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# Alumina composite coatings with enhanced high-temperature electrical insulating properties on Ni-based superalloy substrates

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ABSTRACT

Electrical insulation of nickel-based superalloy substrate, especially at high temperature range, is one of the major challenges for the reliability and stability of the integrated thin-film sensors. Here, we report a solution-processed approach to fabricating high-temperature, electrically insulating coatings on Ni-based superalloy substrates. NiCrAlY coatings were fabricated by DC magnetron sputtering and heat-treated, and then $Al_2O_3$ films were deposited by sol-gel method. X-ray diffraction, X-ray photoelectron spectroscopy and scanning electron microscopy were used to characterize the composition, phase, microstructure and morphology of these composite coatings. The electrical resistance of the composite coating was measured as a function of temperature up to 800 °C. Electrical resistance greater than 1 MΩ were consistently achieved from 600 °C to 800 °C. Moreover, this insulating coating survived thermal shock and thermal fatigue tests without cracking or delaminating. A type S thin-film thermocouple was prepared on the composite coating to verify its high-temperature electrical insulation performance.

## 1. Introduction

Thin-film sensors are multilayer electrical devices with thicknesses in the micrometer range. Unlike conventional wire or foil sensors, thin-film sensors can provide precise surface measurement with fast response because of their negligible thermal mass. Moreover, they have minimal impact on the thermal and vibration patterns of the components and create minimal disturbance to the gas flow over the surface. These advantages make them the best candidate for test, certification and real-time health monitoring of gas turbine engines [1–4]. Since the hot components, such as the turbine blades, work in extremely harsh environments, the adhesion of the sensor and its electrical isolation from the superalloy-based substrate, especially at high temperatures, are of great importance for the reliability and stability of all thin-film sensors. Generally MCrAlY bond coat layer (where M represents either iron, nickel, cobalt, or a combination of nickel and cobalt) is deposited on the superalloy substrate to provide a diffusion barrier and enhance the bonding between the insulating layer and the substrate. Next, an oxide insulating layer is applied to improve the electrical insulation, and the sensitive film is then deposited and patterned on top of that layer. The schematic of a thin-film sensor is shown in Fig. 1. $Al_2O_3$ is one of the typical insulating materials with adequate resistivity and stability at elevated temperatures. Different approaches, including a variety of deposition techniques and post-treatments, have been attempted to improve the electrical insulating property of $Al_2O_3$ coatings. However, the resistance of this insulating coating can reach only $10^3$ Ω at high temperatures, which is much too low to be satisfactory [5–10].

Sol-gel method is a simple, cost-effective approach for the production of dielectric films and coatings. It also has the advantages of being able to coat materials with complex geometries and keeping excellent homogeneity, as well as allowing low-temperature sintering and so on [10–14]. These characteristics of the sol-gel process make it an ideal choice for the fabrication of electrically insulating coatings on the hot components of turbine engines. However, the high-temperature electrical insulating properties of alumina coatings prepared by sol-gel method has rarely been reported. In this work, we report the formation of alumina films on top of a heat-treated NiCrAlY bond coat through a facile sol-gel process. The microstructure and high-temperature electrical insulating properties of this composite coating were characterized; in addition, thermal shock and thermal fatigue tests were performed to examine the adhesion of the coating. Finally, a thin-film thermocouple (TFTC) was fabricated on the composite coating for further verification of the insulation performance of the composite coatings.

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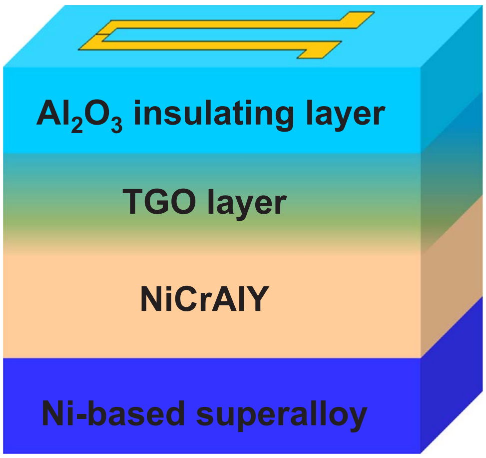


**Fig. 1.** Schematic of thin-film sensors on a superalloy substrate.

**Table 1**
Parameters of DC magnetron sputtering deposition of the NiCrAlY coating.

| Base pressure (Pa) | Sputtering pressure (Pa) | Sputtering power (W) | Substrate temperature (°C) | Deposition time (h) |
|---|---|---|---|---|
| $< 5 \times 10^{-3}$ | 0.45 | 500 | 450 | 6.5 |

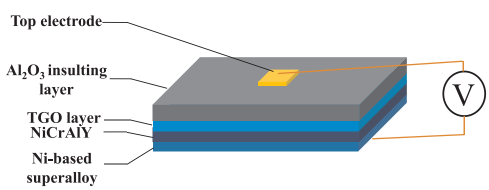


**Fig. 2.** Schematic of transverse resistance measurement of the composite coating on the nickel-based superalloy substrate.

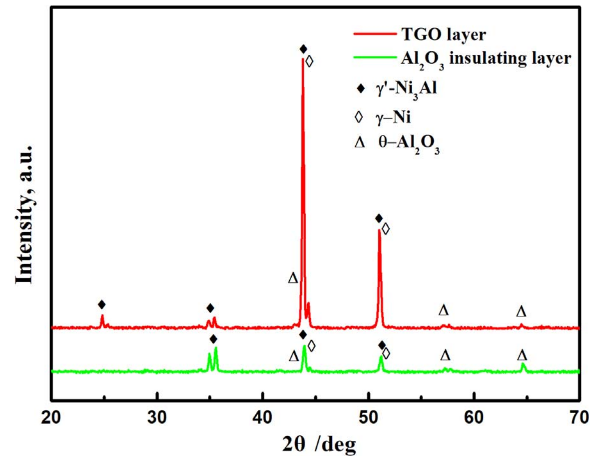


**Fig. 4.** XRD patterns of the TGO layer and the C5 sample.

## 2. Experimental

Nickel-based superalloy substrates were mechanically polished and cleaned with acetone, alcohol and deionized water in sequence. Then, the NiCrAlY coating was deposited on the nickel-based superalloy substrate by DC magnetron sputtering. The optimized parameters of the NiCrAlY coating fabrication are presented in Table 1. After the deposition, the NiCrAlY coatings were annealed for 5 h at 1050 °C in vacuum so that aluminum would segregate to the surface of the coating. Next, the coating was oxidized for 5 h at 1050 °C in oxygen, and a thermally grown oxide (TGO) layer was formed on the top surface of the coating; the TGO is mainly composed of aluminum oxide.

Finally, in order to form an additional insulating layer, an $Al_2O_3$ film was deposited on the surface of the TGO layer by sol-gel method. A water-based particulate alumina sol–gel with nanoparticle size of 2 nm was used, and the mass fraction of alumina sol-gel was 10.00 at%. The superalloy substrate with the heat-treated NiCrAlY coating was immersed into this solution and allowed to soak for 1 min; then it was withdrawn at a speed of 60 mm/min, and the wet coating was heat

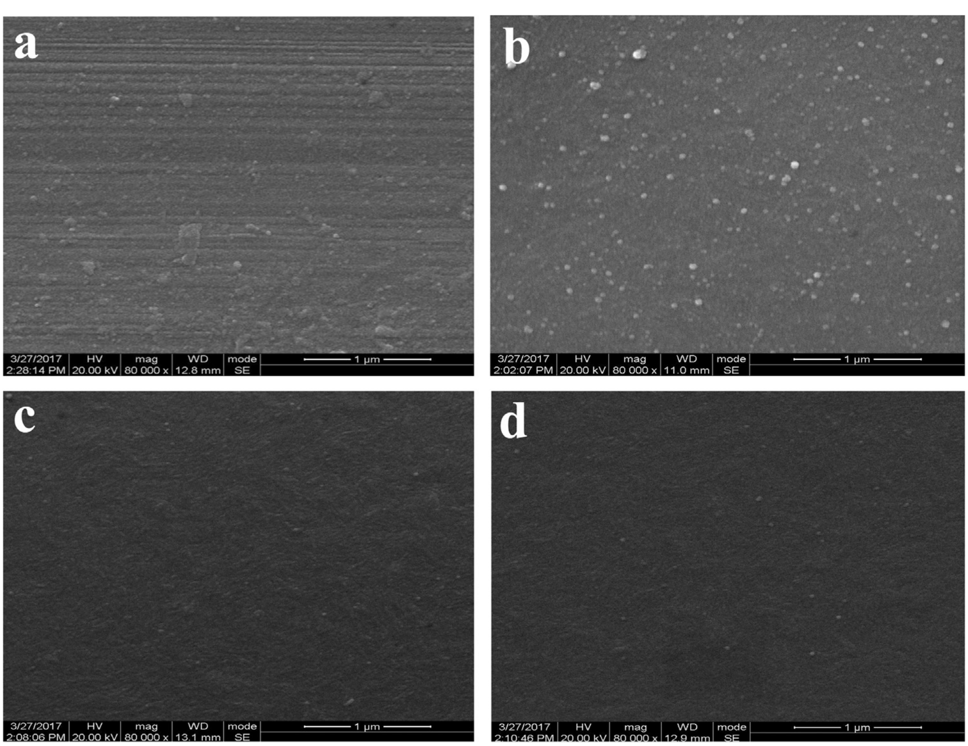


**Fig. 3.** SEM images of (a) as prepared TGO layer and (b) C3, (c) C5, (d) C7 samples.

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