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Development of cylindrical hot-film sensors for measuring instant velocity of fluid flow

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ABSTRACT

The cylindrical hot-film sensor has found wide industrial application because it combines the high frequency response with improved strength and stability. In this work, such sensors were fabricated for application in different fluids. The sensing part of the sensor consisted of a nanostructured sandwich with a 40–60 nm thick nickel film deposited by PVD process onto a 125 micrometer diameter cylindrical quartz wire. An outer 0.5 or 2 micrometer thick protective silica layer was applied onto the nickel film. The sensors obtained were subjected to various functional and quality assessment tests. Using a constant temperature anemometry (CTA) circuit, the sensors were calibrated conforming to well-known procedures. Furthermore, an evaluation of the sensor response was undertaken by measuring an already known turbulent flow and comparing the results with those of the literature. Finally, technical conclusions were drawn from the results.

1. Introduction

Precise measurement of fluid flow is a key step in the optimization of the fluid flow systems. One of the common devices used for this purpose is the hot-wire anemometer (HWA). The hot-wire sensor consists principally of a tungsten or platinum wire with a diameter of ~5 μm. Using HWA, the fluid flow may be measured with a frequency response better than 30 kHz [1]. It has thus found wide application in research works. However, its industrial application is limited due to its delicateness. The hot-film sensor is preferred for industrial application because of its higher mechanical strength, better resistance to corrosion/erosion, lower sensibility to pollutions, and less frequent need for recalibration. However, it has a lower frequency response compared to the hot-wire sensor. The hot-film sensor consists of a conductive layer deposited on an insulator support. It was introduced basically by Lowell and Patton [2] in 1955, and later in a more applied manner by Ling [3] in 1960; though its improvement continues to nowadays. The hot-film sensor works quite similar to the hot-wire sensor and its calibration is done identically [4].

The present work concerns the application of physical vapor deposition (PVD), as a reliable method of making composite thin films [5], to produce cylindrical hot-film sensors. The stages of design and fabrication; the electrical, mechanical and functional tests; the calibration procedure and finally the overall reliability verification of the sensor via the measurement of an already known turbulent flow corresponding to the Kármán vortex are described.

2. Experimental

2.1. Designing

The composite structure of the hot-film sensor was tailored regarding the desired sensitivity, the type of fluid concerned, and the other working parameters. As the essential part of the sensor, the "hot-film" required a material with high temperature coefficient of resistance (TCR).

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Table 1
TCRs of some common materials at 20 °C [6].

Element/alloy	α, °C^{-1}
Nickel	0.005866
Iron	0.005671
Molybdenum	0.004579
Tungsten	0.004403
Aluminum	0.004308
Copper	0.004041
Silver	0.003819
Platinum	0.003729
Gold	0.003715
Zinc	0.003847
Steel (0.5% C)	0.003000
Nichrome	0.000170
Nichrome V	0.000130
Manganin	±0.000015
Constantan	−0.000074

Table 1 lists the TCRs of some common materials [6]. Moreover, the hot-film required a sufficient strength, a good resistance to erosion, and preferably a limited coefficient of thermal expansion so as to maximize the sensor's resistance to thermal shocks. Consequently we chose nickel as the hot-film material.

The substrate material of the hot-film was required to have, regarding its functions, the following characteristics: (1) electrically insulating, (2) having a coefficient of thermal expansion near to that of nickel so as to prevent excessive stresses at the interface, (3) sufficient inherent adhesion with nickel layer, (4) high strength, (5) low heat capacity in order to preserve the sensor's frequency response, and (6) limited thermal conductivity compared to that of nickel. Therefore, we chose silica as the substrate.

The overall structure of the sensor was designed as shown in Fig. 1. A nickel thin film was considered as the hot-film, deposited onto a quartz rod with a diameter of 125 μm. Such a small diameter of the quartz rod was necessary in order to minimize: (1) the undesired turbulence in fluid flow and (2) the overall heat capacity that reduces the sensor's frequency response.

The thickness selected for the hot-film was a compromise regarding two distinct concerns: (1) minimizing the heat capacity and (2) maintaining the sensor's stability and rigidity. A thickness around 50 nm was chosen, corresponding to an electrical resistance of about 6 Ω throughout the sensor.

The surface protection of the sensor was ensured by applying an outer silica coating with a thickness of 0.5 μm (for the sensors to be used in gas) or 2 μm (for those to be used in liquid). The selection of silica as the external layer was based on its good electrical insulation, good resistance to corrosion and erosion, fairly good adaptability of its coefficient of thermal expansion to that of nickel, sufficient inherent adhesion to nickel, limited heat capacity, and sufficient thermal conductivity.

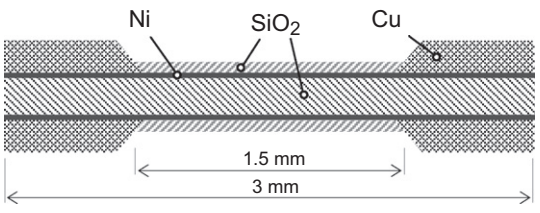

Fig. 1. Schematic design of the hot-film sensor produced.

A 50 μm thick copper coating was planned at both extremities of the sensor in order to facilitate its connection to the probe's prongs. Further details on designing hot-film sensors have been provided previously [4].

2.2. Fabrication

In order to facilitate the fabrication process, several sensors were made using a single substrate rod. First, the substrate quartz rods were heated gently to 300 °C for surface cleaning and preheating. Then they were completely covered with nickel by PVD sputtering. No magnetic field was used in the sputtering process. The deposition thickness was 40–60 nm depending on the sensor type to be made. The structure of the nanofilm could be controlled by deposition parameters, namely the substrate temperature during the deposition, nature and roughness of its surface, rate of deposition, collision angle of the vapor flow with the surface, etc. The experimental results of the deposition process have been published previously [7].

The procedure applied to make the composite structure of the sensors can be summarized as the following: consider the substrate quartz rod divided in its length into segments of 2 mm, 1.5 mm, 2 mm, 1.5 mm and so on. The 1.5 mm segments will make the actual sensor in the final product, and the 2 mm segments will make its extensions. After nickel coating of the entire rods and before their coating with SiO_2, the 2 mm segments were covered by a lithographic photoresist layer. The rods were coated with SiO_2 using electron beam PVD to a thickness of 0.5 or 2 μm depending on the fluid type to which the sensors would be applied. In the next step, the photoresist cover was dissolved in acetone. The rods were lithographed again, this time for covering the SiO_2-coated 1.5 mm segments. Then the rods were coated with copper, by the same PVD system used for nickel coating, to a thickness of 50 μm. Finally, the photoresist cover was removed.

The sensors are required to tolerate temperatures up to 350 °C under working conditions, without undergoing irreversible property changes. So, some kind of annealing was necessary for the nickel hot-film. In conventional annealing treatments, on "bulk" nickel, annealing temperatures as high as 1000° C could be applied for stress relieving, recrystallization and grain growth [8]. However, in the case of the nickel nanofilm, the nanometric thickness of the layer would not allow high temperatures or long times of annealing; because an excessive, uncontrolled migration of atoms at the interface could harm the clean, ultrathin nickel film. Thus, the heat treatment of hot-film sensors of this work was limited to "stress relieving", the phenomenon that occurs at lower temperatures and shorter times compared to those required for recrystallization and grain growth. The stress relieving treatment was carried out at 400 °C for 15 min. The heating rate was 30 °C/min. As described later in this paper, a specific electrothermal