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APPLICATION OF THERMAL SPRAYING METHODS FOR MANUFACTURE OF RESISTIVE COATINGS (REVIEW)

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The review describes the experience of applying thermal spraying methods in manufacture of resistive coatings, as well as the use of appropriate materials containing different alloys and oxides. The positive results of producing resistors by the method of plasma spraying were obtained, providing a service life of more than 10 thou h at a temperature of 150 °C. The examples of practical application of resistive heating elements directly on the working surfaces of parts, requiring preheating to 400–500 °C, by the methods of thermal spraying were considered. The effective application of thermal spraying of resistive coatings on the products of electronic industry is shown, the specifics of which is associated with providing heating of local areas with a minimal thermal effect on the substrate. The advantages and prospects of developments of thermal spraying technology in producing of resistive coatings in different fields of engineering (electrical engineering, electronics, instrument engineering, etc.) are noted. 17 Ref., 6 Figures.

Keywords: *resistive coatings, thermal spraying, resistor, resistive heating element, electronics, electrical engineering*

The list of coatings which can be applied using thermal spraying (TS) methods is predetermined by the possibility of heating the materials sprayed to the stage of melting or high plasticity. Up to nowadays, the experience in producing TS coatings from materials with different physicochemical, physicomechanical, thermophysical, electrophysical, optical, and other properties was gained. Due to this, a wide area for functional purpose of thermal coatings is available. They can be wear-resistant, corrosion-resistant, heat-protective, including also those having different electrophysical properties. The development of works in this direction allowed applying these coatings in the field of electrical engineering, electronics, radio and instrument engineering [1, 2]. The further development of works in this field of engineering is challenging [3, 4].

One of the main areas of developments in the field of functional thermal coatings with special electrophysical characteristics is the creation of coatings with resistive properties. To these coatings the corresponding requirements are specified:

- high specific resistivity;
- low temperature coefficient of thermal expansion;
- ability of long-time operation at elevated temperatures, maintaining the properties;
- stable phase composition;
- minimum porosity;
- uniformity of coating across the thickness;
- high adhesion strength with the base.

Considering the experience of developments related to the formation of thermal coatings with resistive properties, a group of works is distinguished related to the application of the alloy Kh20N80 as a material for spraying, known for its resistive properties, to determine the degree of meeting the abovementioned requirements of these materials in the state of sprayed coating.

The first works in this direction were carried out in 1976 at the Drexel University (USA) with measurement of influence of the size of sprayed particles on specific resistance of plasma-sprayed coatings of powder NiCr [5].

The staff scientists of the State University of New York at Stony Brook (USA) carried out works on manufacture of resistive heating elements (RHE) for kitchen electric cookers, the possibility of heating to 600 °C for 1 min and the stability of the specific resistance of the RHE of NiCr (80/20) to 900 °C is shown [6].

The results of the investigation of the process of producing and properties of RHE in the form of strips, where the deposition of Ni20Cr layer was carried out using the methods of atmospheric plasma (APS), vacuum plasma (VPS), high-velocity oxygen fuel spraying (HVOF), were presented by the Massachusetts Institute of Technology (USA) [7]. On the strip base an insulating ceramic layer was deposited, and then a resistive coating of 75–300 μm thick was sprayed. The advantage of methods VPS and HVOF was shown in connection with more dense, uniform across the thickness and pure microstructure of coating.

A detailed investigation of properties of the resistors produced by the methods of plasma and high-velocity oxygen fuel spraying using Ni and Ni20Cr powders was carried out at the Modena University (Italy) [8]. The effect of cyclic heating and cooling on the stability of characteristics of these resistors was established.

A comprehensive complex of investigations on the application of composite thermal coatings as functional ones in the manufacture of film heaters

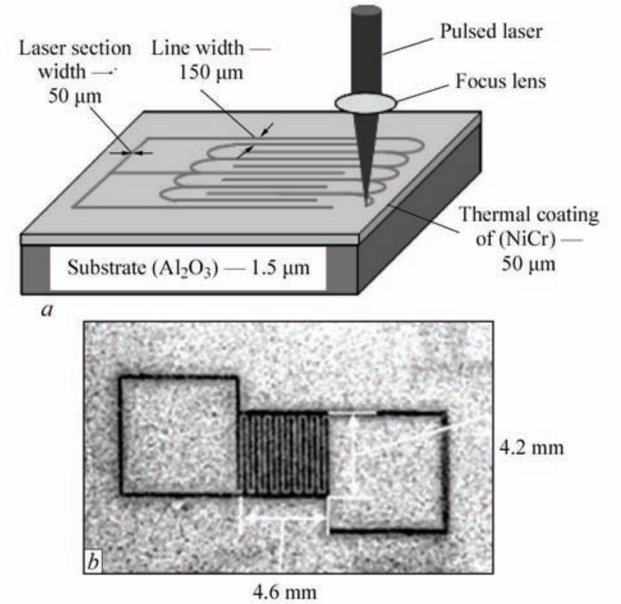

Figure 1. Scheme of producing high-definition sensors applying thermal coating of NiCr with the following flashing by CAD-laser: (*a*) and example of microheating element sensor (*b*)

was performed at the University of Stuttgart (Germany) [9]. Spraying of coatings from the powders and wires NiCr, Fe13Cr, FeCrAl was carried out using the methods APS, HVOF and electric arc spraying. The investigation of the relationship between the electrical properties and service life of heaters and the structure and properties of sprayed layers was carried out.

The development of TS technology in the manufacture of resistive sensors for control of temperature of gas turbine blades was carried out by the Siemens Power Generation (Germany) and MesoScribe Technologies (USA) [10, 11]. The NiCr-based sensors, placed directly on the working surfaces of the blades, provide a constant temperature monitoring of their condition (Figure 1).

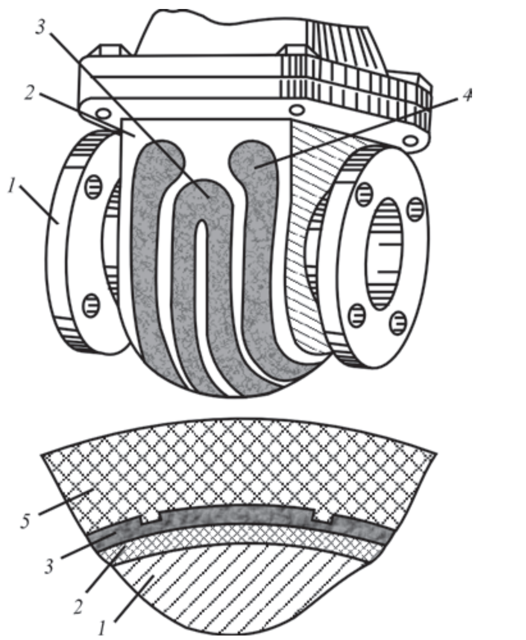

Figure 2. Casing of stop valve with sprayed heating element [12]: *1* — casing; *2* — electrical insulating layer; *3* — resistive track; *4* — supplying electrical contact; *5* — additional external electrical insulating layer

Deposition of heating element by thermal methods directly onto the working surface provides a significant increase in heat transfer efficiency up to 96 %. The I.N. Frantsevich Institute for Problems in Materials Science of the NAS of Ukraine developed at the time such RHE, which were deposited by the TS method [12]. The composite RHE consisted of an electrical insulating coatings based on aluminum oxide or magnesium aluminate spinel of 300–600 μm thickness depending on operating conditions and a resistive heating layer based on nichrome powders, nickel and their alloys of 100–200 μm thickness. The RHE can be operated up to the heating temperatures of 400–500 °C. An example of the Du-100 valve is given, installed in the sulphur transportation line with an operating temperature of 180 °C (Figure 2).

Such RHE sprayed on the surface of valves, stop valves, provide stable, high operating characteristics during outdoor installing and operation under unfavourable conditions. The use of resistive material NiO/Fe_3O_4 with a good stability of electrical properties at elevated temperatures allows manufacturing resistors using the method of plasma spraying for a whole number of products in the electronic industry [13]. The results of duration of stable operation of resistors, produced by the method of plasma spraying from the mixture ($NiOFe_3O_4$ 55/45) during 10 thou h spent in air at 150 °C, and for resistors with a resistance value of 340 Ohms are shown in the form of a histogram (Figure 3). The Figure shows, that the change in resistance is always less than 10 % and the average deviation for most resistors is equal to 5 %, which corresponds to the technical specifications: 2 % for 1000 h of operation. The change in the composition of powder and the film thickness allows withstanding the value of thermal expansion coefficient in the range of $200\cdot10^{-6}$ Ohm/°C, which corresponds to the value for resistors produced by screen printing.

The advantage of TS when applying resistive coatings consists in the high mechanical strength of coatings, produced by plasma spraying, as well as the ability of reducing the production costs due to the use of inexpensive substrates and coating materials in the manufacture of resistive films for integrated circuits, the resistance of which can vary from tenths of Ohms to several MOhms. Other advantages of TS over the method of screen printing with paste application, where the firing procedure leads to increase in labour intensity and limits the selection of bases with the requirement of using expensive refractory ceramics, allow plasma spraying as a method of manufacturing thick-film coatings for microelectronics to significantly expand the practical use of electronic voltage regulators. In particular, the use of resistive coatings in the

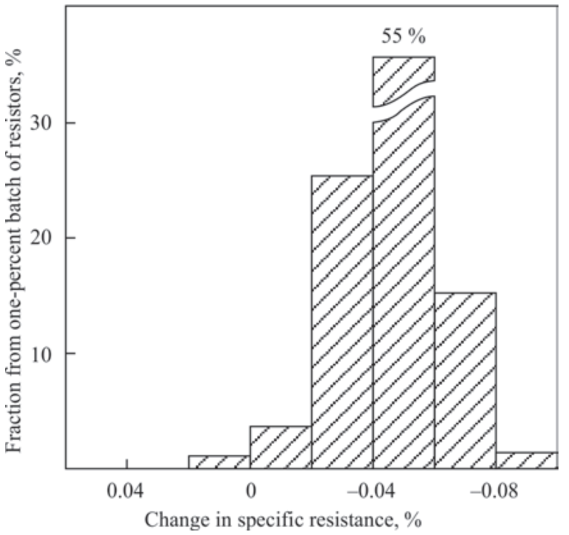

Figure 3. Change in specific resistance of batch of resistors after 10 thou h of operation at 150 °C in air

automobile industry requires accounting for the operating conditions: environmental temperature range from –40 to 110 °C with sharp temperature fluctuations; change in humidity; vibration forces of up to 30 g; resistance to a whole number of polluting materials, including gasoline, diesel fuel, detergents, antifreeze, dust, salt; abrasive influence of sand; fungi. In this regard, the use of plasma spraying in the manufacture of microcircuits significantly allows increasing the reliability of their operation under the conditions of vibrations, temperature and humidity fluctuations, which will allow using them in the automobile industry (creating electronic speed controllers, windscreen wiper control, systems of fuel injection and ignition).

At the Fraunhofer Institute for Ceramic Technologies and Systems (Germany), RHE of TiO_2 were produced, applying the methods of HVOF and APS at a thickness of resistive coating from 100 to 200 μm in the form of a plane and tubular heater with a heating temperature of 300 °C (Figure 4) [14]. The electrical insulation properties were obtained by applying a deposited spinel layer with a thickness of up to 300 μm.

According to the work results the conclusions were made concerning the further development of the investigation with the spraying of coatings with resistive properties of 20 % Cr_2O_3–TiO_2 mixture to increase the operating temperature of heating over 300 °C.

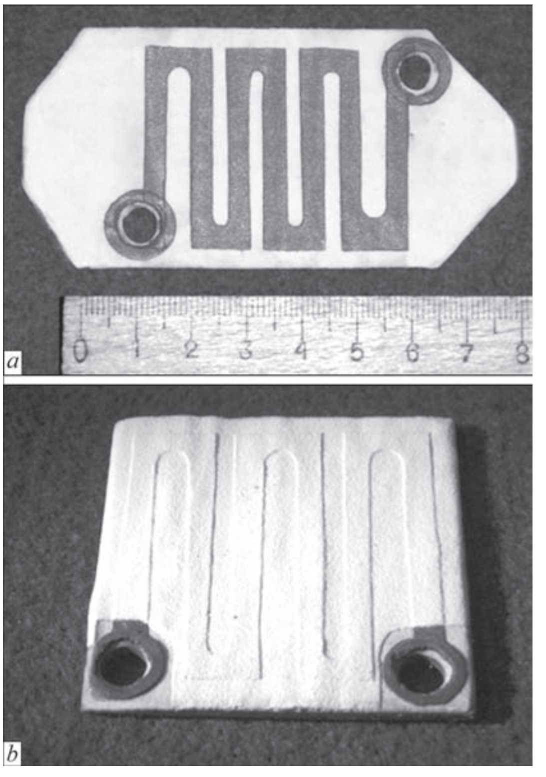

Figure 5. Resistive heating element: *a*, *b* — respectively, two-layer and three-layer coating of Al_2O_3 and TiO_2

At the E.O. Paton Electric Welding Institute the specimens of RHE from multilayer coatings were produced, applied on a steel base by microplasma spraying method (Figure 5) [15].

To form narrow resistive tracks, the powder TiO_2 with particles size of 15–40 μm was used. For electrical insulation of resistive tracks from the steel base, a sublayer of the powder Al_2O_3 with particles size of –40 μm was preliminarily applied to the latter. The carried out tests of resistive heating elements showed their serviceability up to a temperature of 230 °C at a specific power of 75 W (Figure 6).

Using plasma spraying method, the State Scientific and Production Powder Metallurgy Association (Republic of Belarus) manufactured RHE applying lanthanum chromite ($LaCrO_3$) coatings [16]. This material allows increasing the operating temperature of the RHE to 1800 °C. With RHE of $LaCrO_3$ the electric furnaces for testing and treatment of ceramic products of refractory metals were equipped, which allowed

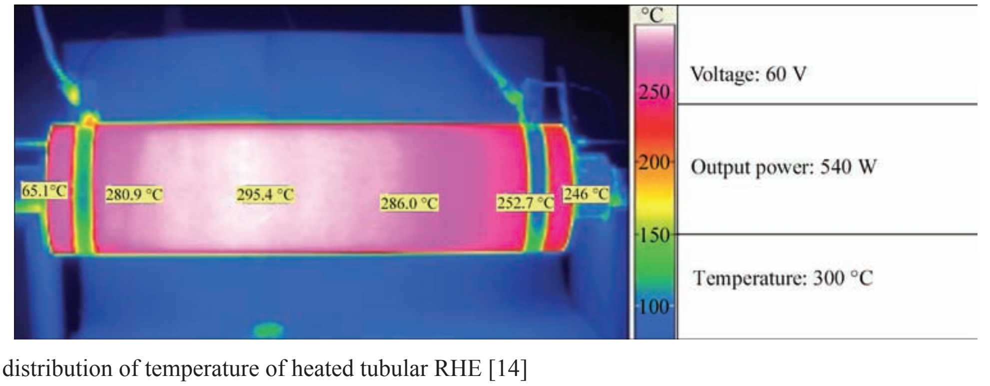

Figure 4. Heat distribution of temperature of heated tubular RHE [14]

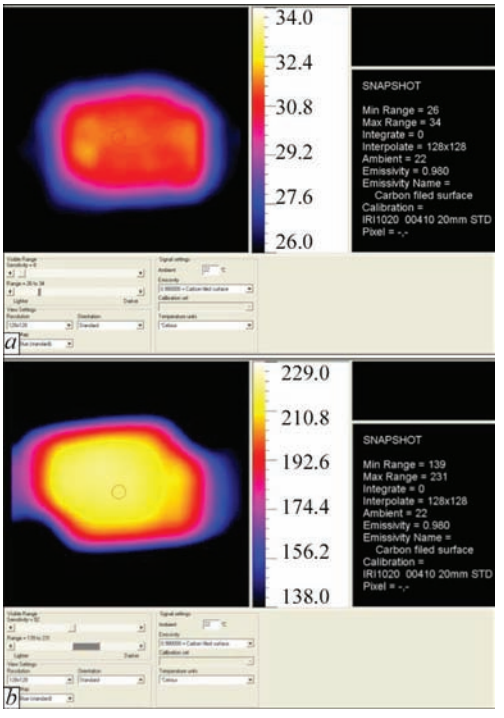

Figure 6. Heat distribution over resistive tracks of TiO_2 depending on time (*a* — initial heating temperature; *b* — final temperature)

not only achieving higher heating temperatures, but also replacing RHE of silicon carbide with multiple prolongation of their service life in electric furnaces with the heating temperature to 1450 °C [17].

Conclusions

1. For thermal application of resistive coatings the methods of atmosphere (APS) and vacuum (VPS) plasma, high-velocity oxygen fuel spraying (HVOF) were used. The best results on the quality and service life of such resistive coatings were obtained in case of using VPS and HVOF due to the formation of a denser and purer microstructure of sprayed layers.

2. As materials for spraying of resistive coatings, the powders of alloys NiCr, NiAl, FeCr, FeCrAl were used. The most widespread is producing a resistive coating of the alloy Kh20N80. The list of applied ceramic materials includes Al_2O_3, $MgAl_2O_3$ — for deposition electric insulating coatings, TiO_2, $LaCrO_3$, $MoSi_2$, SiC — for manufacturing heaters, NiO/Fe_3O_4, spinel Mn–Co–Ni–O — for elements of microcircuits.

3. The practical purpose of thermal spraying of resistive coatings consists in manufacture of heaters and components of microcircuits (resistor, thermistor, posistor), as well as sensors of different functional purposes.

4. The examples of tested practical application of thermal spraying of resistive coatings are the spraying of a resistive heating element on the working surface of the heating unit, instrument, device, which provides an improvement in heat transfer efficiency up to 96 %; manufacture of plane and tubular heaters, manufacture of microcircuits with improved mechanical strength, in particular, for challenging application in the automobile industry as electronic speed controllers, fuel injection and ignition systems, etc. The application of thermal spraying in manufacture of resistive films for integrated circuits will allow reducing production costs, costs for substrates and coating materials.

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