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Technical Note

Novel High-Temperature Reliable Heaters in Plasma Spray Technology

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Novel high-temperature (600 °C) self-regulated heaters have been developed with air plasma spray technology on metal supports, according to the design and processes disclosed in the U.S. patent that was recently published. In the present article, the essential steps of this development are delineated together with the results achieved.

Keywords air plasma spray, heaters, high-temperature operation, multilayer coatings, temperature sensors

1. Introduction

The use of electric heating elements pervades all of the fields of scientific instrumentation, industrial apparatus, medical equipment, and everyday life. Different applications require different characteristics in terms of, for example, size-, shape-, power-, and temperature-rated values, response time, and life span. Therefore, various technologies are applied to fulfil the various requirements (e.g., microelectronic, thin and thick film technologies, etched foils, cable, and tubular heaters).

In this context, the introduction of novel heaters (Ref 1), that are manufactured with an old and mature technology, the air plasma spray (APS) technology, may appear surprising. Yet, this latter technology, in principle, offers some relevant advantages over other assessed processes, including the capability to coat large surfaces of substrates having complex shapes quickly and with a variety of materials (Ref 2). In fact, thermally sprayed heaters have been developed for systems operating at relatively low temperatures (<200 °C), for example, pipelines for hot air and water (Ref 3) or copying and printing machines (Ref 4). On the contrary, the development of high-temperature heaters appeared to be a very hard task, beset by defeats and limitations (Ref 5).

This article describes the feasibility and performance of new heating elements operating reliably over long time periods at temperatures up to 600 °C in air.

2. Design and Experimentation

The design included planar and cylindrical heaters on metal substrates with heating elements based on nonprecious metals, to be realized with standard atmospheric plasma spray equipment, commercially available powders, and masks for defining the heating element layout. Moreover, the metal base had not to be restricted to high-quality corrosion-resistant alloys but rather had to include, for instance, low-carbon steels. A schematic representation of the heater plate is given in Fig. 1: a blank alumina coating electrically insulates the heating element (a meander made of Ni, Ni20Cr, or Ni5Al) from the substrate, and a second alumina near-blank coating protects the conductive meander from the environment.

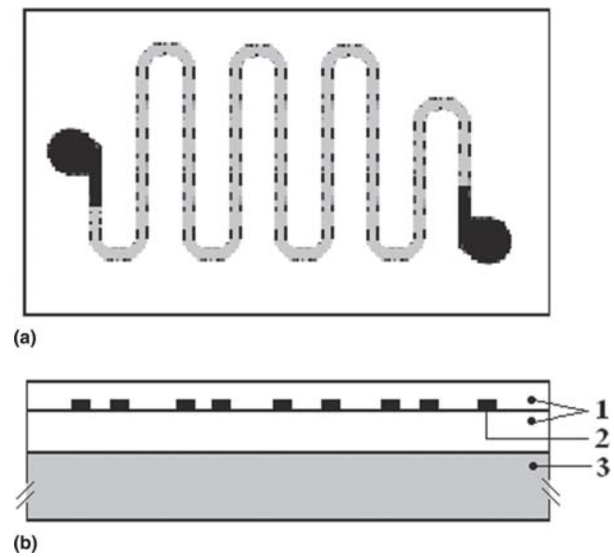

Fig. 1 Heating plate design: (a) plane view; (b) cross-sectional view. The alumina coatings (1) are ~100 µm thick, the conductive meander (2) is ~30 µm thick and 2 mm wide. The substrate (3) is a metal coupon.

In the early stage of the implementation of this simple design, the following problems were identified at the origin of the catastrophic degradation of the heaters:

- The low corrosion/oxidation resistance of blasted steels, even blasted stainless steels (Fig. 2)
- The reactivity of base metals during APS deposition as well as during the heating operation
- Inadequate configuration of the heating layers in terms of composition, thickness, and width homogeneity or roughness of the heating stripe pads

All of these features may also be of some importance in the development of passive thermally sprayed coatings but assume a

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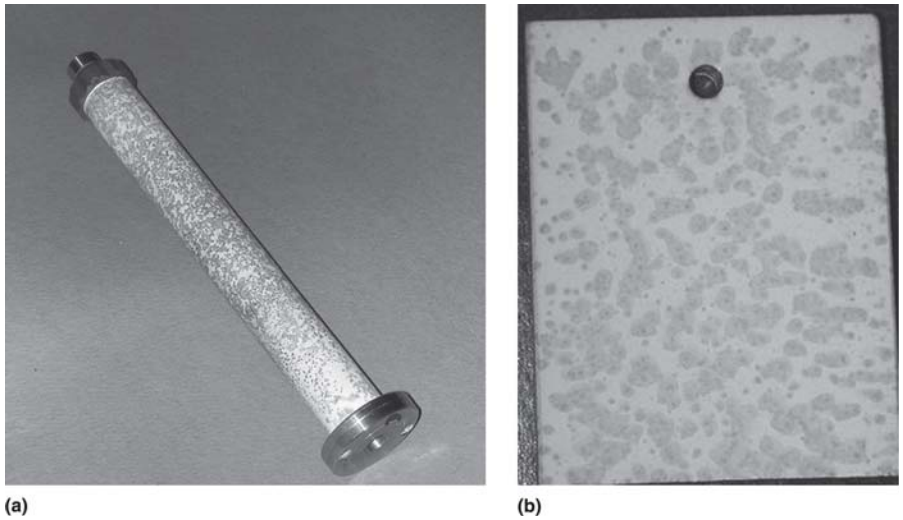

Fig. 2 Stains on the first alumina layer due to: (a) oxidation of a nozzle left at room temperature in a humid environment after the spray process; (b) corrosion of the plate in NaCl + H_2O saturated solution

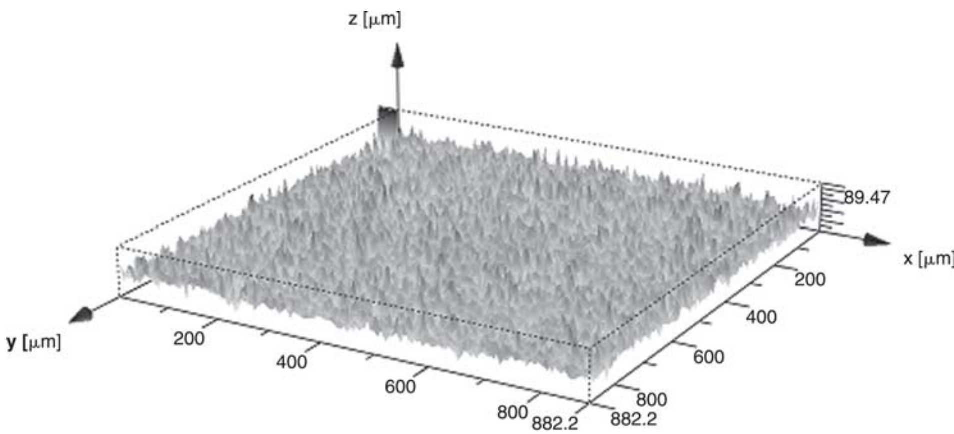

Fig. 3 Laser scanning confocal microscopy topographical image of a blasted steel

dramatic relevance in the development of high-yield and reliable heaters (Ref 5).

After a close scrutiny of the degradation modes and failures by means of many analytical techniques (Fig. 3) the following solutions were identified:

- Oxidation/corrosion phenomena were removed with substrate interfacial layers that were able to prevent any interaction between the coatings and the iron and iron-bearing underlying materials (Ref 1).
- Problems due to the contamination of the sprayed layers were solved by means of a selection of the sprayed powders and the control of the equipment used for the APS process. Essentially any contamination of the conducting stripe for iron had to be removed.
- Problems due to the reactivity of the base metals for the heating element were circumvented with the proper choice of the spraying parameters as well as by their adequate "protection" from the environment. It was found that reproducible and homogeneous stripes are easier to achieve in Ni than in Ni20Cr; the latter can in fact result in layers with newly formed phases (oxides and chromite) that are responsible for hot-spots and the degradation of the heaters. Moreover, the heating elements have to be protected from the environment, especially to prevent oxide formation during the high-temperature operation. Also, on the pads a uniform film of Au, Cu, or AuCd alloy allows reliable connections.

Finally, a metal thin film flash evaporated on top of the heater minimizes the power loss due to infrared radiation emission at high temperature.

A detailed report of the experimental work, findings, and strategies will be given in a forthcoming article.

3. Results

Figure 4 shows, for example, two types of heating elements: a runner nozzle for a polymer injection moulding apparatus as described in the patent publication (Ref 1) and a heating plate.

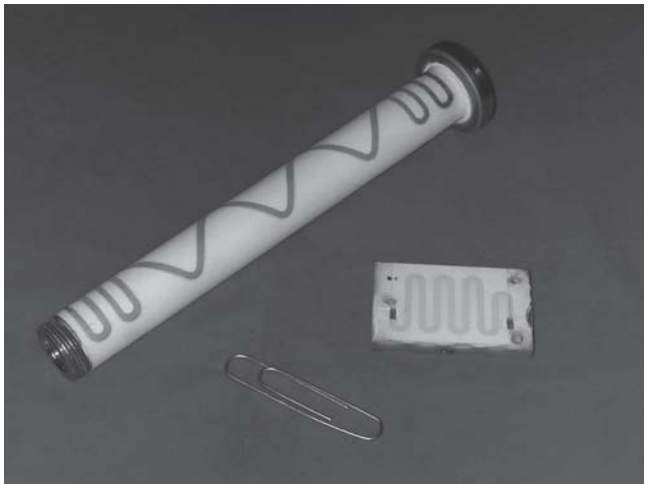

Fig. 4 Two types of heating systems implemented in APS (i.e., a hot runner nozzle for injection moulding apparatus and a heating plate)

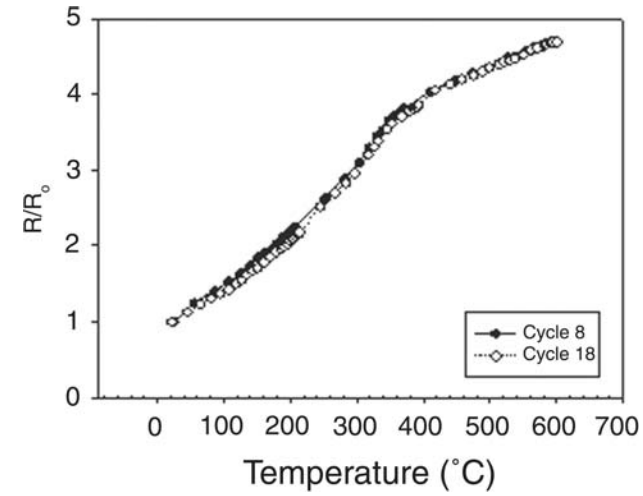

Fig. 5 Temperature dependence of resistance R normalized to that measured at 25 °C. The data are reported for different thermal cycles.

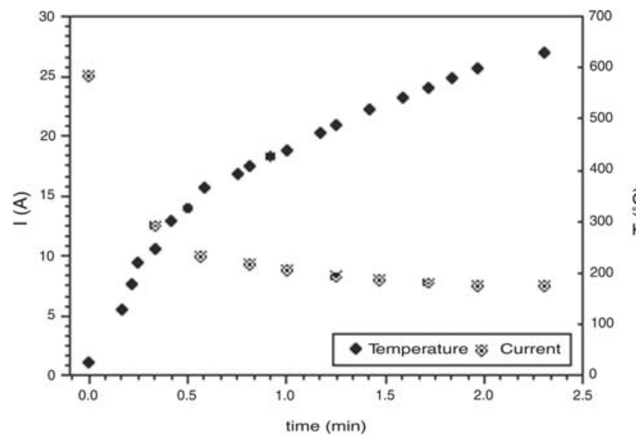

Fig. 6 Temperature versus time for the heating plate shown in Fig. 4, under constant bias voltage of 24.5 V

The newly developed heaters implemented with Ni-based stripes exhibit the following distinct characteristics:

- Operating temperatures ranging from room temperature to at least 600 °C. This range is uncommon for heaters built with other technologies (e.g., thick film technology); also, micro-hot plates fail at high temperatures in a short time (Ref 8).
- Direct reading of the heater temperature from the resistance-temperature relationship (Fig. 5); hence, any control of the heater is possible without further temperature sensors
- Fast warmup (e.g., Fig 6)
- Heat transfer at the theoretical limit at start up
- Homogeneous temperature distribution over a wide area as a result of the intimate contact between the heating element and the substrate as well as the good thermal properties of the constituents, especially of the substrate
- Immunity from thermal shocks, which notably affects heaters on ceramic substrates
- Industrial reliability over long time periods even at high temperatures

3. Conclusions

We have reported for the first time the design and main characteristics of self-regulated heating elements prepared with APS, for operation over a wide temperature range (20-600 °C). The natural applications of the plates are in the field of sensors (e.g., as platforms for high-temperature operating sensors, as well as for the integration of sensors and actuators on engineering components and structures). In a forthcoming article, we will give supporting evidence for the origin of failures occurring without an accurate design and implementation of these elements and related systems (Ref 1), together with the expedient strategies used to avoid them. These results are not only interesting per se, but also prove that “smart thermally sprayed coatings” (Ref 6, 7) can become a reality, opening up a new dimension for an active APS technology.

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