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APPLICATION OF THE METHOD OF MICROPLASMA SPRAYING FOR MANUFACTURING RESISTANCE HEATING ELEMENT

Yu.S. BORISOV, S.G. VOJNAROVICH, A.N. KISLITSA, S.N. KALYUZHNY and **V.Yu. GLUKHOVSKY**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazimir Malevich Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

The paper gives a description of producing a resistance heating element from multilayer coatings, which were deposited on a steel base by the method of microplasma spraying. TiO_2 in the form of powder with particles of 15–40 μm size was used to deposit narrow resistive paths. A sublayer from Al_2O_3 with 40 μm particle size was deposited to provide electrical insulation from the steel base. Performed testing of resistance heating elements showed their serviceability up to the temperature of 200 ºC at specific power of 75 W. Increase of heating temperature of resistance heating element in air above 230 ºC leads to loss of electrical conductivity. The main possible areas for such resistance heating element application are mechanical engineering, chemical and radioelectronic industries. Performed experiment allowed demonstrating the fundamental possibility of manufacturing resistance heating elements with resistive paths from TiO_2 with application of microplasma spraying technology. 18 Ref., 1 Table, 5 Figures.

Keywords: *electric heater, resistance heating element, titanium dioxide, microplasma spraying*

Electric heaters are widely used in household and industrial devices. Such electric heating devices as electrical stoves, irons, electric water heaters, electric boilers, etc. have become widely applied in the household. In industry electric heaters are used for heating chemical solutions, metal treatment furnaces; heating automatics cabinets and control stations, in manufacturing fan heaters, etc.

The main part of an electric heater is the resistance heating element (RHE). The following requirements are made of materials applied in industrial manufacture of RHE: high electrical resistance in combination with low temperature coefficient of linear expansion and high heat resistance. RHE the most widely accepted by industry are made from iron-chromium-nickel and nickel-chromium alloys of Kh23Yu5, Kh23Yu5T, Kh27Yu5T, Kh15N60 and other grades, featuring high specific resistance. Application of these materials in RHE allows using them up to 1200–1300 ºC temperatures. The next class of high-temperature RHE are batch-produced cylindrical heaters from semiconductor ceramic materials SiC, $MoSi_2$. This type of heaters is used for heating up to higher temperatures, of the order of 1500–1700 °C, compared with metal ones. Other ceramic materials, characterized by semiconductor properties, such as ZrO_2, TiO_2, TiC, Cr_3C_2, $LaCrO_3$ have also found application in RHE production [1–3]. Wide application of semi-conductor ceramic materials is due to them having higher specific resistance and smaller temperature coefficient of linear expansion than metallic ones. A design feature of metal RHE is the need for electrical insulation of the current-conducting coil from the surface being heated. An air gap is mainly used as an electrical insulator. Such a design of metal RHE leads to lowering of the coefficient of heat transfer, heat dissipation into the environment, more complicated structure and increase of overall dimensions of RHE that in some cases influences their further mounting. In order to increase the coefficient of heat transfer and reduce the overall dimensions of electric heating devices, it is possible to apply RHE in the form of resistive coatings (paths) deposited directly on the surface to be heated [4–6]. Titanium dioxide (TiO_2) is a promising material for application in RHE based on its electrophysical properties. The material has the properties of a semiconductor [7, 8] with melting temperature of 1800 °C; it is successfully used in electronics, mechanical engineering and other industries, being the most affordable semiconductor ceramic material in the market. There are also data on successful application of TiO_2 for RHE manufacturing in the form of a cylindrical roller of 540 W power [1]. Ceramics-based materials are used as electrical insulation. Al_2O_3, ZrO_2, Cr_2O_3 are the known representatives of such materials. Al_2O_3 became the most widely accepted. Its application is due to high dielectric properties at higher temperatures (5–9 kW/mm) [9] and low cost.

At present resistive paths are produced by such methods as screen printing, spreading, photolithography, vacuum-condensate deposition, etc [4, 5]. Thermal spray technology (TST)) is considered as a promising technology among the currently-available methods of producing resistive paths. Such a technology has the following advantages: broad selection of materials, coating formation on the surface or in the local area of the item, made from practically any material, high efficiency, and simplicity of the technological process with the possibility of its automation.

Materials and equipment for coating deposition. Over the recent years TST methods allow producing coatings on different parts for radioelectronics and instrument making. There are successful results, demonstrating the possibility of their application also for manufacturing RHE [10, 11]. The main disadvantages, preventing TST application for RHE manufacturing in the currently-available equipment for thermal spraying, are great material losses at deposition of narrow resistive paths less than 6 mm wide, as well as the probability of item overheating and distortion, as a result of strong thermal impact of the plasma jet. Considering the need to form thin, narrow resistive paths, and prevent substrate distortion, it was proposed to use the technology of microplasma spraying (MPS). It allows producing coatings from different kinds of both metal and ceramic materials, significantly reducing the spraying material losses due to a small diameter of the spraying spot, thus making a minimum thermal impact on the substrate [12].

Based on the performed analysis, titanium dioxide powder with particle size of 15–40 μm and flowability of 83 s^{-1} was selected as the material to produce resistive coatings (GOST 20899–75). This material has a linear coefficient of thermal expansion of $8.19\cdot10^{-6}$ 1/ºC and high specific electrical resistance of $3\cdot10^{5}$ Ohm·m [13], chemical stability and electrical conductivity in oxidizing gaseous media, sufficient for resistive self-heating from room temperature. Titanium dioxide is one of the most affordable semiconductor ceramic materials in the market. Al_2O_3 powder (MRTU 9-09-3916–75) with particle size of 40 μm and flowability of 130 s^{-1} was used for deposition of electrical insulation coatings. Microplasma spraying technology was applied to increase the coefficient of spraying material utilization (CMU). This technology allows deposition of narrow-strip coatings from various kinds of materials and markedly reduces spraying material losses, owing to a small diameter of the spraying spot (3–5 mm) with minimum thermal impact on the substrate that enables producing coatings on thin-walled parts without their distortion [14, 15]. MPN-004 unit developed at PWI was used as equipment for coating deposition (Figure 1).

Figure 1. General view of MPN-004 unit

Specifications of MPN-004 unit

Working gas	Argon
Shielding gas	Argon
Plasma jet power, kW	up to 3.0
Current, A	10–60
Voltage, V	20–50
Working gas flow rate, l/min	0.5–5
Shielding gas flow rate, l/min	2–10
Efficiency, kg/h	0.1–2.5
CSMU, %	0.6–0.9
Overall dimensions, mm	500×360×50
Weight, kg	44

RHE working surfaces of 70×45×1 mm (sample No.1) and 50×50×2 (sample No.2) size were made from steel of St3 grade. Gas-abrasive treatment of the working surface was performed by fused corundum of grade A95F with F20-F22 grit size, with subsequent five minute cleaning of the surface in ULTRASONIC CLEANER PS-2 unit, using isopropylene alcohol. Dielectric strength of Al_2O_3 coatings was determined by megohmmeter F4102/1. Heating temperature influence on resistive path performance and RHE power was studied in the stand (Figure 2), consisting of

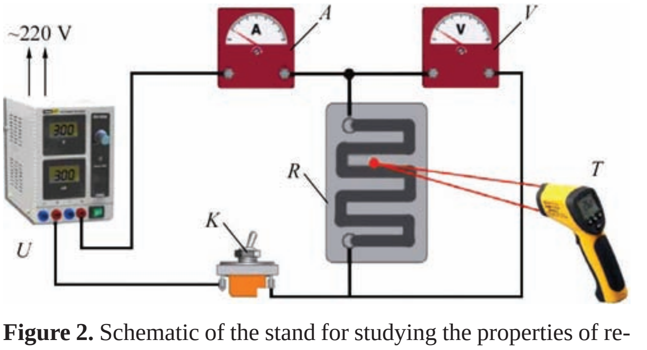

Figure 2. Schematic of the stand for studying the properties of resistive coatings: *U* is the adjustable power source; *K* is the switch for interruption of electric current supply; *A* is the ammeter; *V* is the voltmeter; *R* is the sample with resistive coating; *T* is the thermal imager (pyrometer)

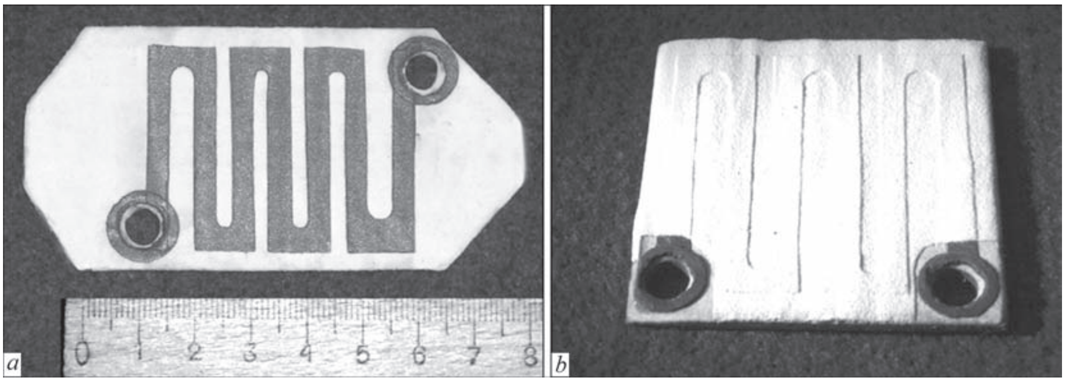

Figure 3. Resistance heating element: *a* — sample No.1 (two-layer coatings from Al_2O_3 and TiO_2); *b* — sample No.2 (three-layer coating from Al_2O_3 and TiO_2)

adjustable power source *U*, switch for interrupting electric current supply *K*, digital multimeter UNI-T UT170B for measuring current and voltage *A*, *V*, thermal imager IRISYS 1020 for measuring temperature and heat distribution through RHE *T*.

Technical characteristics of IRISYS 1020 thermal imager

Measured temperature range, °C	–10–300
Detector	pyroelectric detector 16×16
Temperature sensitivity threshold, °C	0.3
Temperature measurement error, °C, not more than	±5
Optical field of vision, horizontal×vertical, deg	20×20
Spectral range, μm	8–14
Image sweep frequency, frames, Hz	< 9
Guidance system	class 2 laser

Microstructure of TiO_2 coatings produced by MPS method, was examined in Neophot 32 microscope, porosity was determined by the method of image processing by Image Pro 3 computer program.

Manufacturing and study of resistance heating element. The process of RHE manufacturing consisted of the following stages.

1. Before deposition of electrically insulating and resistive coatings the sample bases from steel of St3 grade were subjected to liquid blasting at compressed air pressure of 7 atm. This was followed by ultrasonic cleaning of the bases to remove contamination and grease films.

2. To ensure electrical insulation of resistive paths from the metal base, MPS method was used to deposit electrical insulation layer of Al_2O_3 300 μm thick.

Mode of microplasma deposition of electrical insulation and resistive coatings

Parameters	Coating composition	
	Al_2O_3	TiO_2
Current, A	45	40
Voltage, V	30	28
Spraying distance, mm	150	150
Flow rate of working gas Ar, l/min	1.3	1.3
Flow rate of shielding gas Ar, l/min	4	4
Efficiency, g/min	1.2	2

3. After deposition of electrical insulation layer masks (from 7 spirals on sample No.1, and from 6 spirals on sample No.2) were applied on the samples to give a meander shape to the paths during spraying, with subsequent deposition of TiO_2 resistive coating by MPS method. The Table gives the parameters of deposition of electrical insulation coating and resistive paths.

4. Formed resistive paths had the following geometrical dimensions: path length on samples Nos 1 and 2 was 312 and 295 mm, respectively, path width on both the samples was 4 mm, thickness of resistive layer (TiO_2) was 150±50 μm.

5 To provide insulation of resistive paths from the environment, the same method was used to additionally deposit a layer of Al_2O_3 150 μm thick over the paths on sample No.2 (deposition modes are given in the Table). Appearance of the manufactured ceramic RHE and deposited coating microstructure are given in Figures 3 and 4.

Analysis of the microstructure of coatings (Figure 4) showed that the obtained resistive paths have a uniform thickness of 150±50 μm, electrical insulation layer (base is the resistive path) is 400±100 μm thick and external electrical insulation layer is 150±30 μm

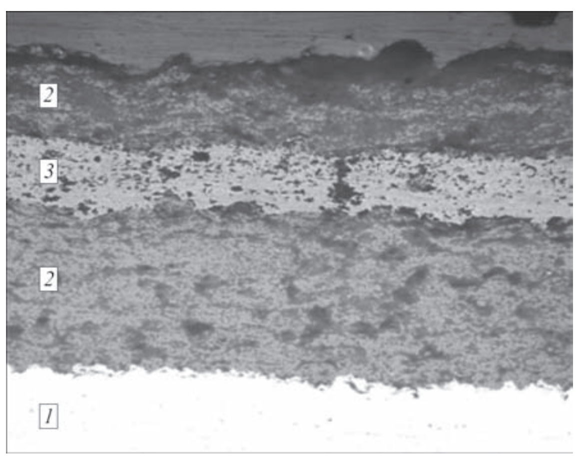

Figure 4. Microstructure (×200) of RHE three-layer coating No.2: *1* — base; *2* — Al_2O_3 layer; *3* — TiO_2 layer

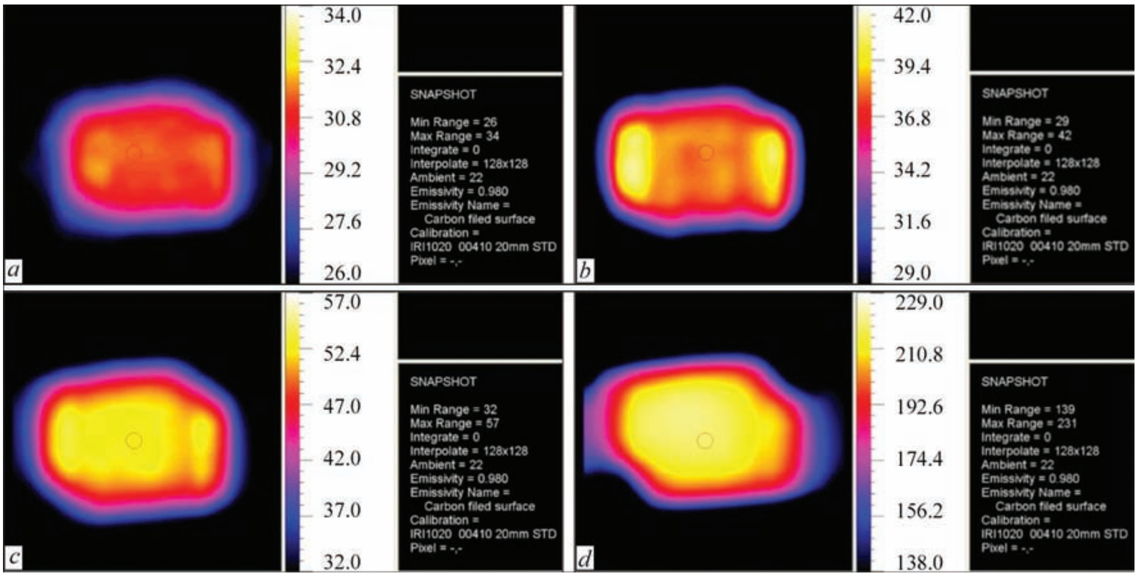

Figure 5. Heat distribution along resistive paths from TiO_2, depending on time (for *a–e* description see the text)

thick. Porosity of Al_2O_3 coatings was equal to 20–25 %, and of those from TiO_2 — 10 – 13%. Performed study of dielectric strength of electrical insulation layer from Al_2O_3 400±100 μm thick showed that it is equal to 500 MOhm at 1000 V per 6 mm^2. Obtained data are indicative of the fact that Al_2O_3 coating provides the required electrical insulation properties [16].

Electrical conductivity was studied on sample No.1, as it did not have any external protective Al_2O_3 coating that allows measuring the temperature of the resistive path directly on its surface without the impact of the external electrical insulation layer. At application of alternating voltage of 250 V to RHE current-supplying contacts, a maximum value of current of 0.3 A was obtained that corresponds to RHE specific power of 75 W. During the experiment, gradual heating of the resistive paths and heat distribution through the element took place that was recorded by IRISYS 1020 instrument (Figure 4) with 5 s time interval.

Figure 5, *a–d*, shows heat distribution through RHE according to temperature scale, recorded by IRISYS instrument. RHE initial temperature was equal to 26 °C (Figure 5, *a*). After the resistive path has reached the temperature above 230 °C, the coating lost its conducting properties.

Discussion and prospects. Conducted experiment showed the principal possibility of MPS application for RHE manufacturing using TiO_2 powders to form the resistive paths. Resistive coatings from TiO_2 produced by MPS method, allow heating the base up to 200 °C temperature without loss of RHE serviceability. Temperature increase above 230 °C, leads to local overheating of the path with loss of its electrical conductivity. Temperature limitation and conductivity loss are, obviously, due to the structure of thermal coatings, which are characterized by nonuniformity and porosity. During heating in air of resistive coatings produced by MPS method from TiO_2, coating resistance increases in the zone with nonuniform coating structure with their subsequent overheating and loss of electrical conductivity [17, 18].

These resistive coatings can be applied in practice in manufacturing RHE for protection of electric motors and generators from humidity, heating of water pumps in winter to prevent their icing, maintaining constant temperature inside electric cabinets with automatics, heating of slide valves, as well as in manufacturing special equipment for severe climatic conditions, where heating of fuels and lubricants in internal combustion engines is required.

Conclusions

1. Analysis of design features of RHE and materials used in their manufacture was performed. Materials, suitable for producing resistive paths by the method of thermal spraying were determined.

2. Possibility of manufacturing RHE by microplasma spraying method was proved experimentally. Resistive paths from TiO_2 4 mm wide with resistive layer thickness of 150±50 μm were produced.

3. Conducted testing demonstrated the serviceability of RHE manufactured by the method of MPS from TiO_2 at specific power of 75 W up to 200 ºC temperature without loss of electrical conductivity.

4. Areas of practical application of RHE with use of these coatings were determined in the instrumentation and components of equipment for mechanical engineering, chemical and radioelectronic industry.

5. Alloying, for instance with application of Cr_2O_3, can be a way to improve the working temperature and stability of electrophysical properties of the resistive path from TiO_2.

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