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Thin-Film Sensors for Reusable Space Propulsion Systems

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SUMMARY

Thin-film thermocouples (TFTC'S) have been developed for aircraft gas turbine engines and are in use for temperature measurement on turbine blades up to 1800 °F. Established aircraft engine gas turbine technology is currently being adapted to turbine engine blade materials and the environment encountered in the Space Shuttle Main Engine (SSME) - severe thermal shock from cryogenic fuel to combustion temperatures. Initial results with coupons of MAR M-246 (+Hf) and PWA 1480 have been followed by fabrication of TFTC on SSME turbine blades. Current efforts are focused on preparation for testing in the Turbine Blade Tester (TBT) at the NASA Marshall Space Flight Center (MSFC).

INTRODUCTION

Instrumentation to provide test data on surface thermal properties is needed in the development and performance evaluation of liquid-propellant rocket engines, in particular the Space Shuttle Main Engine (SSME) (ref. 1). In the past, surface temperature on jet aircraft engine turbine blades had typically been measured with a wire thermocouple attached to or embedded in a groove cut on the surface of a test component. The bulky mass of sensors and leadwires on the surface can disrupt gas flow over the airfoil. In addition, any physical alteration of a highly sophisticated test component is frequently unacceptable. Thin-film sensors are uniquely suited for measuring surface temperature since they do not affect gas flow. Furthermore, they add negligible mass to the surface and have a minimal impact on the temperature distribution on a test component.

A comprehensive development program was conducted by Pratt & Whitney Aircraft (PWA) under NASA contract to develop basic thin film sensor technology for application on jet engine components such as turbine blades (refs. 2 to 4). In this program, jet engine turbine blades were coated with a thermal barrier coating of NiCoCrAlY. Pt-13% Rh/Pt thermocouples were then deposited on the furnace-grown Al_2O_3 layer and tested for about 60 hrs. up to 1250 K. The technology developed in this program has become the foundation of current thin-film sensor technology.

The objective of this effort is to develop thin film-thermocouples TFTC's for SSME components such as High Pressure Fuel Turbopump (HPFTP) blades. The goal is to obtain blade temperatures for computational models (ref. 5). The technical approach of this program is to investigate preliminary aspects of TFTC technology using flat specimens made of the same material as SSME turbine blades. Fabrication procedures and test results were then applied toward developing TFTC's on actual flight hardware SSME turbine blades. This approach was taken to avoid waste of SSME blades and to separate effects due to material differences from effects due to irregularly-shaped engine components. TFTC's are to be tested in a simulated SSME-like environment provided in the TBT facility located at the NASA MSFC. Preparation for such tests is discussed below.

The basic technology involved in this program is the multi-layer sensor. The thermocouple is sputter deposited on an electrically insulating Al_2O_3 layer grown on NiCoCrAlY. A comparison of jet aircraft and SSME turbine blade TFTC technology is shown in figure 1. The thermocouple legs are Pt and Pt-13% Rh. The most noticeable difference between the two is a plasma jet sprayed NiCrAlY coating applied to the base metal of the SSME turbine blade. The underlying NiCoCrAlY coating is applied to both blades, it is 23% Co, 18% Cr, 12% Al, 0.3% Y, and the balance Ni. This coating is one of a variety of MCrAlY coatings available as thermal barrier coatings; M is Fe, Ni, Co, or a combination of Ni and Co. At high temperatures, Al_2O_3 can be grown on the MCrAlY surface. Additional Al_2O_3 is sputter deposited on top of the thermally grown aluminum oxide to insure a coherent electrically insulating coating.

The most critical aspect of the structure is the aluminum oxide layer. The oxide layer is mechanically adherent through temperature cycling from cryogenic temperatures to about 2000 °F. A Pt versus Pt-Rh thermocouple was chosen because of its chemical inertness and its stability at high temperatures in oxidizing environments. Leadwire connections to thin films are accomplished by parallel gap welding which produces more rugged connections than diffusion bonding (ref. 6).

FABRICATION AND TESTING OF TFTC's ON COUPONS

Flat specimens were wire-cut sectioned from bar stock of the three alloys chosen for this work. MAR-M 200 (+Hf) was chosen to represent material commonly used in jet engine turbine blades and vanes. Much thin-film sensor work has been done on this alloy. Thus, this material serves as a basis for developing thin-film technology for other materials. The bill-of-material for SSME HPFTP blades is directionally solidified (DS) MAR-M 246 (+Hf). Single crystal (SC) PWA 1480 material was chosen because it is a candidate material for future SSME blades. The elemental compositions of the alloys are listed in table I.

Test coupons were chemically cleaned and dried for 1 hr. at 100 °C. They were sent to Chromalloy Corporation (Orangeburg, NY) and coated with a 0.005 in. (125 μm) thick NiCoCrAlY coating. This electron beam physical vapor process deposits a PWA 270 Specification coating, a proprietary NiCoCrAlY coating developed by PWA. The samples were glass bead peened to increase density and effectively eliminate microscopic defects on the surface (ref. 7). The samples were then diffusion heat treated in vacuum at 10^{-7} torr for 4 hrs. at 1975 °F (1350 K). The vacuum heat treatment stabilizes the alloy coating, starts migration of Al toward the surface, and begins gradual growth of a dense, hard, and adherent Al_2O_3 film.

Throughout the remainder of the fabrication process at Lewis Research Center, samples were processed in a cleanroom (fig. 2) without delay between each step to minimize contamination. Samples were then chemically cleaned; particulate matter was removed from the surface by spraying freon gas. Samples were dried for 1 hr. at 100 °C, then thermally oxidized for 50 hrs. at 1880 °F (1027 °C). Onto the thermally grown Al_2O_3 film, an additional Al_2O_3 film of approximately 1.0 μm in thickness was sputter deposited to augment the electrically insulating layer. A 99.99% pure Al_2O_3 target was used for RF diode sputtering at a 1000-W power level in an argon-10% oxygen gas mixture.

The sputtered Al_2O_3 film was heat treated at 1250 K for 1 hr. to convert β- and γ-Al_2O_3 into α-Al_2O_3.

In order to deposit the thermocouples, metal masks were prepared from 3-mil thick stainless steel shim stock by wire cutting the thermocouple leg patterns. Before sputtering, the target was presputtered to remove any surface contamination. Five μm thick Pt and Pt-10% Rh films were sputtered to form TFTC's. Both films were RF diode sputtered at a 500-W power level in pure Ar gas. Clean glass slides were included in the sputtering chamber to monitor film thickness and to determine the elemental composition of sputtered films. Sputtered films were then tape tested for adherence using masking tape pressed firmly in place and then removed by pulling the tape vertically. If no more than 1 percent of the film area was removed, film adherence was judged to be acceptable. Finally, electrical measurements were made to determine if the thermocouples were shorted to the metal substrate. If a short was detected, it was removed by heating the blade in air at 1000 °C, growing additional Al_2O_3 to provide the needed electrical insulation.

Successful thin film-to-leadwire connection was accomplished by parallel gap welding 3-mil diameter leadwire to the 5 μm thick thermocouple films. A parallel gap welder with a constant-voltage power supply was used for the resistance welding. High-purity Pt and Pt-10% Rh wires were used for pigtail leadwires. A typical welding schedule for welding 3-mil diameter leadwires to 5 μm sputtered thin films is presented in table II. The thin film-to-leadwire welded area was routinely covered with Aremco Ceramabond 571, a magnesia-based adhesive with high coefficient of thermal expansion, to provide mechanical protection. Figure 3 shows an example of a TFTC on a superalloy coupon.

Thin-film thermocouples were thermal shock cycled to determine whether the thin films could survive repeated cycling between high temperature and liquid nitrogen. Since TFTC's were being developed for use in an SSME-like environment, the thermal shock cycling parameters were selected to be similar to an SSME environment. The high temperature was 2000 °F (1100 °C), the limit of the furnace used. Liquid N_2 (-320 °F) was selected as the cryogenic fluid. During thermal shock cycling, a TFTC was subjected to 2000 °F (1100 °C) for a few minutes then immediately plunged into liquid nitrogen. After immersion in liquid nitrogen for a few minutes to allow for thermal equilibrium, the TFTC was again subjected to 2000 °F (1100 °C). Six thermal shock cycles was decided upon as the minimum requirement for use in the SSME-like environment.

The TFTC as fabricated survived the thermal shock cycling test; many TFTC's survived as many as 20 cycles without failure. Figure 4 shows a typical emf output of a TFTC during thermal shock cycling between 2000 °F (1100 °C) and liquid nitrogen. The emf output in millivolts of the TFTC is compared with the output obtained from a reference wire thermocouple that was placed as close as possible to the TFTC junction. The reference was made of bare 3-mil diameter thermocouple wires of Pt and Pt-10% Rh. Figure 4 shows results for a coupon of SC PWA 1480; success was also achieved with coupons of DS MAR-M 246 (+Hf).

FABRICATION AND TESTING OF TFTC's ON SSME BLADES

First stage rotor blades of the HPFTP in the SSME were obtained for sputter deposition of TFTC's (fig. 5). These turbine blades were made from DS MAR-M 246 (+Hf). Initial cleaning and NiCoCrAlY coating of blades was the same as superalloy coupon fabrication described previously. Thermal oxidation was carried out on blades using the same parameters as for superalloy coupons. On the oxidized surface, approximately 3 μm of Al_2O_3 was sputtered to augment the insulating layer. Sputtered Al_2O_3 was then heat treated for 1 hr. at 1790 °F (977 °C) to ensure complete conversion into α-Al_2O_3.

The main difficulty in depositing a TFTC on an SSME blade is sputtering thin films over the blade platform. As shown in figure 5, the platform on the SSME blade is very narrow. In order to obtain more evenly deposited films over the platform, the blade was held on a mount that can be tilted while sputtering. The mount was designed to be tilted back and forth by rotating the sputtering chamber platform. Tilting of the blade platform allowed more uniform deposition of sputtered material over the blade platform or shoulder. On the insulated airfoil surface, two thin strips of mylar tape (instead of metal masks) were used to delineate the thermocouple leg pattern. One leg was sputtered with 5 μm of Pt while the other leg was covered during the sputtering run. Then the Pt leg was covered, and 2 μm of a Pt-13% Rh film was sputtered.

Work is underway to prepare for testing of the TFTC's on SSME blades in MSFC's TBT (shown schematically in fig. 6). The instrumented blade will be inserted into a blade holder, supplied by MSFC (fig. 7), in the middle position and will be surrounded by two other SSME blades with or without instrumentation, depending on the test requirements. The test will be conducted with the instrumented blades in a wired holder installed in the TBT at either blade position A or B (fig. 6). Since only the middle blade experiences close to SSME conditions, only one blade per holder assembly will model SSME conditions during a run on the TBT. Design qualification at MSFC is complete; final design and modification of a holder to accommodate the wiring and the instrumented blades is nearly complete.

SUMMARY OF RESULTS

Established aircraft gas turbine engine sensor technology has been successfully transferred to the materials and environment similar to that found in the SSME. Experience with relevant materials in coupon form led to the successful instrumentation of SSME turbine blades. Upon the conclusion of tests on the TBT at MSFC, follow-on work will include transfer of the technology to industry for instrumentation and testing of SSME components in the Test Bed Engine at the MSFC.

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TABLE I. - ELEMENTAL COMPOSITION OF MATERIALS

Element	MAR-M 200(+Hf)	MAR-M 246(+Hf)	PWA 1480
Ni	59	60	62.5
Cr	9	9	10
Co	10	10	5
Mo	----	2.5	----
W	12	10	4
Ta	----	1.5	12
Al	5	5.5	5
Ti	2	1.5	1.5
C	0.1	0.15	----
B	0.01	0.015	----
Zr	----	0.05	----
Hf	2	1.5	----

TABLE II. - REPRESENTATIVE SCHEDULE FOR WELDING LEADWIRES TO THIN FILMS

Wire diameter, μm (mil)	75 (3)
Thin film thickness, μm	5
Parallel gap welder	
Power supply	Constant voltage
Voltage, V	1.10
Time, msec	10.0
Electrode	
Type	Molybdenum-based alloy
Gap, μm (mil)	125 (5)
Tip size, mm	0.635 × 1.14
Force, g	400

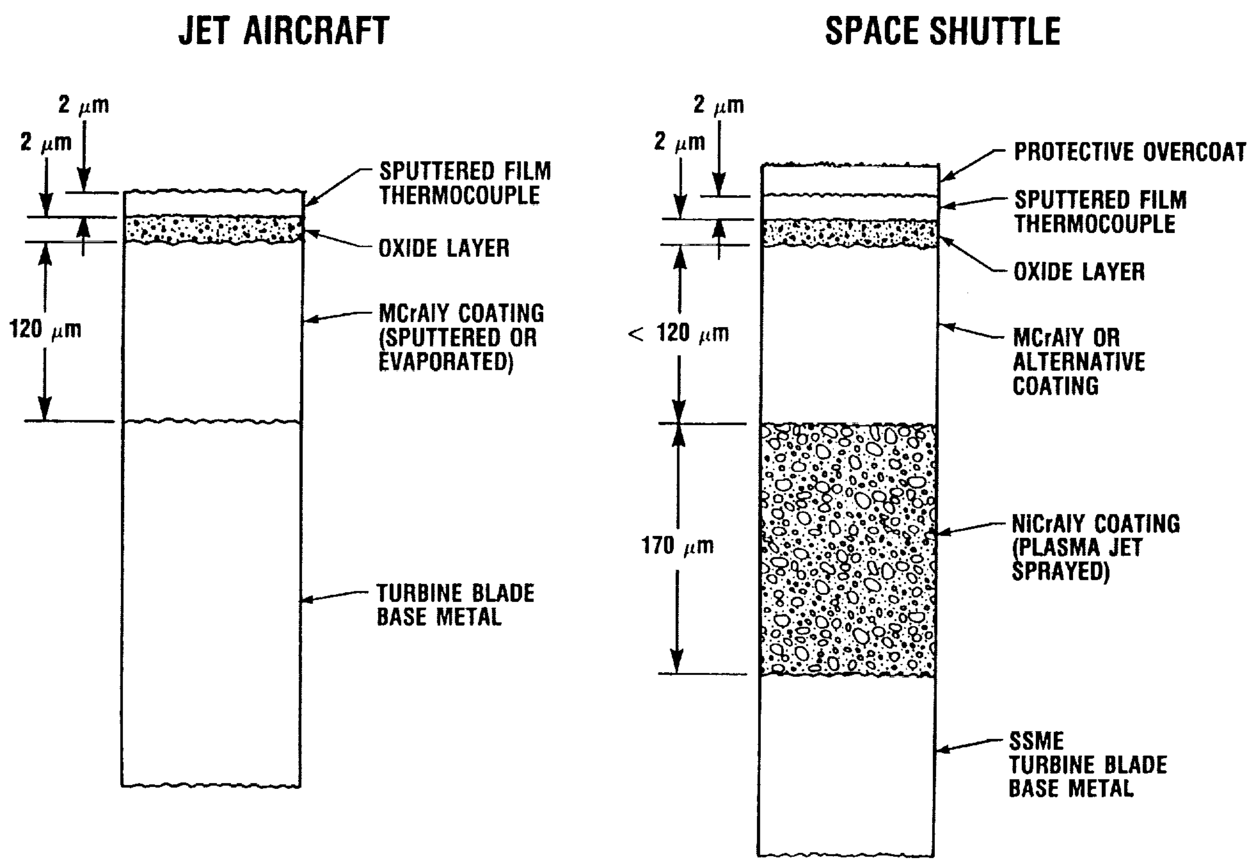

Figure 1. - Turbine blade thin-film temperature sensor technology.

Figure 2. - Thin-film sensor cleanroom.

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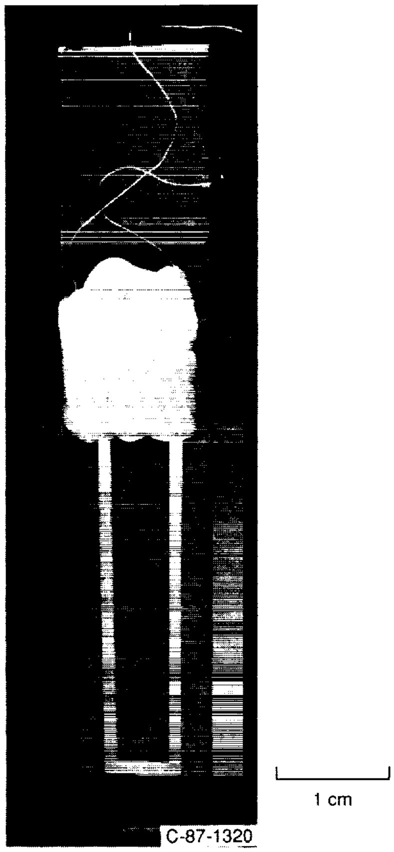

Figure 3. - TFTC on coupon of SC PWA 1480.

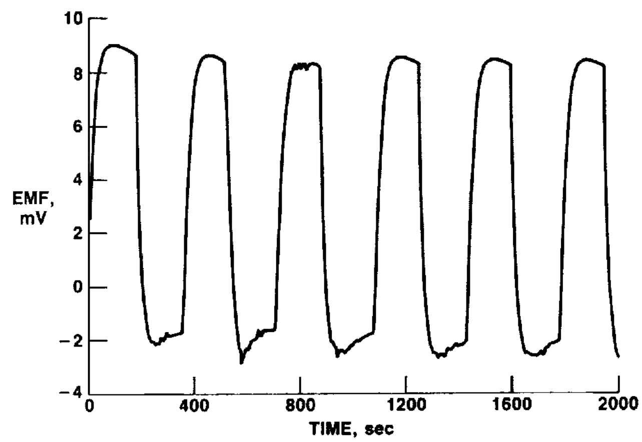

Figure 4. - Signal output of TFTC shown in figure 3 during thermal shock cycling between 2000 °F and liquid nitrogen.

Figure 5. - TFTC'S on airfoil of SSME HPFTP blade, chromel/alumel wire thermocouple on shank.

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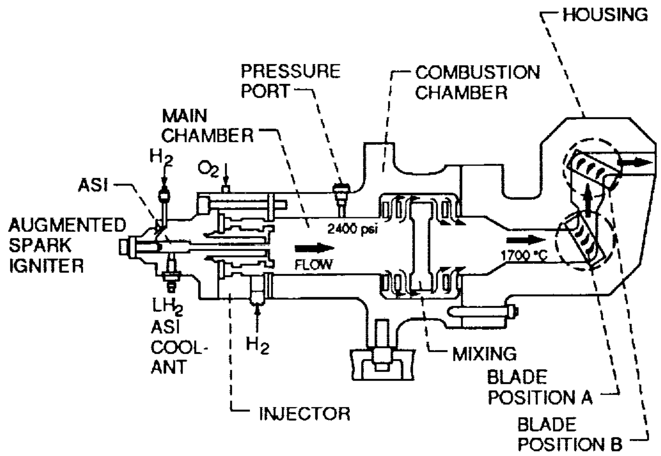

Figure 6. - Schematic of TBT at the NASA MSFC.

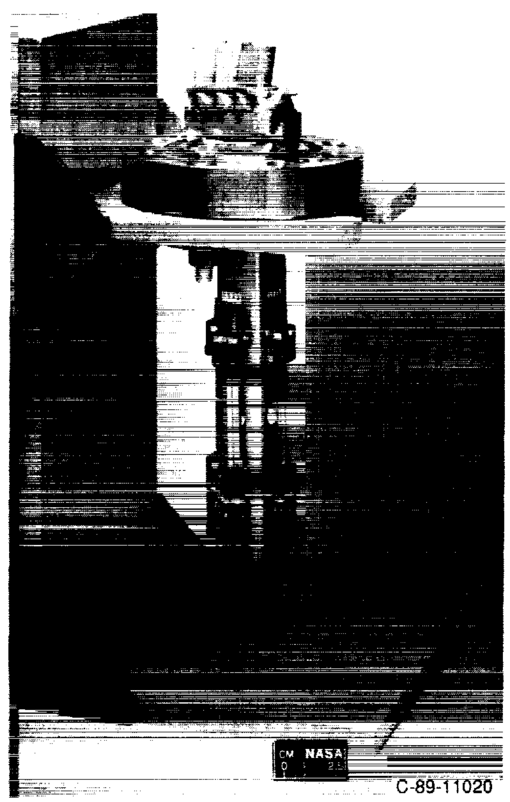

Figure 7. - Blade holder assembly (on wooden stand) instrumented SSME blades wired for test on TBT.

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16. Abstract

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