polymer structures from substrate; (f) crosslink and pyrolyze polymer to obtain PDC structure.

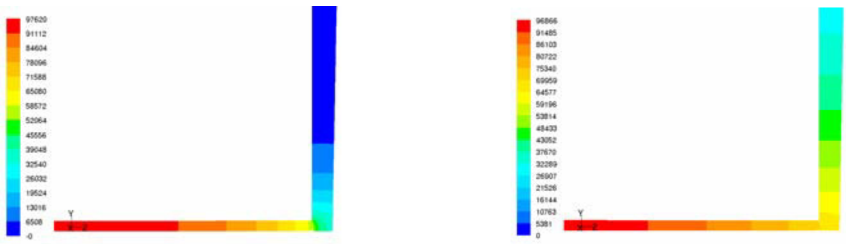
These PDC structures are then joined together by polymer-based bonding to form the final assembly of PDC-HWA[7]. With the description of the fabrication process of PDC-MEMS Hot wire Anemometer, the analytical characterization of steady state characteristics and frequency response in constant temperature mode shown impressive results [8]. Further computational study of Conduction losses and estimate of maximum stresses presented in the following section.

4. Conduction heat loss through prongs

For wire geometry with small aspect ratio end conduction heat loss rate Q may contribute significantly to the total heat transfer rate $Q_{tot} = (\phi + Q)$ where ϕ is the heat transfer rate by convection from the wire [9]. End conduction losses are a consequence of the temperature gradient at both wire ends, i.e.

$$Q = 2\left(-K_w A \frac{\partial T}{\partial X}\right) \qquad (1)$$

An estimate of static end conduction losses for PDC-HWA as well as conventional HWA is analyzed using FLUENT (commercial CFD package). A drastic decrease in conduction loss through prongs was observed when PDC material is used. Table 1. Shows quantitative measure of conduction loss for both cases. Figure 6. Below shows the heat flux contours obtained using FLUENT for both PDC-HWA and Platinum-HWA.



(a) (b)

Figure 6. Contours of total-surface-heat-flux-W/m^2 (a) PDC-HWA (b) Platinum-HWA

Table 1. The quantitative measure of conduction loss

Sensor	q (W) (Generated in wire)	ϕ (W) (Through wire)	Q (W) (Through 2 prongs)	% Of conduction loss
PDC-HWA	0.01	0.00882	0.00106	11.44
Conventional-HWA	0.02	0.00878	0.01123	56.12

5. Stress Analysis

Stress analysis attempts to estimate the maximum stress at which the proposed sensor is subjected to when examined under real engine conditions. The SiCN prongs and SiAlCN wire are used in place of conventional stainless steel prongs and platinum wire. The model was analyzed using ANSYS Finite Element (FE) based commercial code and meshed using tetrahedral elements (Solid 92). Table 2. Shows maximum allowable stress and deflection of both sensors. From these results it can be observed that the new material selection adds to a more robust sensor capable to withstand Ultra high temperature and the harsh environment to which it is exposed.

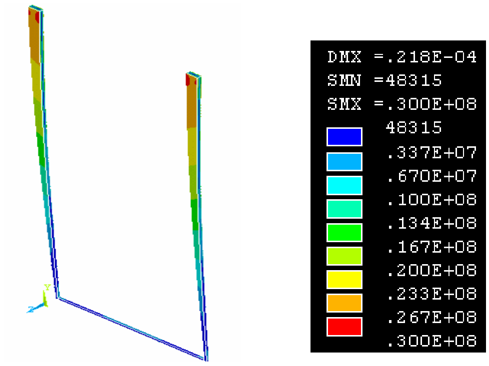


Figure 7. Contours of Von Mises stress distribution

Table 2. Quantitative measure of conduction loss.

Sensor	PDC-HWA	Conventional-HWA
Max. Von Mises stress (MPa)	30	30
Strength (MPa)	800	480
Yield Strength (MPa)	----	170
Deflection (δ)µm	2.18	25.79

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.

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