SUPERALLOY SENSORS

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ABSTRACT

A new method of constructing thin sensing films directly on superalloy surfaces has been developed and several applications of the technology are described in this paper. In this technique, a component is coated and oxidized to form an adherent, high dielectric strength metal oxide surface layer and arrays of sensing devices are sputtered on the oxidized surface. Example temperature and heat transfer coefficient measurements with noble metal film thermocouples are presented and future applications of the technology to strain, erosion, and corrosion measurements are discussed.

Introduction

There has been a longstanding need in the gas turbine industry for methods of measuring the local surface temperatures, strains and heat fluxes on turbine airfoils. Conventional surface measurement techniques perturb the boundary layer on the surface of an airfoil or the heat flows within the airfoil to the extent that detailed analyses of the data are quite difficult. This problem is particularly acute in air cooled turbine airfoils, where increases in the turbine inlet temperatures have been accompanied by complex air cooling designs and attendant reductions of the component cross sections. To meet this need, a new technology for constructing arrays of unusually thin, insulated, sensing films directly on turbine airfoil surfaces has been developed (1) and several applications of the technology are described in this paper.

While the use of thin film sensors for low temperature surface measurements has been common for some time (2,3,4) practical thin film devices for use in harsh environments must satisfy several design constraints which preclude the use of conventional methods and materials of construction and severely limit the choice of alternate materials and techniques of construction. The new method of construction uses a thermally grown metal oxide to electrically insulate the sensing element from the substrate. In this technique, a turbine component is coated with an alloy capable of growing an adherent, high dielectric strength metal oxide. The coated component is then oxidized and arrays of sensors and leads are sputtered on the oxidized surfaces. Wire leads are attached to the sensors and the assembly is reoxidized (Figure 1). The development of practical surface sensors for use in harsh environments is primarily dependent on the development of a coating which is compatible with the substrate material and capable of growing useful insulating surface oxide layers. For turbine alloys, the iron base alloy, Fe 25Cr 5 Al 0. 1Y, has been selected from the group of MCrAlY high temperature alloys which form adherent aluminum oxides during oxidation. An extensive investigation of the electrical properties of the aluminum oxides grown on these alloys led to the initial selection of FeCrAlY (5). The dielectric strengths of oxides grown on this alloy ($>5 \times 10^4$ V/cm at 1093°C) are over an order of magnitude higher than the dielectric strengths of oxides grown on (Ni, Co) CrAlY alloys, while the conductivities of the oxides ($10^{-8} \Omega^{-1}$ cm^{-1} at 1093°C) are an order of magnitude lower than those of the (Ni, Co) CrAlY alloy oxides. In addition, the alloy has desirable mechanical properties throughout the operating range of the sensors and devices using this alloy are unusually durable.

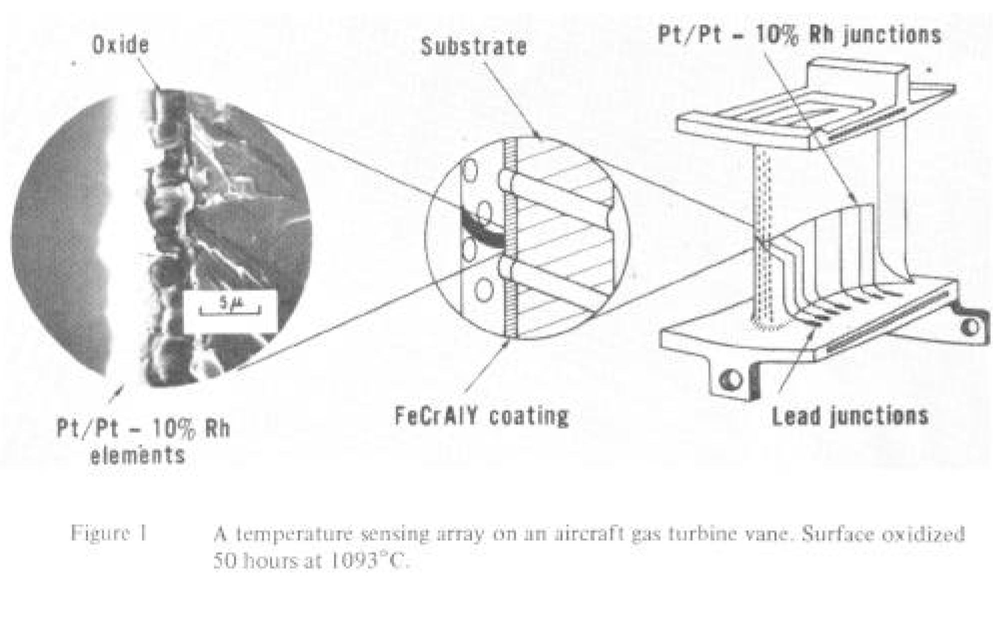

Figure 1 A temperature sensing array on an aircraft gas turbine vane. Surface oxidized 50 hours at 1093°C.

Accommodating the Thermal Mechanical Strains Within the Sensor

Each element of the sensors is chosen for its specific electrical, chemical, or mechanical properties and, as a result, it is necessary to combine materials with widely varying types of chemical bonding. The metal oxide is an insulator with strong ionic bonds, the coating is a high temperature metal alloy and the sensing element is usually a noble metal alloy. Therefore, when the temperature of the assembly is changed, thermal mechanical strains develop within the assembly. In a gas turbine, the assembly experiences unusual thermal mechanical strains during normal operation. When the engine is decelerated from takeoff to idle, a compressive strain of 1.7% (5,860 MN/m^2 stress) is developed in the uniform oxide layer (6,7). At imperfections in the oxide, shear tractions are applied to the metal/metal oxide interface and cause a concentration of inplane stresses at the interface. In addition, the combustor exhaust gases induce small, high frequency temperature oscillations at the metal surface; in a typical gas turbine, the oxide and metal coating near the surface oscillate ±5°C several times a second (6 - 8). These temperature oscillations induce only a ±60 μm/m strain (±21 MN/m^2 stress) in the oxide and a ±120 μm/m strain (±12 MN/m^2 stress) in the coating but the latter strain is adequate to cause plastic deformation of coatings which are sufficiently weak and ductile to accommodate the strains associated with the large infrequent temperature cycles. The deformation of the substrate displaces the surface material into the boundary layer where the oxide and metal are apparently subjected to additional large heat flows (6, 7).

The resultant thermal mechanical strains within the assembly can be accommodated by a limited number of techniques. A scanning electron micrograph study of devices after extensive use in laboratory combustor exhaust gases shows that, in general, the thermal strain in useful (<1-2μm) thin oxides is stored as elastic strain energy in the oxide, while strain relief in usable thick (2-5μm) oxides occurs by buckling and attendant plastic deformation of the substrate (9). It is concluded that, in order for the sensor assembly to remain intact, it is necessary to select a system in which: 1) the compressive shear stress of the oxide is greater than the buckling ›ss of the oxide when it is attached to the coating, 2) the metal oxide/metal interface yield and shear strengths are greater than the coating yield strength, 3) the coating yield strength is small and 4) the coating is ductile over the entire operating range of the sensors. In successful devices, the oxide buckles and cracks when the assembly is thermally cycled, but the strain relief within the coating is sufficiently uniform that the oxide layer remains attached to the coating and continues to insulate the sensing film from the coatings (Figure 2). FeCrAlY satisfies these requirements; the oxide is adherent and the material is sufficiently weak and ductile throughout the operating range that thermal strain relief occurs primarily by oxide buckling and deformation of the FeCrAlY.

The thermal mechanical strains across the noble metal/oxide interface are much smaller since the thermal expansion coefficients of both materials are similar and the yield stress of the noble metal is low. However, it was found that high velocity combustor exhaust gas flow over the sensors does cause delamination of the sensing elements deposited on smooth oxide surfaces. There is no significant bonding between aluminum oxide and useful noble metal alloys, and therefore, the films must be mechanically attached to the oxide (1). The coating is abraded before oxidation in order to cause the growth of an irregular oxide. The films are then sputtered into the irregular surface and interlocked with the oxide (Figure 1). This technique is quite successful. At present, the sensors fail after 20 hours in 1093°C combustor exhaust gases due to gradual carbon particle erosion of the films or changes in the electrical properties of the films.

Applications

Heat Transfer Measurements in Gas Turbines

The new sensors represent quite a change in turbine airfoil instrumentation. The oxide layer and coating are common to high temperature turbine components and the only alteration in the component configuration is due to the thin, 2.5 μm, sensing films. These films are over two orders of magnitude thinner than the conventional strain and temperature sensors which are externally applied to the airfoil surfaces or placed in slots in the airfoil surface. The sensor height is five to ten times smaller than the critical height which will cause a disturbance of the boundary layer on a turbine airfoil (10). The thermal impedance of the sensor elements is over one thousand times smaller than the thermal impedance of the boundary layer on the turbine airfoils or the airfoil wall. Therefore, the sensors do not perturb the airflow near the component, the heat flow from the gas stream to the component, or the heat flow within the component. The sensor metallurgy is based on the superalloy and coating technology developed for gas turbines so that the sensors can be applied to a number of common gas turbine component alloys.

A primary use of the sputtered sensor technology is the measurement of steady state and wide bandwidth surface temperatures of stationary and rotating turbine components. In general, useful information is received within a 0 - 1000 hz bandwidth with an accuracy equal to standard grade platinum-platinum/rhodium thermocouples. An example of a large scale thermocouple array on a first stage turbine guide vane is shown in Figure 1. In principle, any array can be sputtered on an airfoil using available, high resolution, microcircuitry masking techniques. The rugged nature of the sensors and the ability of the FeCrAlY coating and adherent aluminum oxide to endure most superalloy forming and heat treating cycles suggests that the sensors can also be sputtered on subassembly surfaces which can then become internal surfaces in a final assembly. The heat transfer to a component and heat fluxes within the component can be described in some detail from the steady state temperatures measured with arrays of sensors on the component surface or combinations of internal and external sensor arrays.

The local heat transfer to an airfoil in combustor exhaust gases can also be obtained from an analysis of the surface temperature waves induced by the combustor exhaust gas temperature fluctuations (Figures 3 and 4). Surface temperature fourier components within the 2-200 hz bandwidth have been found useful for this purpose (9); these fourier components are rapidly attenuated near the surface of the component and the ratios of their amplitudes to the amplitudes of corresponding gas temperature fourier components are a simple function of the local heat transfer coefficient, h, and the square root of the frequency of the fourier components, f, and the density, ρ , heat capacity, c, and thermal conductivity of the component (see Figure 4). The local heat transfer coefficient is obtained directly from simultaneous wide bandwidth measurements of the exhaust gas and surface temperatures. An example of this type of data measured at the stagnation line of a 6.4 mm cylinder in crossflow in the exhaust gases of a laboratory combustor is shown in Figure 4. A simple linear dependence of the ratios of the surface and gas temperature fourier components on the square root of frequency is observed over the indicated bandwidth. Heat transfer coefficients (in the form of non-dimensional Nusselt numbers, Nu) obtained from analyses of surface temperature waves are compared in Figure 5 with those obtained from more conventional analyses of the transient response of the cyclinders when they are rapidly inserted into the same gas streams. The agreement is excellent over the entire Reynolds number range. Extensive experiments with small cylinders in crossflow in combustor exhaust gases show the precision and accuracy of the surface wave analysis method is ± 5% and the spacial resolution is approximately 0.50 mm (9).

It is also interesting to note that within the indicated Reynolds number range, the stagnation line heat transfer coefficients in combustor exhaust gases are 35% higher than those measured in uniform cold gas streams. The increased heat transfer to the stagnation line is due to the turbulence (10%) of the combustor exhaust gases. The data are in agreement with earlier data measured in turbulent cold gas streams with equal turbulent intensities (11). It is quite useful to establish that the extensive heat transfer data obtained in turbulent cold gas streams can be applied to small components in the actual combustor exhaust gases.

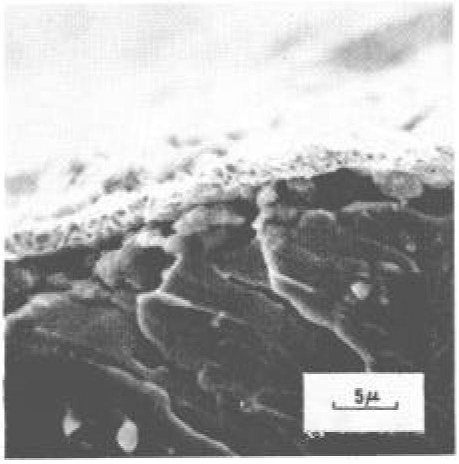

Figure 2 Oxide damage in sensor after extensive use in combustor exhaust gases.

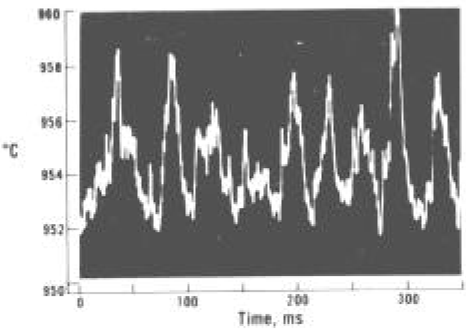

Figure 3 Surface temperature wave at stagnation line of cylinder in crossflow in combustor exhaust gases (see Figure 4).

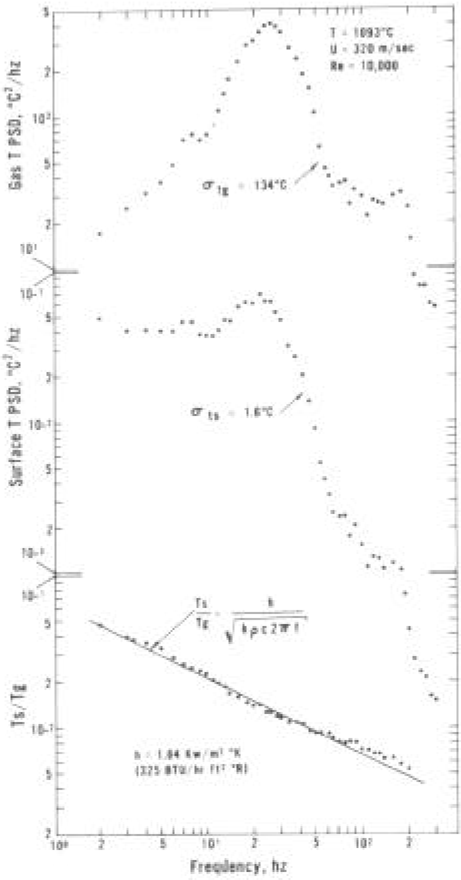

Figure 4 Gas and surface temperature power spectral density functions.

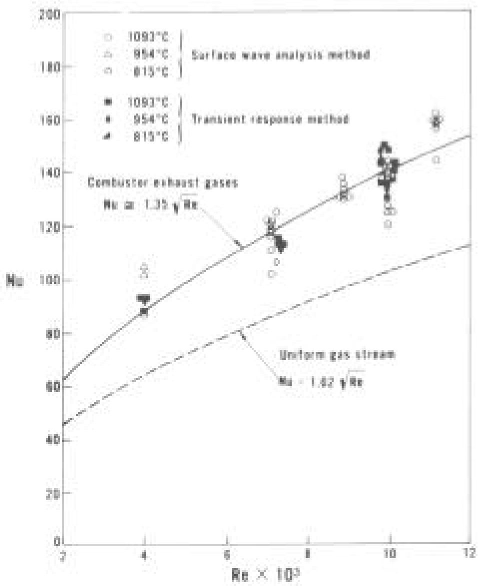

Figure 5 Dependence of Nusselt number at stagnation line on Reynolds number of cylinders in crossflow in combustor exhaust gases.

Dynamic Oxidation

The sputtered sensors have been used in dynamic oxidation experiments where they have provided the first direct measurement of surface temperature waves which can damage the protective metal oxide and significantly increase the rate of oxidation of a material (6, 12). The thermal/mechanical strains induced near the surface of aluminized superalloys in gas turbine main burner exhaust gases do cause fragmentation and separation of the protective aluminum oxide and it is suspected that the gas dynamics of some high temperature gas streams found in power generating units may also significantly affect the oxidation and corrosion processes in these units. Therefore, while the initial interest in this phenomenon has focused on the behavior of materials in gas turbine main burner exhaust gases, where the heat transfer coefficient is constant and the gas temperature fluctuates, it will also be of interest to consider those environments in which the temperature of the gas is constant but the local heat transfer coefficient fluctuates and there is a large steady state heat flux from the gas to the exposed material. This condition arises at changes in the flow path (valves, diffusers, etc.) which can produce flow instabilities. In heat exchangers, where turbulent flow and boundary layers are developed to obtain efficient performance, boundary layer fluctuations also may result in temperature oscillations of the heat exchanger walls. For example, at the surface of fuel elements in nuclear reactors, where the heat flux is on the order of 3.2 MW/m^2, changes in the surface temperature will be directly proportional to changes in the local heat transfer coefficient over a wide bandwidth, and it is suspected that the conditions for dynamic oxidation occur at this location in a reactor. The sputtered sensors should be able to measure the surface temperatures of the fuel elements to define the oxidizing conditions.

Future Applications

It is apparent that a wide range of sensing elements can be applied to the surface of a component once an adherent, high dielectric strength oxide layer is developed on the component. An example temperature compensated strain gage is shown in Figure 6. The unit consists of a strain sensing Pt-W element and a Pt/Pt-10% Rh thermocouple (1). Any number of arrays can be contemplated to provide temperature compensation because the temperature and strain sensing elements can be sputtered in such intimate arrangements that the temperature compensation is quite accurate. In these devices, a thin protective aluminum oxide layer should be sputtered on the assembly to reduce the rate of oxidation of the strain sensing element.

Erosion and salt deposition monitoring devices can also be constructed on the surface of turbine components. In laboratory combustor exhaust gases, it has been found that the life of the thermocouple elements on small cylinders is a sensitive function of the hard carbon particle density and the position and thickness of the sputtered noble metal films. The rate of erosion of an airfoil in an engine could be observed while the engine is operating by monitoring the resistance of platinum films sputtered on the airfoil or by inspection of the films after an engine test.

Pronounced hot corrosion requires ash deposition on the surface of the turbine component (13). However, the rate of ash deposition is a complex function of the chemistry of the ingested gases, combustion dynamics, and the air flow and temperature along the turbine airfoil. Therefore, it is difficult to predict the rate of ash deposition in an engine. The problem can be avoided by sputtering thin films of reactive nickel-base alloys on an airfoil and monitoring the degradation of the films through changes in their resistivity or thickness. In this manner, it should be possible to isolate those engine conditions which cause extensive ash deposition and to monitor the total amount of ash deposition in an operating engine.

Finally, the rate of oxidation can be controlled by applying electric fields between the noble metal films and the substrate. Electric fields have been applied across oxides growing on FeCrAlY and control of the oxidation has been demonstrated (Figure 7) (5, 14). Only a one volt retarding potential is required to completely stop the oxidation of this alloy. The initial experiments were performed to investigate the ionic and electronic conduction across the growing oxides but, in some environments, it may be possible to use the applied electric fields in a practical manner to retard the oxidation of a material for an indefinite period of time.

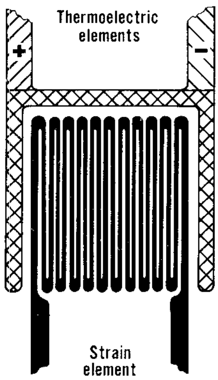

Figure 6 A temperature compensated high temperature strain gage.

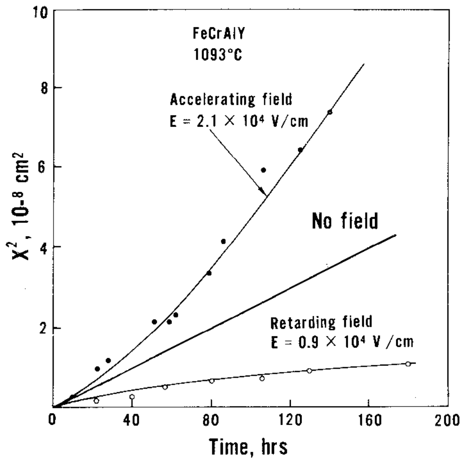

Figure 7 Control of superalloy oxidation with electric fields.

In conclusion, the superalloy sensor technology described in this paper can be used to measure or monitor the response of the surface of a superalloy to a harsh industrial environment. In the future, it will be interesting to record the new directions of superalloy development and component design which will obtain from the new information generated by these devices.

References

1. Dils, R.R., "Process of Coating a Gas Turbine Engine Alloy Substrate", U.S. Patent 3,890,456, 17 June 1975.

2. Burger, H.C., and Van Citter, P.H., "Preparation of Bismuth-Antimony Vacuum Thermal Elements by Vaporization", Z. Phys., Vol. 66, 1930, p. 210.

3. Harris, L., and Johnson, E.A., "Technique of Sputtering Sensitive Thermocouples", Rev. Sci. Inst. 5, 1934, p. 153.

4. See, for example, Chopra, K.L., Thin Film Phenomena, McGraw Hill, New York, 1969.

5. Dils, R.R. and Follansbee, P.S., "Electronic and Ionic Conduction in Aluminum Oxides Grown on High Temperature Metal Alloys", presented at Symposium on High Temperature Electron and Ion Transport in Solids, Electrochemical Society Meeting, San Francisco, May 12-17, 1974.

6. Dils, R.R., "Dynamic Oxidation and Corrosion in Power Generating Units", presented at Symposium on Corrosion Products in Fossil-Fueled Power Generation: The Future, Corrosion/75, NACE, Toronto, April 14-18, 1975, Paper No. 166.

7. Wells, C.H., Follansbee, P.S., and Dils, R.R., "Mechanisms of Dynamic Degradation of Surface Oxides", Stress Effects and the Oxidation of Metals J.V. Cathcart, ed, Met. Soc. of AIME, New York, 1975, p. 221.

8. Dils R.R., "Dynamic Gas Temperature Measurements in a Gas Turbine Transition Duct Exit", Journal of Engineering for Power, Trans. ASME, Vol. 95, Sec. A, No. 3, 1973, p. 265.

9. Dils, R.R., and Follansbee, P.S., unpublished research.

10. Schlichting, H., Boundary Layer Theory, 4th Edition, McGraw-Hill, New York, 1960, p. 557.

11. See, for example, Smith, M., and Kuethe, A., "Effects of Turbulence on Laminar Skin Friction and Heat Transfer" Physics of Fluids, Vol. 9, No. 12, 1966, p. 2337.

12. Dils, R.R., "Fatigue of Protective Metal Oxides in Combustion Chamber Exhaust Gases", Fatigue at Elevated Temperatures, ASTM STP 520, American Society for Testing and Materials, 1973, p. 102.

13. Bornstein, N.S., and Decresente, M.A., "The Role of Sodium in the Accerated Oxidation Phenomenon Termed Sulfidation" Met. Trans, Vol. 2, 1971, p. 2875.

14. Dils, R.R., and Follansbee, P.S. "Control of Metal Alloy Oxidation with Electric Fields" 31st Annual Proc. Electron Microscope Society of America, C.J. Arceneaux, ed., Claitors, Baton Rouge, La., 1973, p. 164.