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DEVELOPMENT AND APPLICATION OF HIGH-TEMPERATURE-APPLICABLE PIEZOELECTRIC FILM SENSORS

by

Barend R. Jooste

A DISSERTATION

Presented to the Faculty of

the Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Doctor of Philosophy

Major: Interdepartemental Area of Engineering (Chemical and Materials Engineering)

Under the Supervision of Professor Hendrik J. Viljoen

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DISSERTATION TITLE

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GRADUATE COLLEGE
UNIVERSITY OF NEBRASKA

DEVELOPMENT AND APPLICATION OF HIGH-TEMPERATURE-APPLICABLE PIEZOELECTRIC FILM SENSORS

Barend Rudolf Jooste, Ph.D.

University of Nebraska, 1999

Adviser: Hendrik J. Viljoen

Piezoelectric transducers are used extensively as acoustic sensors and actuators in the non-destructive testing (NDT) of engineering structures and materials at room temperature. There is also a need for acoustic sensors that can operate at high temperatures, for example the monitoring of acoustic disturbances in gaseous combustion processes that cause combustion instability in the gas phase and structural vibrations in combustion apparatus. The sensors could be integrated into a smart control system to stabilize the combustion process and minimize structural vibrations. Another application is in an embedded sensor network for NDT of high temperature composite vessels.

Tantalum pentoxide (Ta_2O_5) was investigated as a possible high temperature resistant piezoelectric material. Thin films of Ta_2O_5 were deposited by reactive sputtering with and without substrate heating. Crystalline films were obtained by film deposition at

450°C and by annealing films deposited without substrate heating. Crystalline β-Ta_2O_5 is formed at these conditions with either monoclinic or orthorhombic crystal structure, which is stable up to 1360 °C and piezoelectric. The piezoelectric response of thermally crystallized Ta_2O_5 film was investigated qualitatively for different annealing temperatures. The piezoelectric response for Ta_2O_5 films deposited in the crystallized form at 450°C were found to have a stronger piezoelectric response than thermally crystallized Ta_2O_5 films and the piezoelectric constant, d_{z1} , of the film determined, based on a freely vibrating cantilevered beam technique. The technique could possibly be extended to measurement of piezoelectric properties of films at elevated temperatures. The constant d_{z1} was determined for Ta_2O_5 film deposited at 450 °C, and for film subsequently exposed to 700 °C in air.

A spring-node model with simulation results is also presented for stress wave propagation in isotropic and transversely isotropic materials with or without piezoelectric properties for intact and flawed material. The model was applied to the impact-echo NDT technique for thick fiber composite materials where a piezoelectric film sensor is used. Experimental and theoretical sensor responses are compared.

for KAREN and THEO

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LIST OF SYMBOLS

Symbol	Meaning of Symbol and Units
A	Surface area of electrode (m^2)
c_{11}, c_{13}, c_{33}, c_{44}	Stiffness constants in abbreviated subscript notation (N/m^2)
c_{damp}	Voltage lost due to damping (V)
c_{fric}	Voltage lost due to initial friction at beam release (V)
c_{ijkl}	Stiffness tensor (N/m^2)
c_{loss}	Total peak to peak voltage lost due to damping and initial friction (V)
C_{kv}	Kelvin-Voigt damping constant (internal damping) (kg/m.s)
$C_{kv,s}$	Kelvin-Voigt damping constant for uncoated beam (kg/m.s)
$C_{kv,sf}$	Kelvin-Voigt damping constant for beam coated with piezoelectric film (kg/m.s)
C_v	Viscous damping constant (kg/m.s)
$C_{v,s}$	Viscous damping constant for uncoated beam (kg/m.s)
$C_{v,sf}$	Viscous damping constant for beam coated with piezoelectric film (kg/m.s)
D_b	Flexural rigidity of beam ($N.m^2$)
$D_{b,s}$	Flexural stiffness of uncoated beam with piezoelectric film ($N.m^2$)
$D_{b,sf}$	Flexural stiffness of beam with piezoelectric film ($N.m^2$)
$d_{centroid}$	Shortest distance between the bottom of the beam and the beam centroid (m)
d_f	Piezoelectric film thickness (m)
D_{FN}	$d_s - d_{centroid}$ (m)

D_{id}	Initial displacement distance of cantilevered beam tip (m)
D_s	Thickness of cantilevered beam (m)
D_x, D_y, D_z	X, y and z components of the dielectric displacement vector (charge displacement vector) (C/m^2)
d_{z1}, d_{z3}, d_{z4}, d_{z6}	Piezoelectric stress constants defined in figure 2.1 (C/N)
E	Young's modulus (N/m^2)
E_f	Young's modulus of piezoelectric film (N/m^2)
E_L	Young's modulus in fiber direction (N/m^2)
E_T	Young's modulus in transverse direction (N/m^2)
E_s	Young's modulus of substrate (N/m^2)
e_{13}, e_{15}, e_{33}, e_{31}	Piezoelectric strain constants (N/C)
E_s	Young's Modulus of uncoated beam (N/m^2)
E_z	Electric field in the z-direction (V/m)
$f_{exp,s}$	Experimental frequency of uncoated cantilevered beam with small piezoelectric sensor (Hz)
$f_{exp,sf}$	Experimental frequency of cantilevered beam coated with a piezoelectric film on one side (Hz)
G_{LT}	Shear modulus of unidirectional fiber composite (N/m^2)
H	Height of material section modeled by SNM (in z-direction) (m)
I	Moment of inertia (m^4)
I_f	Moment of inertia of piezoelectric film (m^4)
I_s	Moment of inertia of substrate (m^4)
I_{sf}	Moment of inertia of cantilevered beam coated with piezoelectric film (m^4)
k_p, k_s	Diagonal spring constants in the SNM (N/m)