Modern Applied Science; Vol. 9, No. 4; 2015
ISSN 1913-1844 E-ISSN 1913-1852
Published by Canadian Center of Science and Education

Technological Aspects of Detonation Coating on Working Surfaces of Electrical Contacts on the Basis of the Alloy AD-31 with a Copper Sublayer

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Received: October 30, 2014 Accepted: November 6, 2014 Online Published: December 10, 2014

doi:10.5539/mas.v9n4p1 URL: http://dx.doi.org/10.5539/mas.v9n4p1

Abstract

We considered technological parameters of the formation of the conductive coating with the detonation method. We set modes to form a copper sublayer with the detonation method before silvering aluminium contact elements, as well as obtained optimal settings according to the flight speed of the sprayed particles of the powder material, the ratio of gas fuel in the barrel of the detonation unit, the structure of the coating application. The use of the spraying modes allows increasing the adhesion of copper coating and to ensure the layer formation with conductive properties.

Keywords: contact element, detonation spraying, particle velocity, porosity

1. Introduction

Electrical contact elements (ECE), used in metal-clad switchgears (MCS), in most cases, are made of copper. Today it is urgent to achieve a more efficient task to ensure transition resistance, which is the main parameter of the quality of data of MCS elements. One of the solutions is to replace the ECE material from copper to aluminium with multilayer conductive coating. Currently thermal spray methods are used for the formation of functional coatings in domestic and foreign practices, including gas-flame, plasma and detonation coating methods. At the same time, as it is shown in the works of (Nenashev and Demoretsky, 2010; Hasuy, 1988), the detonation method provides the best performance coatings (maximum strength and adhesion to the substrate, minimum porosity and permeability). This method has been developed and used for hardening, manufacture and repair of drilling tools; camshafts and crankshafts of internal combustion engines; reinforcement in chemical engineering; parts of agricultural machines and machines for agricultural products processing; metalworking and medical tools and many others.

2. Methods

The Detonation Method of Coating is based on a High-Speed Tossing of a Pulverized Powder Material with Detonation Products of a Gas Mixture. Figure 1 Shows a Diagram of the Detonation Unit Used for These Purposes.

A mixture of detonating gas through the gas feeding mechanism 1 is supplied to the barrel bore, and powder which is distributed in the gas mixture 3 is supplied through the tube 4. Using the spark gap 2, the gas mixture is initiated. The burning rate (with the pressure increasing) increases in the barrel bore to a speed of the mixture detonation. The detonation wave accelerates the powder up to a speed of 400 ... 800 microns per second. The detonation products are taken out to the surface of the substrate 5, particles collide with it, and this is accompanied by the formation of the coating 3 ... 15 microns thick (Bartenev, Fedko, & Grigorov, 1982).

The barrel bore and the mixing chamber are purged with nitrogen gas to remove the detonation products. Then they are filled with a new portion of the explosive mixture, and the cycle repeats. Depending on the design of the unit the cycle frequency can be up to 8 ... 10 Hz, but in most cases it is equal to 3 ... 4 Hz (Nenashev, Ibatullin, Ganigin, & Shashkina, 2010).

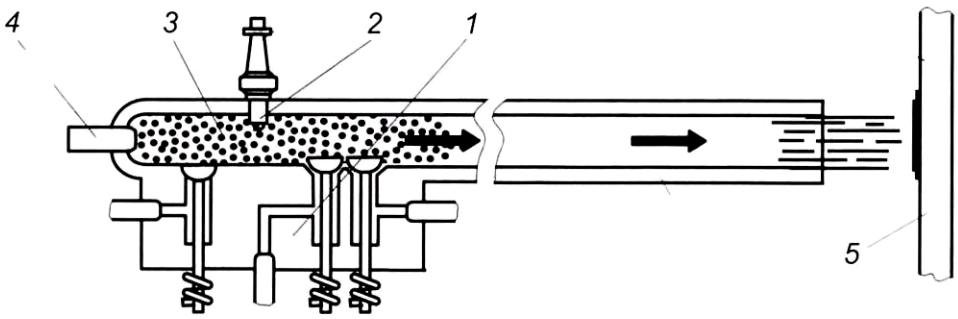


Figure 1. Schematic detonation spraying: 1 – gas distribution mechanism; 2 – glow plug; 3 – explosive mixture; 4 – introduction of the powder; 5 – substrate

Heating the particles to a plastic state together with the significant acquired kinetic energy substantially allows obtaining coatings with high bond strength and low porosity (Samsonov & Sharivker, 1977).

The process of coating formation is characterized by a significant number of factors; the main ones are as follows (Shorshorov & Kharlamov, 1978):

- Chemical composition and physical properties of the particles material and the substrate surface;
- Composition of the detonating gas mixture;
- Powder fill (the distance from the powder inlet to the barrel cut);
- Spraying distance;
- Aggregative state of the particles prior to reacting with the substrate;
- Concentration of melted particles;
- Speed and particle size;
- Geometry of the substrate surface;
- Chemical composition of the environment in which the substrate is located;
- Temperature of the particles and the substrate surface prior to spraying;
- The concentration of particles in different parts of the two-phase flow and others.

So the time of the powder particles being inside the barrel, the fullness of physical and chemical interactions with the detonation products depends on the depth of feeding.

The composition of the mixture significantly affects the energy characteristics of the powder particles and determines a chemical reaction between the sprayed material and the detonation products.

The level of the barrel fill (fill factor) has a significant impact on the temperature of the particles, as with a small fill factor in the barrel zone free of fuel gas appears.

The thickness of the single layer depends on the dose of powder fed into the barrel and is determined by the resistance of the layer and the adhesion, which in turn depend on the quality of the surface preparation, the temperature of the particles and the substrate, the particle velocity, thermal conductivity of the particles and the substrate material, the substrate form, the particles size. The thickness of the single layer is 5 ... 20 microns.

The spraying distance is determined from the condition of minimal impact on the flow of particles reflected from the surface of the wave substrate. In most cases, this value is 150 ... 200 mm.

The Process of Forming the Detonation Coatings is Largely Similar to the Process of Forming Plasma Coatings (Kudinov, 1977), Which Mainly Consists of Spreading and Solidification of Liquid Particles on a Substrate Surface or on Previous Layers of Coating.

Advantages of the detonation coatings, compared with plasma and flame ones, are explained by the difference of their formation mechanisms (Dalskiy, Barsukov, Bukharkin et al., 2004). In this case the determining role is played by a higher tossing velocity of the spraying material (up to 1 km / s) and the presence at the end of the two-phase flow of not melted large particles which interact with the coating formed from the particles entering the beginning and the middle of the two-phase flow. This leads to the effect of impact hot pressing, which increases the density of the already formed coating. This effect is also seen in the interaction of two-phase flow with a coating formed as a result of the previous shot (Dalskiy et al., 2004).

Another important difference of the detonation spraying, in comparison with the plasma one, is a significantly higher concentration of particles at the moment of the coating formation (Kudinov, 1977), that also enhances the effects of impact hot pressing. Besides, the higher velocity of particles ensures additional thermal energy when hitting the surface of the substrate, which leads to an increase in temperature of the particles in the contact zone. In addition, due to the high velocity of the particles and their relatively low temperature, it is possible to spray powders with a dispersion of about 1 micron.

The technological process of the detonation spraying provides a high performance of coating and has a relatively low complexity and sensitivity to the initial purity of the treated surface as well as a high growth rate of the coating thickness (5 microns per second) (Kalashnikov, Demoretsky, Nenashev, Trokhin, & Rogozhin, 2012).

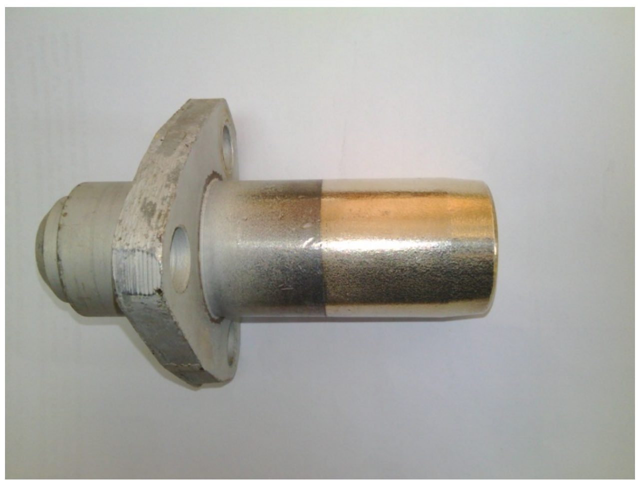
Detonation coatings have higher adhesion strength (200 MPa); low porosity (0.1 ... 2.0) %; low temperature of heating sprayed details (150 ° C); low surface roughness of the coating (not exceeding 3 ... 6 mm); relatively low cost (Nenashev and others, 2010).

In addition, physical, mechanical and performance properties of detonation coating, such as density, resistance, heat resistance, wear resistance under conditions of friction and erosion, impact resistance is much higher than the corresponding figures for the coatings obtained with the flame and plasma spraying.

In this regard, the use of detonation spraying method for producing a multilayer conductive coating for aluminium ECE to replace the primary switchgear contact material is promising. However, to create a detonation technology of conductive coatings manufacturing with high uniformity of the layer thickness for ECE of complex shapes it is necessary to carry out the corresponding theoretical and experimental studies related to identifying the most efficient modes of the coating formation.

For example, the plug-type contact "tulip" is made of copper with the followed silvering of the working part (20-30% of the whole surface) (see Figure 2a). When replacing a main contact material for aluminium, with the subsequent formation of the copper coating with the method of detonation spraying, considerable technical and economic effects are obtained only on the functional part that is subject to silvering (see Figure 2b).

a) The regular contact of the "tulip" type made of copper



b) Silver-plated contact of the "tulip" type on the basis of aluminium with a copper detonation layer

Figure 2. Electrical contacts for the cells of metal-clad switchgears

To ensure the most important parameter of MCS contacts – transition resistance, it is necessary to link the optimal technological parameters for the method of detonation spraying, taking into account providing high values of precision adhesion of the applied copper underlayer. For functional coatings for a wide range of assignments, technological factors and techniques, as shown in the works (Vikas, C., & Prakash, 2008; Sidhu Buta Singh et al., 2005; Goyal Rakesh et al., 2010; Rajasekaran et al., 2008; Souza, & Neville, 2007; Nenashev, Demoretsky, Ibatullin, Ganigin et al., 2011) have specific and individual characteristics related to the selection of a powder material spraying distance, structural features of detonation units, type of a fuel gas, frequency synchronization of shots during spraying with the work of sprayed objects manipulation systems.

For formation of the surface layer, providing the ECE contact resistance of a cylindrical shape based on aluminium, a method is suggested based on coating with a detonation gun in which gaseous combustion products of a detonating explosive mixture and condensed explosive charge have temperature up to 4000°C and the initial velocity (at the output from the barrel) about 1 km/s (Nenashev et al., 2010). The gas stream heats and melts the particles of the powder fed into the barrel (totally or partially) and tosses them at high speed onto the ECE work piece surface mounted in front of the gun barrel. During that micro welding of tossed material particles with the substrate surface occurs.

In the case of forming a conductive layer applied on the surface of the aluminium contact (AD31 alloy) with the detonation method, it was decided to use a mechanical mixture $70Cu/30Al_2O_3$. Copper electrolytic powder of the PMS-1brand, which is made for the electrical industry, is selected for the mixture. The copper content therein is 99.8%, particle size distribution is 40-60 microns.

For the formation of the ECE multilayer coating it is suggested to use detonating mixtures which are a mixture of fuel and oxidant. As fuel for detonation spraying units acetylene or propane butane as well as propylene are used. Acetylene (C_2H_2) is of particular interest, as its possibility of detonation decomposition depends on many factors, including the method of detonation initiation. So, clean acetylene can explode at a pressure above 65 psi, but only at the initiation with an explosive charge. Under other methods of initiation, such as via sparks, it does not explode at a pressure below 140 kPa. Acetylene significantly surpasses other fuels in thermal characteristics: the temperature of the detonation products is 4534 K, while the one of propane is 3865 K, and the one of propylene is 3980 K (Zverev & Sharivker Astakhov, 1979).

The oxidizing agent for detonation mixtures is oxygen, air or their combination.

For production of coatings with the required parameters of adhesion, porosity, wear resistance and other parameters, gas mixtures that have specific values of the detonation velocity, pressure, density, temperature of the detonation products should be used.

In the work of (Bartenev et al., 1982) it is shown that the detonation velocity is weakly dependent on the initial state of a mixture (pressure, temperature), mode of initiation, and geometric parameters of the vessel or pipe diameter, in which it extends. It is primarily determined by the physical nature and composition of the explosive mixture (Bartenev et al., 1982). For each gas mixture, there are certain limits of concentration below which detonation mode is impossible (see Table 1).

Table 1. Concentration limits of detonation gas mixtures expansion (Kalashnikov et al., 2012)

Mixture	Share of fuel in oxygen or air,%		Detonation velocity, m/s	
	lower limit	upper limit	at the lower limit	at the upper limit
H2 + O2	20.0	90.0	1457	3550
H2 + air	18.2	58.9	1500	2100
CO +O2	38.0	90.0	-	1473
(CO+H2) + O2	17.2	90.0	1500	2150
(CO+H2) + air	19.0	58.7	1480	1690
C2H4 + air	5.5	11.5	1675	1801
C2H4 + O2	3.5	92	1607	2453
C2H2 + air	4.2	50.0	1509	1871
C2H2 + O2	3.5	92.0	-	-
C3H8 + O2	3.2	37.0	1587	2210
C4H10 + O2	2.9	31.3	1595	2188

Overfueled mixtures for detonation spraying are not used, since their detonation products may form soot, which can lead to contamination of the coating. It is believed that under detonation of an oxygen-acetylene mixture in the ratio of 1.2/1 soot build is insignificant (Miller, 1969). Depletion of the fuel content that makes up to less than 10% of the explosive mixture is impractical due to the sharp decrease in the detonation mixtures effect.

The main parameter that determines the possibility of deflagration to detonation transition is pre-detonation distance 1pd, i.e. the distance from the initiation point to the point where a stationary detonation occurs.

Thus, for the acetylene-oxygen mixture, according to most researchers the pre-detonation distance reaches 50 cm (see Table 2). For mixtures of hydrocarbons with air the pre-detonation distance can amount to several meters (Miller, 1969).

Table 2. Pre-detonation distance for gas mixtures

Mixture	Pressure, Pa·10-4	pre-detonation distance, cm
2H2 + O2	1.0	70
	3.0	52
	5.0	35
	6.5	27
C2H2+2.5O2+4N2	1.0	52
	2.0	30
	3.7	22
	4.1	18

For spraying material with different properties, certain detonating mixtures with different ratios of fuel and oxidizer should to be applied. Thus, for spraying materials containing copper and most oxides, it is appropriate to use acetylene as fuel, since the explosion temperature of propane and propylene mixtures is insufficient and, moreover, propane cannot provide a reducing environment necessary for quality coatings from carbide powders (Bartenev et al., 1982; Nenashev et al., 2010; Samsonov et al., 1977; Shorshorov et al., 1978; Kudinov, 1977).

In this regard, the acetylene-oxygen mixture was used as a gas fuel for melting and dispersal of the powder material (PM) $70Cu/30Al_2O_3$.

We suggest using a special detonation complex (Gavrylenko, Kiryakin, Nikolaev, & Ulianitsky, 2006) as a unit, which performs melting, acceleration and spraying of powder material on the outer surface of the cylindrical ECE. This complex includes a detonation gun, a control computer, a manipulator, which allows moving the work piece independently in three directions, and a cooling unit. The installation is controlled by an industrial computer, which programs the spraying mode and coordinates movement of the work piece, and during the spraying process controls implementation of the given program.

The detonation gun consists of the following main components (see Figure 3): support frame; gas distributor; chamber with an initiation system; barrel; powder dispensers.

The frame serves for fastening the gun components and has four guide rails for moving the frame in order to change the distance from the barrel to the item and a stopper for locking the gun in position.

Gases from feeding hoses come to the gas distributor 10, where their pressure is reduced to the reference pressure, and then through the hoses are fed into the ignition chamber 17 and further into the barrel 1 through the valve barrel 13 which is covered by a dust cover.

Initiation of an explosive mixture in the barrel is performed via the automotive candle 16 with the help of the ignition coil 9.

The ignition unit 14 is screwed to the sectioned water-cooled barrel 1 fixed in the rack 4. To automatically manipulate the barrel up and down a stepper motor with a worm gear is used.

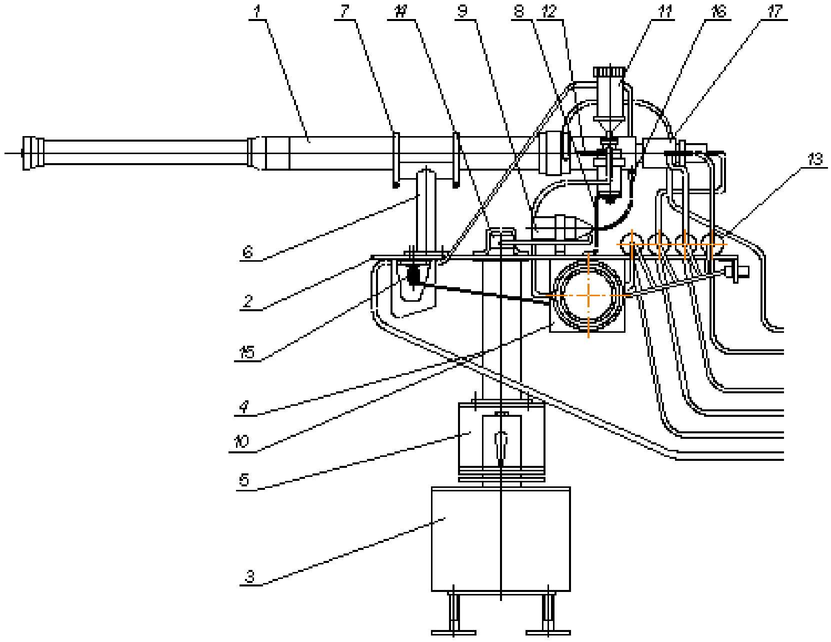


Figure 3. Scheme of the detonation installation: 1 – barrel; 2 – base; 3 – a mechanism for moving the gun; 4 – rack; 5 – arm; 6 – rack; 7 – bolt; 8 – arm; 9 – ignition coil; 10 – distribution block; 11 – dispenser; 12 – powder sipper; 13 – solenoid valve; 14 – block of electronic ignition; 15 – sensor of the water flow; 16 – the spark plug; 17 – block of the gas mixer

The barrel sections are fastened with screws. Between the breech section and the muzzle section of the barrel there is a spacer for locking the powder dispenser 11. Removable powder dispensers are fixed on the spacer.

Air is supplied to the dispenser through the hose. Power to the dispenser valve is supplied through a wire, the sensor, which is connected to the cable, monitors triggering of the dispenser.

The control computer of the unit contains an integrated controller of the detonation unit, a driver of solenoid valves and spark, three identical drivers of stepper motors. Besides the communication function of connecting blocks, drivers, valves and sensors of the gun and the manipulator, the computer separately monitors the state of the gun and safety of commands, has an automatic safety system which stops the gun in case of emergency (with a purge of the barrel). This prevents accidents due to faulty valves or programme defects.

Performance of the detonation complex consists of the following basic operations:

- One end of the installation barrel is open and is being filled by the explosive gas mixture;

- Portion of the powder is fed into the barrel;

- In the gas mixture at the closed end of the barrel detonation is initiated and combustion products escaping from the barrel disperse and heat the sprayed powder material (usually up to the melting point);

- After the shot the barrel is purged with nitrogen (air);

- Falling on the surface of the contact element, the powder particles firmly connecting with the work piece form a coating 10 ... 15 microns thick;

- The necessary thickness of the coating is built up with a series of shots during which the item is moved by the manipulator.

When the barrel diameter is 20 mm, a spot of spraying on the fixed part has a size of 20 ... 25 mm and an area of 3.1 ... 4.9 cm^2. The nominal firing speed of the unit is 4 shots per second, maximum – up to 10 shots per second.

At the same time, to obtain a high-quality conductive ECE layer, optimization of the complex of factors, determining the behaviour of detonating gas mixture and the powder particles from the moment of appearance in the barrel of the detonation unit until the formation of a coating, is required (Nenashev et al., 2010).

3. Results

The main controlled technological factor of the detonation process of forming coatings from powder materials is the fill factor of the detonation installation chamber with an explosive mixture. This factor represents the ratio of detonating mixture to the total volume of the barrel and the mixing chamber. In this work we carried out experimental studies related to identifying the optimal values of the barrel fill factor, which ensures detonation formation of copper sublayer on the surface of the aluminium switchgear contact. When conducting the experiments we used: fuel – acetylene (48%); oxidizer – oxygen (52%); inert gas – nitrogen. The frequency of shots amounted to 5 Hz; flow rate of the powder material ($70Cu/30Al_2O_3$) – 1.8 kg / hour; spraying distance – 200 mm.

For the experiments the samples of (plates made from alloy AD31, 1.0 mm thick) were sprayed by $70Cu/30Al_2O_3$ with the barrel fill factor of the detonation unit with a gas mixture of 60, 70, 80 and 90%. At the same time the velocity of the sprayed powder particles was determined by high-speed shooting of the process.

While conduction the experiments aimed at determining the speed of flight of the sprayed material particles we used the powder $70Cu/30Al_2O_3$, the detonating gas mixture – equimolar mixture of acetylene and oxygen; photographs were taken after 300 microseconds after the initiation with the same exposure time for all experiments (20 microseconds). A typical photograph, obtained during the registration process of detonation spraying, is shown in Figure 4.

An analysis of the images determines the length of the tracks of the powder particles, and their speed is calculated by the formula (1):

$$V_{particles} = l_{tr} / t_e, \quad (1)$$

where ltr – length of the particle track, m;

te – exposure time, s.

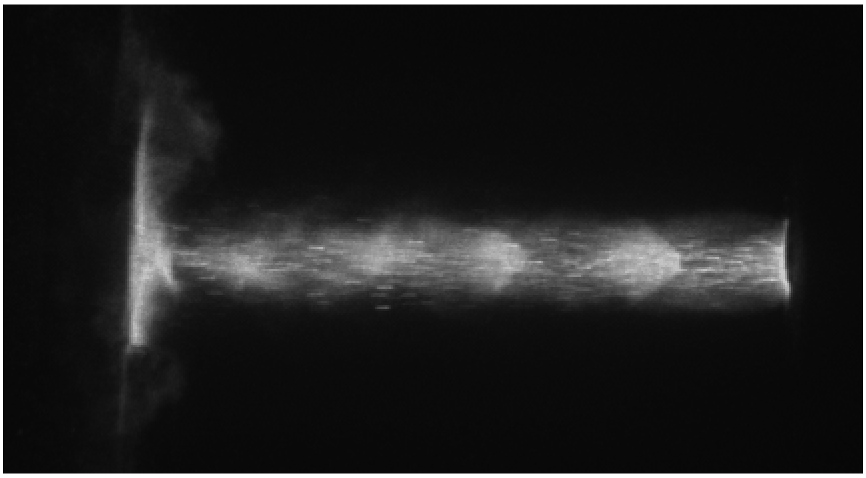


Figure 4. A typical photo of the process of detonation formation of copper coating on the alloy AD31 plate

The results of experimental showed that when increasing the weight of detonating gas mixture, the speed of the sprayed powder particles increases as well. At the same time, the flow rate of particles increases from 480 to 790 m/s when increasing a filling degree of the detonation installation from 40% to 80%.

During the experiments we also determined the dependency of the formed material porosity from the fill factor of the installation barrel with a detonating gas mixture.

The porosity of the coating was determined by hydrostatic weighing of samples and was calculated as the ratio of maximum density $70Cu/30Al_2O_3$ (ρ_{max} = 6.26 g/cm^3) to the material density (ρ_m) obtained during the experiments:

$$\Pi = \frac{\rho_{max}}{\rho_m} \cdot 100\text{ , \%} \quad (2)$$

$$\rho_{co} = \frac{(M_{w1} - M_{w2}) \cdot \rho_1}{M_{w1} - M_{w2} - M_{l1} + M_{l2}}, \quad (3)$$

where $\boldsymbol{Mw_1}$ – weight of the coated sample weighed in the air, grams; $\boldsymbol{Mw_2}$ –weight of the uncoated sample weighed in the air, grams; $\boldsymbol{Ml_1}$ – weight of the coated sample, weighed in liquid, grams; $\boldsymbol{Ml_2}$ – weight of the uncoated sample, weighed in liquid, grams; $\boldsymbol{\rho_l}$ – liquid density, g/cm^3.

Figure 5 shows the dependence of the porosity of the material internal layer of the cumulative coating from the filling degree of the barrel with gas fuel.

The figure shows that by increasing the filling degree of the detonation unit barrel with gas mixture (Fd) up to 60%, the porosity of the material decreases from 0.6 to 0.2 %. Further increase of the filling degree does not lead to a substantial reduction in porosity of the coating, but increases the load on the detonation unit components.

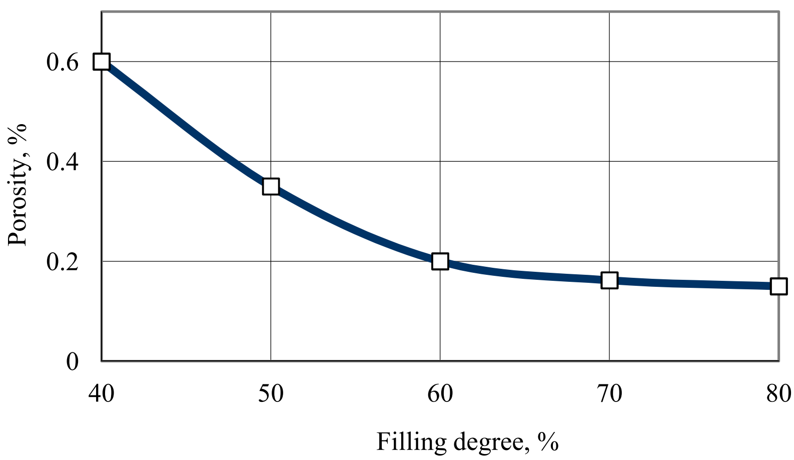


Figure 5. Dependence of the coating porosity on the filling degree of gas mixture of the detonation unit barrel

Method for determining the adhesion is as follows (Nenashev, Ibatullin, Ganigin, Gallyamov, & Neyaglova 2011; Ganigin, Ibatulin, Nenashev, Ulianitsky, Shashkina, & Shtertser, 2010). The tear element having a recess in the form of a funnel with a central calibrated orifice is fastened to the base with retainers (see Figure 6) before coating so that the surface of the funnel in the centre is tightly pressed to the base.

The coating is applied so that a part of it was on the surface of the funnel and another part – on the base through a calibrated orifice in the centre of the funnel on the detachable element. Thereafter the retainers are removed, and the detachable element is connected to the substrate only by the force of coating adhesion. Further, the tear element with the base are fixed on the rotary element, the latter is rotated around the axis relative to the biasing mechanism so as to apply normal tensile load for evaluating the coating adhesion to the detachable element, relative to the base. Then the biasing mechanism smoothly creates force acting on the detachable element up to separation and with a measuring device (a strain gauge and a dial indicator), we determine the maximum load applied on the detachable element in the moment of separation from the base coating. Next, we determine the adhesion strength of the coating with the base for separation as the ratio of maximum load acting on the detachable member to the area of the calibrated orifice.

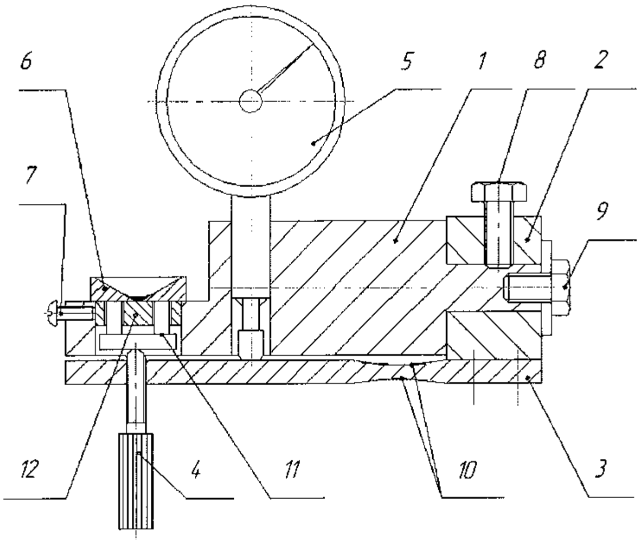


Figure 6. Schematic structure of the adhesion tester. 1 – the rotary element; 2 – base; 3 – leaf spring; 4 – charging screw; 5 – dial gauge; 6 – detachable element; 7 – fixing screw; 8 – positioning bolt; 9 – tightening bolt; 10 – gages; 11 – pusher; 12 – foundation

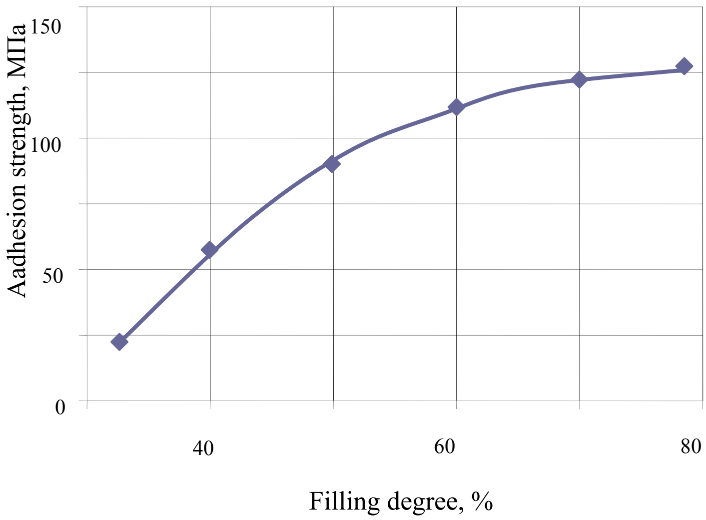


Figure 7. Dependence of adhesion on the filling degree of the barrel with the gas mixture

As shown in Figure 7, coatings formed by the detonation method with the barrel filling degree of 60% or more have the optimal parameters of the adhesion with the base. For the used detonation unit (Gavrilenko et al., 2006) with the barrel diameter of 22 mm and the barrel length of 1200 mm, this ratio corresponds to the mass of the gas mixture of 150 ... 200 mg.

One of important quality indicators of switchgear contacts cells is high precision of a uniformity of a layer. It is a rather complicated task to provide precision of a layer on the cylindrical surface of the contact element.

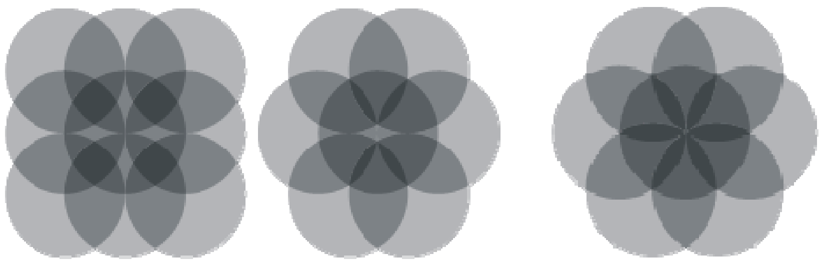
The number of layers of detonation copper coating depends on the configuration of spot formed by spraying, the coefficient of spot overlapping and a shape of the surface of the contact element.

The powder material is formed by a uniform spot on the contact surface. This is provided by particles, which due to the high velocity (over 500 meters per second) obtained in the detonation unit barrel, reach the contact surface, forming a main spraying spot zone deposition. Its area is slightly greater than the cross sectional area of the barrel and the coating characteristics in this area are highly homogeneous.

Coating on surfaces with an area bigger that the spraying spot may be formed by applying spots according to a specific scheme.

The characteristic thickness of a single spraying spot is (5 ... 10) microns and, as shown in performed calculations it is necessary to form the surface layer of the switchgear contact element 40-60 microns thick.

Figure 8 shows three possible schemes of layer formation. In the first option (Figure 8a) centres of spots form a square grid with a step equal to the half diameter of the spot. In this case, the coating layer comprises fragments of 2, 3 and 4-fold overlap of major spots. At the same time in the areas with a 2-fold overlap the highest concentration layer is observed with poor adhesion properties. Due to parallel shift of adjacent rows for a quarter of spots while maintaining the shift of the spots in the row and the row relative to the other (Figure 8b) it is possible to increase the area of the primary zone thickness (with 3-fold overlap of major spots). In general, the structure of the layer remains the same.



a) b) c)

Figure 8. Options of spot overlapping while forming a coating

The most homogeneous layer structure occurs when the centres of the spots are located at the nodes of a regular triangular grid (Figure 8c). The layer consists of fragments with 3 and 4-fold overlapping of major spots.

Thus, for the formation of the switchgear contact transition layer we selected a scheme of spots arrangement in the nodes of a regular triangular grid (see Figure 8c).

4. Discussion

As a result of the experiments we analyzed influence of the factors on the speed of detonation tossing of powder material particles based on copper and the porosity of the working surface of the combined switchgear contact. We found out that at the 60% gas mixture fill factor of the detonation unit barrel, the porosity of the surface material of the contact element is 0.2%. Coatings formed by the detonation method with the fill factor of the barrel equal to 60% and more have the optimal parameters of the adhesion strength with the base. For the unit with the 22 mm barrel diameter and 1200 mm barrel length, this ratio corresponds to the mass of the gas mixture – 150 ... 200 mg.

We identified the most effective scheme of detonation forming of the detonation copper layer on the working surface of the contact element, which provides the most uniform structure of the conductive copper coating.

Conclusion

The most rational basic parameters of the technological process of forming a multi-layer conductive coating for ECE on the basis of aluminium are as follows:

- Explosive mixture – acetylene-oxygen 50:50

- Fill factor of the barrel with the gas mixture – 60%.

- Dispersion of powder particles based on copper – 40-60 microns.

To confirm the adequacy of the performed theoretical and experimental studies, following stages of work will be aimed at testing the functional characteristics of multilayer ECE based on aluminium, in particular, heating with electric current in compliance with the GOST8024-90 P.1 requirements.

This work has been conducted with the financial support of the Ministry of Education and Science of the Russian Federation on the basis of the grant agreement (RFMEFI57414X0010) #14.574.21.0010 from 06.17.2014.

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