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Відновлення деталей типу «вал» при одночасному підвищенні їх ресурсу – важливий резерв розвитку та підвищення ефективності ремонтного виробництва. Підвищення зносостійкості та довговічності деталей сільськогосподарської техніки і машин є пріоритетним напрямком сучасного машинобудування. З цією метою виконаний аналіз та розглянуто процес електроконтактного зміцнення напилених зносостійких покриттів деталей типу «вал».

Проведені експериментальні дослідження фізико-механічних властивостей зносостійких покриттів, отриманих комбінованою технологією. Встановлені залежності міцності зчеплення, пористості напилених зносостійких покриттів від струму і тиску процесу електроконтактного зміцнення. Зі збільшенням тиску зміцнення до 30–40 МПа і сили струму до 14–16 кА спостерігається зростання міцності зчеплення напиленого покриття до 180...220 МПа та зниження пористості до 2...5%.

Зносостійкість покриттів, отриманих за комбінованою технологією, у всьому діапазоні досліджених навантажень і швидкостей виявилася вищою, ніж у покриттів, отриманих окремо за класичними технологіями газополуменового і електродугового напилення. Найвищі показники зносостійкості виявлено у покриття з матеріалу ФМІ-2, отриманого комбінованою технологією.

Дослідження втомної міцності зміцнених деталей показали, що покриття отримані комбінованою технологією підвищили межу витривалості деталей, відновлених напиленням, на 20%, а деталей без покриттів – на 50%.

Проведена порівняльна оцінка фізико-механічних і експлуатаційних властивостей покриттів отриманих електродуговим, газополуменовим напиленням та комбінованою технологією. Встановлено, що застосування електроконтактного зміцнення напилених зносостійких покриттів при тиску 20...40 МПа, силі струму 11...16 кА, тривалості імпульсів струму і пауз 0,02...0,04 с, значно підвищилися їх фізико-механічні властивості та експлуатаційні характеристики.

Ключові слова: напилені покриття, пористість, міцність зчеплення, зносостійкість, електроконтактне зміцнення, довговічність, витривалість, комбінована технологія, відновлення

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STUDYING THE EFFECT OF THE COMBINED TECHNOLOGY ON DURABILITY OF THE SHAFT-TYPE PARTS

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1. Introduction

Wear of parts is the main cause of declining reliability of machine operating parameters. It leads to surface damage, loss of

power and worsening of reliability and durability of a machine in general. The mechanical, physical and electrochemical processes taking place in tribologically conjugated assemblies and units result in damaged and deteriorated friction surfaces [1].

The part wear rate varies depending on activity of such factors as duration and unevenness of loading and thermal conditions.

In the course of major repair of agricultural machinery, some parts are discarded because of inadmissible wear and lack of part recovery technologies. Quantity of such parts makes 22 % of the parts checked for defects [1, 2].

According to study [1], surface wear of parts in tractors, cars and agricultural machinery is divided as shown in Fig. 1.

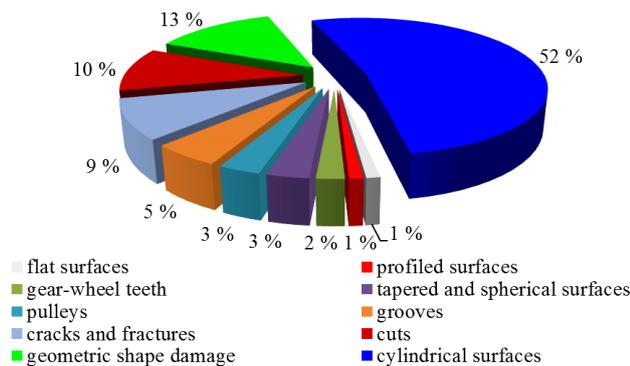


Fig. 1. Diagram of surface wear types

The shaft-sleeve friction couple forms the largest portion of worn surfaces. Media, dynamics and kinematics of relative motion of friction couples, contact nature and properties of the part material are the main factors determining the type of wear and tear of parts and moving working elements of agricultural machinery [3, 4]. The wide range of shaft parts in the machine assemblies, variety of actuating forces and operating conditions determine the large scatter of values of their working surface wear (0.1–3.0 mm per side).

Considering that the total share of cylindrical parts in agricultural machinery is more than 50 %, the problem of improving durability and reliability of shafts is of high relevance [1].

The market demands competitive low cost and simple technologies which would give a tangible economic effect [5].

Bettering of coating quality by means of the electro-contact strengthening of sprayed surfaces will improve fatigue strength and resistance to wear, heat and corrosion due to the change of the surface material structure.

Application of the combined technology when restoring machine parts with the use of materials of various compositions will make it possible to get definite effects from their introduction into production, extend life of the restored parts, even those working in hostile environments. When performing major repairs, rejection of inadmissibly worn parts of agricultural machinery can be reduced due to the combined technology of application of more than 1 mm thick coatings.

2. Literature review and problem statement

There are many technological methods of influencing and controlling composition, structure, and properties of surface layers of parts. However, introduction of such means into production is hampered by the lack of scientifically substantiated recommendations for a rational choice of ways of strengthening the part surfaces. It is advisable to choose methods of surfaces modification depending on the wear

type, nature and intensity and characteristics of the working media [6].

The technological processes of plastic working and heat treatment of metals and alloys include high-temperature heating operations. As a rule, the heated surface of metals and alloys undergoes oxidation under the influence of oxygen and temperature and alloying components burn out with scale formation [7, 8]. This, in turn, complicates application of this technology to repair parts with a significant wear.

Electron-beam, ion-beam, ion-plasma, vacuum, and other methods have been developed in recent years. However, the diffusion surface layers resulting from application of the chemothermal treatment methods are characterized by an increased brittleness, relatively small thickness of the diffusion layer and a long period of saturation [8].

Currently, a number of methods for increasing strength and wear resistance of surface layers of machine parts are known but their application is limited in solving this problem [9]. For example, methods of high-energy ion implantation significantly increase the coating cost and the depth of ion penetration is usually no more than 0.1–0.2 microns.

Increase in microhardness and wear resistance is provided by electron beam processing (EBP) of sprayed coatings [10]. Such coatings are characterized by a 60–80 % increase in fatigue limit and a 2.5 to 3.5-fold increase in bonding strength. Laser and electron beam processing provide high uniformity of heating, selectivity and ensure processing in hard-to-reach places. Disadvantages of this technology include heterogeneity of the surface macrostructure, excessive melting depth and formation of microcracks which extend to the depth of the heat-affected zone [11].

Laser melting [11, 12] of sprayed coatings ensures a two-fold increase in microhardness and a 1.3 to 1.8 times higher wear resistance. However, surface macrostructure gets heterogeneous and chemical modification of the coating is not ensured at large coating thicknesses.

Chemothermal treatment is characterized by a large process duration and impossibility of processing large-sized parts. For example, the use of inexpensive low-carbon steels for gas-thermal coating with subsequent modification enables a 10-fold increase in dry-friction durability of the coatings applied with the use of Sv-08 wire [13]. However, it should be noted that the maximum thickness of the coatings applied according to this technique does not exceed 1 mm.

Ionic nitriding of 40Cr13 and Cr18N10Ti steels provides microhardness from 6.5 to 15 GPa in a 5 to 40 μm thick surface layer. In this case, an 8-fold increase in wear resistance is observed [14]. High hardness of the nitrated layer resulting from formation of phases which in turn make impossible strong bond between the coating and the diffusion layer is disadvantage of this method.

The above methods of application of wear-resistant sprayed coatings have become the basis for introduction of the restoration processes for strengthening and extending life of parts of agricultural machines and mechanisms.

Application of the above-mentioned methods of application of sprayed wear-resistant coatings is limited by a number of their shortcomings.

In particular, EBP leads to a heterogeneous macrostructure of the surface and does not provide chemical modification. High wear resistance, hardness and other properties of electric arc/gas-thermal coatings can be ensured by electro-pulse treatment [15].

The methods of high-energy ion implantation significantly increase the coating costs [16].

Machining with a laser beam is a form of non-traditional machining which can process almost any known materials. This is a thermal contactless process that does not cause mechanical stresses [17]. The process is characterized by minimal deformation of parts and increased wear-resistance of their surface. Its disadvantages are explained by the fact that metals with different physical and mechanical properties are processed by one laser beam with specific parameters of power and power density. This results in that the metals “react” to the laser action in different ways.

Comparing energy efficiency and technical indicators of various methods for restoration of parts of machine and mechanisms of the machine-building industry (parts from steels, iron, non-ferrous metals and their alloys) and taking into consideration the cost of materials used for coating, it was found that activated gas flame spraying and hypersonic metallization are the most efficient and cost-effective methods [18]. They provide rather high mechanical and cohesive characteristics to the coatings though mostly with a thin implanted layer (15–18 μm) because of a larger quantity of oxides present and a small size of the spray particles (1–25 μm).

Cold spraying was used in the last decade as a promising solid-state coating method for the mass production of high-quality alloys and/or metal matrix composite coatings [19]. Only plastic metals can be used for coating by this technology. Its disadvantage is low bond strength.

The use of cheap and simple in implementation methods of flame and electric arc spraying according to the conventional scheme gives the maximum coating hardness of 35–50 HRC which does not ensure necessary durability [20]. At the same time, with an increase in the coating thickness, stresses on the “base – coating” boundary increase resulting in degradation of the system strength properties which leads to coating peeling.

Improvement of wear resistance, hardness, and other surface properties of gas-thermal coatings with a thickness of more than 1 mm can be achieved by electro-contact strengthening, a highly efficient and cost-effective method [21]. This method has made it possible to elaborate a combined technology consisting in formation of a wear-resistant coating by flame and electric arc spraying with subsequent modification by means of electro-contact strengthening. Electro-contact strengthening (ECS) does not allow the sprayed material to reach its melting point which opens up wide possibilities in creation of protective coatings with high physical, mechanical and operational properties.

3. The aim and objectives of the study

This study objective was to make a rational choice of a technology and substantiate the use of electro-contact strengthening of sprayed coatings for restoration of agricultural machinery shaft details worn by more than 1 mm.

To achieve this objective, the following tasks were solved:

- to study influence of the electro-contact strengthening parameters on physical and mechanical properties of coatings obtained by the combined technology;
- to determine the rate of abrasive wear of the sprayed coatings before and after their electro-contact strengthening;
- to determine fatigue strength (endurance) of materials with a sprayed coating and with no coating;

- to compare properties of wear-resistant coatings obtained by spraying and coatings obtained by the combined technology.

4. Materials and methods used to study effect of the combined technology on durability of restored parts

4.1. Studied materials and equipment used in the experiments

PG-S1 hard-alloy powders and FMI-2 powder wire were used in the studies.

The PG-S1 (GOST 21448-75) iron based self-fluxing powders are produced by the Torez Enterprise of Surfacing Hard Alloys. Chemical composition of the PG-S1 hard-alloy powder: Fe base; 28.7 % Cr, 3.17 % C; 3.2 % Si; 0.7 % Mn; 3.5 % Ni; 0.04 % P; 0.04 % S. Particle size: 63, 169, 315 μm ; melting point: 1,270 $^{\circ}\text{C}$; the average microhardness value: 8,000 GPa; average resistivity of powder at $T=293\text{ K}$: $2.5 \cdot 10^{-7}\text{ Ohm}\cdot\text{m}$.

1.8 mm diameter FMI-2 powder wire (TU 03534506-001-95, The Powder Wire for Electric Arc Metallizing) was used. The wire was developed at the Physical-Mechanical Institute of the National Academy of Sciences of Ukraine and manufactured by Iskra Co., Dubrovtytsi, Rivne Oblast, Ukraine. The wire consists of a shell (a 0.4 mm thick tape of 08 kp steel) filled with a powder charge. A FeCr+Al base charge was used. Powder of FeCr 800 grade by GOST 9849-74 (73 % Cr, 8.3 % C, the rest is Fe) was used as carbon ferrochrome. Powder of PA-40 grade (99.3 % Al) was used as aluminum.

The expediency of choosing these materials for the study relates to their composition and the ability to significantly improve wear resistance, hardness and other properties of gas-thermal coatings [22]. Significant content of chromium in these materials can increase corrosion resistance and bond of the coating. Chrome practically does not burn out during spraying.

Peculiarity of the combined technology is that the design features of the installations for electro-contact strengthening and spraying, technological parameters and characteristics of materials non-additively influence conditions of formation of the sprayed coatings strengthened by the electro-contact process. Necessity of diverse equipment is the main disadvantage of the combined methods of coating and multi-operational technologies. The process of combined spraying and subsequent electro-contact strengthening is schematically shown in Fig. 2.

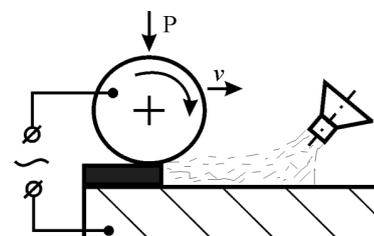


Fig. 2. The process of gas-thermal spraying and subsequent electro-contact strengthening

Equipment for electric arc spraying was developed at the Physical-Mechanical Institute of the National Academy of Sciences of Ukraine (Lviv, Ukraine). The EM-14 metalizer was mounted on the support of the 16K20 thread-cutting lathe.

The equipment for electric arc spraying had the following parameters: voltage: 18...36 V, current: 50...600 A, arc power: 5...20 kW, distance from the nozzle to the working surface: 50...200 mm, speed of the longitudinal movement of the metallizer: 5...10 mm/s, rotational speed of the shaft: 0...60 rpm, gas pressure: 0.35...0.5 MPa, gas flow: 60...150 m³/h, wire diameter: 1.6...2.0 mm, wire feed rate: 0.05...0.35 m/s.

The process of flame spraying was carried out using the UPTR-90 rig developed by Amalgamated Machine Building Institute of the National Academy of Sciences of Belarus. The UPTR-90 rig has the following parameters: the powder feeder volume: 0.006 m³, the main fraction particle size: 40...120 μm, the spraying distance: 100...350 mm. Gas consumption: 1.0...4 m³/h for oxygen, 0.7...2.0 m³/h for acetylene, 0.2...1.5 m³/h for propane-butane, up to 2 m³/h for industrial gas. Gas working pressures: 0.1...0.4 MPa for oxygen, 0.07...0.11 MPa for acetylene, 0.03...1.0 MPa for propane-butane, up to 0.2 MPa for industrial gas.

Maximum spraying efficiency: 1.1...10 kg/h; stock usage: 98 %.

The process of strengthening of the sprayed coatings and the study of the process of electro-contact strengthening were carried out with the use of a machine for contact tape surfacing, model 011-01-2, developed by Remdetal Scientific and Production Amalgamation, Russia (Fig. 3).

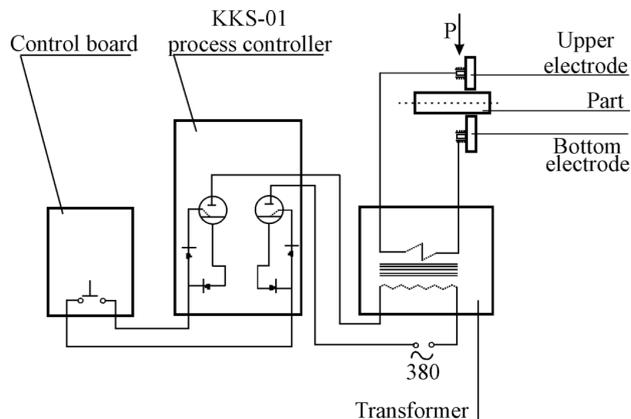


Fig. 3. Electrical schematic diagram of the rigs for electro-contact strengthening

The test unit works in a semi-automatic mode and includes the following main elements: a rotary device, a feeder, a carriage with a surfacing head, a rack, a pneumatic movable sleeve, a control panel, a cooling system, and a pressure air supply system. Strengthening of the sprayed layer was accomplished by overlapping points using controlled current pulses. The electrodes for experimental studies were made of copper M3, GOST 859-78.

The process of strengthening was carried out with simultaneous hardening and cooling of the sprayed layer which practically excludes the specimen heating. Technical characteristics of the installation and its parameters are shown in Table 1.

The process of electro-contact strengthening of spray coatings is realized by a joint action of high temperature on the powder layer (not higher than 0.8...0.95 of the melting point of the main component) and pressure. Electro-contact strengthening is characterized by high heating rates (up to 100,000 °C/s). Permanent or alternating electric current (up to 25...30 kA) and voltage (1.5...6 V) can be used.

Table 1

Parameters of electro-contact strengthening

Parameter name	Parameter value
Primary voltage, V	380
Secondary voltage, V	3.3...6.6
Primary current, A	100...450
Strengthening current, kA	8...30
Efficiency, cm ² /min	up to 120
The highest electrode force, kN	1...3
Width of the top electrode, mm	8...16
Strengthening current pulse duration, s	0.02...0.04
Pause duration, s	0.02...0.04
Spindle rotation speed, rpm	0.6...1.5
Carriage speed, m/s	1.5...75×10 ⁻⁴
Coating thickness, mm	0.15...3

4. 2. Methods for measuring technological parameters of the process of electro-contact strengthening of sprayed coatings

The strengthening secondary voltage and current were recorded by H-701.1 loop oscilloscope of Kalibr Enterprise, Minsk, Belarus. Voltage calibration of the loop was conducted with the voltmeter D574 (accuracy class: 0.2) within 0–7.5 V. The strengthening current was recorded on the oscilloscope tape with the use of one of the elbows of the upper electrode feeder as a bridge. To exclude influence of inductance on the measurement accuracy, a bridge with a high inductive to reactive resistance ratio was used. A recess of small cross section was made in the hollow current feeder and a calibrated section with resistance of 30 μΩ was cabled to the oscilloscope galvanometer with the voltage taken from the bridge being proportional to the current recorded and practically coinciding with it in phase. Internal cooling of the current feeder made it possible to exclude temperature effect on the process of current oscillography.

The current curve was calibrated by direct measurement of the amplitude current value in a pulse by means of ASTs-1M electronic amperemeter. The secondary circuit current was measured by means of E3-78 voltmeter specially calibrated with a current transformer. Temperature of the resulting coatings was measured using thermoelectric converters of TKhA-2088 model (GOST 3044-97) produced by Etalon Co., Russia, with 0.3 mm diameter wire which were fixed directly on the specimen surface and the data were recorded by the H-071.1 oscilloscope.

To measure temperature of the surface coating layer, the thermocouple junctions were placed in a cylindrical 0.3...2 mm diameter hollow to reduce heat flow in the coating. When conducting temperature measurements in the process and in order to smooth the strengthening current interference, a block of inductive-capacitive filters was switched to each thermocouple circuit. It consisted of a 2,000 μF capacitor and a choke with active resistance of 1,250 ohms and inductance of 1.2 Gn.

4. 3. Procedures used for measuring the physical and mechanical properties of coatings

The strength of bond between coating and the base metal was measured by normal tearing in accordance with a pin procedure using the R-20 tear-off machine produced by ZIPO Enterprise of Testing Devices and Equipment, Russia. Coatings were tested on specially modified specimens with

a tapered shape of the and hole in the washer. This shape of the pin along with exclusion of the effect of friction forces reduced clearance in the junction and increased measurement accuracy.

The strength of bond of the coating layer with the base, σ , was determined by the formula:

$$\sigma = \frac{F}{S},$$

where F is the separation load, N; S is the area of active surface of the pin, mm²,

$$S = \pi \cdot \frac{D^2}{4},$$

where D is the diameter of the active surface of the pin, $D=4$ mm.

Porosity was determined by a planimetric method of metallographic analysis (GOST 18898-73). The method has made it possible to estimate pore distribution in the volume of coating and determine the pore shape and size.

The fatigue strength tests were performed using the experimental calculation procedure and the U-10 installation developed at Pisarenko Institute of Strength Problems of the National Academy of Sciences of Ukraine [23].

Standard round 5 mm diameter specimens were used with gas-thermal coating applied on their working surface. For comparison, 3 to 5 noncoated specimens and the same number of coated specimens were used. The tests were carried out for 100 hours at the temperature limited for the coating. Tensile force was calculated with no taking into account the coating thickness since the coating strength is an order of magnitude lower than the base material strength.

The magnetostriction unit operation principle is based on the resonance with a frequency about 10 kHz. The general idea underlying the effective operation of such units consists in ensuring fatigue fracture of the specimens at minimum energy inputs.

The installation operating frequency at which it is applicable for fatigue tests was approximately within 9.8 to 10.8 kHz (Fig. 4).

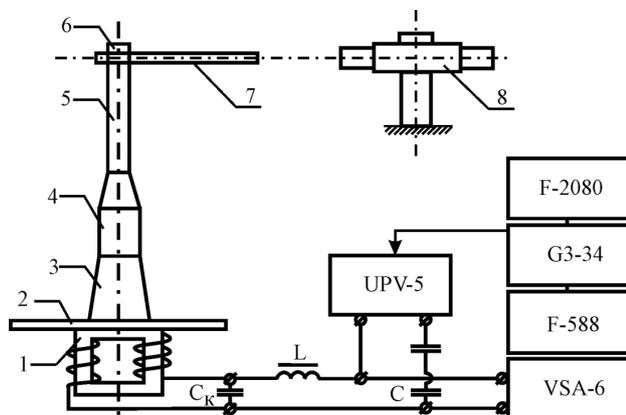


Fig. 4. Block diagram of the magnetostriction unit: vibrator (1); concentrator (2); flange (3); sleeve nut (4); half-wave concentrator (5); nut (6); specimen (7); microscope (8)

The vibrator 1 operation principle is based on the use of magnetostriction, which is the ability of some materials to change their linear dimensions under the action of an

alternating magnetic field. The magnetostrictive effect was realized using O-shaped 0.1 mm thick nickel plates collected in a package forming the vibrator 1. The alternating magnetic field of the vibrator was generated by passing alternating current through its winding. The current frequency was equal to the working frequency of the unit. The winding also served to excite a constant magnetic flux in the package.

To increase amplitude, concentrator 2 was used. It was a half-wave rod of a variable cross section with a flange 3 in the nodal cross section of the rod. Diameters of the concentrator end faces were 2–24 mm and 120 mm.

The electrical part of the unit consisted of a G3-34 generator, an F-588 cycle counter, an F-2080 frequency meter and a VSA-6 rectifier as a source of direct current.

The required oscillation amplitude of the specimen 7 fixed with the help of the nut 6 on the face end of the concentrator 5 was set by varying the acoustic generator output voltage fed to the powerful amplifier.

Matching of the output transformer of the powerful UPV-5 amplifier with the vibrator was done by selection of an optimal number of turns of the vibrator winder provided the maximum amplitude of the vibrator oscillations is obtained. Inclusion of the choke L and the capacity C (Fig. 4) enables parallel connection of the powerful amplifier, DC source and the vibrator winder. Capacity C_K is connected in parallel to the vibrator winding, so that resonance of currents takes place in the C_K – Vibrator Inductance circuit. This improves conditions for matching the vibrator with the powerful amplifier. Magnetizing currents were set to 15 A at voltage of 2–3 V. To measure the specimen 7 oscillation amplitude, a microscope 8 with a set of lenses and eyepiece was used in the tests. By varying the amplitude of oscillations, the stress level necessary for fatigue failure of the specimens was established at a certain number of loading cycles.

4. 4. Procedures used for measuring the abrasive wear of coatings

The tests for abrasive wear of coatings were carried out using non-rigidly fixed abrasive particles in accordance with GOST 23.208-79 which coincides with ASTM C 568.

This method is used in wear tests of the materials with a high hardness. The essence of the method is that under equal conditions, the specimens are subjected to wear exerted by abrasive particles fed to the friction zone and pressed to the specimen with a rubber roller. Wear of the specimens without coating, with a sprayed coating and with a coating applied by the combined technology was measured (Fig. 5).

Studies were carried out on a test installation having the drive 7 that provides rotation around the horizontal axis of the rubber roller 6. The specimen holder 2 and the lever 3 press the specimen 1 to the roller, the device 5 batches the abrasive particles to the friction zone along the guide tray 4. The device 8 serves to control the total number of rotations of the roller 6.

The roller diameter should be in the range of 48–50 mm, the roller width: (15 ± 0.1) mm, the roller material hardness: 78–85 Shore units.

Hardness of the abrasive particles should exceed hardness of the material not less than 1.6 times. Therefore, the abrasive material was alumina abrasive grains of 16-P size according to GOST 3647-80 with relative moisture content not more than 0.15 %.

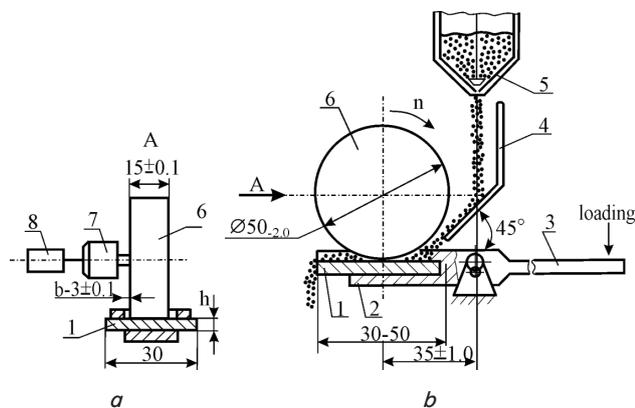


Fig. 5. The diagram of the installation for abrasive wear testing: a side view (a); appearance of the installation (b): the specimen (1); the specimen holder (2); the lever (3); the guide tray (4); the device for dosing the abrasive particle feed (5); the rubber roller (6); the drive (7); the speed control device (8)

Wear of the test and reference specimens was determined by weighing before and after tests with an error not more than 0.1 mg according to the weight method by means of ADV-200M analytical scales. The friction path length was 1,000 m. The weight loss in the wear test must be at least 5 mg.

5. Results of studying the properties of coatings

The study of physical and mechanical properties of materials with coatings enables an objective prediction of behavior of the parts during operation and influences operation life, composition and structure by controlling the coating technology.

The 20 mm diameter, 40 mm thick specimens of steel 45 were coated with PG-S1 and FMI-2 materials by spraying. Electro-contact strengthening was realized with the help of the 011-01-2 unit through variation of technological parameters, namely, current and pressure. Duration of current pulses and pauses was 0.02 s. Three measurements in each experiment of determining the bond strength and porosity were made. The graphs of dependence of coating porosity and bond strength on current and pressure on electrodes were plotted using arithmetic mean values.

As a result of the experimental tests, dependence of the bond strength, porosity and wear resistance on the technological parameters of the strengthening process (current, pressure) was established. Significant decrease in porosity of the sprayed coatings after electro-contact strengthening in comparison with the effect of flame treatment was due to the positive role of the mechanical factor. Analysis of the study has shown that pressure in electro-contact strengthening under the influence of high temperatures determines development of plastic deformations contributing to "healing" of pores (Fig. 6).

Interaction of materials in the solid phase is activated by both temperature and pressure. At the same time, for a considerable acceleration of material interaction at high temperatures, very low pressure is required which initiates the directed motion of structural defects.

Increase in pressure to 30–40 MPa has brought about growth of the bond strength of the sprayed coating but its further increase leads to a decrease in the bond strength.

This is because of the insufficient temperature of coating sintering, appearance of microcracks and, as a consequence, a decrease in its strength with the growth of pressure (curves 2, 3, Fig. 7). Similar dependencies in this study can be traced on an example of a coating of the powdered GH-S1 alloy and the use of powder wire FMI-2.

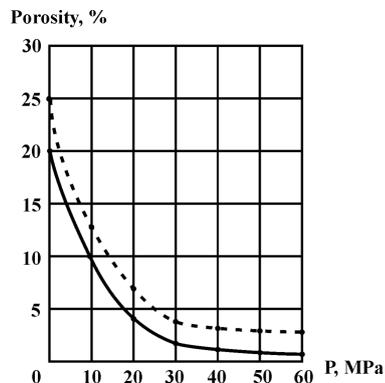


Fig. 6. Dependence of porosity of the sprayed coating on the strengthening pressure at current strength of 16 kA, duration of the strengthening current pulses and pauses: 0.02 s: PG-S1 (1); FMI-2 (2)

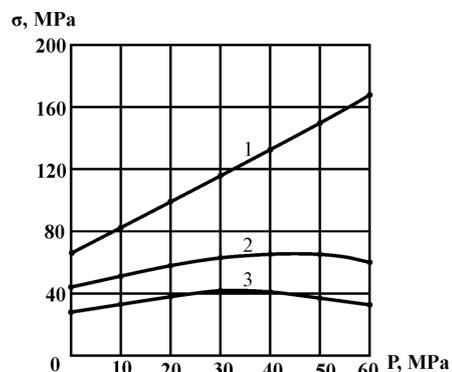


Fig. 7. Dependence of the bond strength of the sprayed coatings on the electrode pressure at strengthening currents: $I = 14...16$ kA (1); $I = 11...14$ kA (2); $I = 8...10$ kA (3)

The next stage of the study was the determination of the bond strength of the coatings depending on variation of the reinforcement current.

The studies have shown that the maximum values of the coating bond strength were achieved at 16–18 kA (Fig. 8). This is due to the change of crystalline lattice during coating sintering.

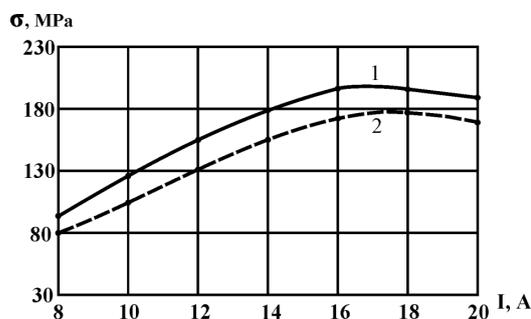


Fig. 8. Dependence of the coating bond strength on current (at ECS pressure $P=40$ MPa, thickness of the powder layer $d=2$ mm), PG-S1 (1), FMI-2 (2)

Wear tests were carried out on the friction unit (Fig. 5) with sprayed coatings and the coatings obtained with the use of the combined technology according to the standards GOST 23.208-79 and ASTM C 568. Experimental specimens having dimensions of 30×30 mm and thickness 4.0 mm were tested at a rubbing speed of 0.158 m/s and a load of 20 kg. The study data were written into a table according to which graphs of dependence of the wear weight loss on the friction path were plotted.

The study of wear resistance of coatings with PG-S1 and FMI-2 showed that with an increase in the strengthening current, wear decreased and the nature of this change was qualitatively consistent with the dependence on the ECS modes. Wear resistance of the coatings obtained by the combined technology was higher in the entire range of the studied loads and speeds (curves 3, 4, Fig. 9). However, durability of the coatings applied separately by flame and electric arc spraying was inferior to the proposed technology with electro-contact strengthening (curves 1, 2, Fig. 9).

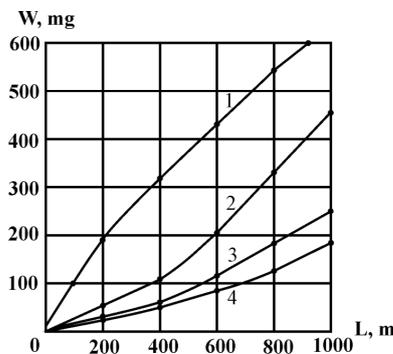


Fig. 9. Dependence of weight-loss wear (*W*) on friction path (*l*): coating of material PG-S1 (1); coating of material FMI-2 (2); coating of material PG-S1 obtained by the combined technology (3); coating of material FMI-2 obtained by the combined technology (4)

The wear resistance of the coating is largely determined by their microstructure. Electro-contact strengthening makes it possible to preserve the so-called hereditary structure of the original powder material in the sprayed coatings. For example, when PG-S1 alloy powder is used for coating, the high speed of metal during its spraying results in formation of a fine-grained structure.

No less important characteristics of the material are fatigue properties. When fatigue takes place, cracks originate and grow to large sizes without any noticeable changes in the part shape.

Fatigue limits were determined with three sets of the specimens under study: original specimens 3 without coating (steel 45); specimens 2 with an electric arc coating; specimens 1 with a coating obtained by the combined technology. The test results are shown in Fig. 10.

In the process of testing with intensive bending, the specimens with coatings behaved unstable because of cracking and peeling of the coatings. Cohesive cracking in the coatings obtained by spraying began after 10⁵ cycles and after 10⁶ cycles in the sprayed coatings with electro-contact reinforcement. Cracking preceded partial peeling of the coating. Amplitude of oscillations increased during peeling. The moment of adhesive peeling of individual coating areas was precisely noticeable by the change of the resonance

frequency. The moment of base destruction was noticeable by a sharp decrease in the amplitude of oscillations and a sharp change of the resonance frequency. Reduction of force and sound frequency was the external manifestation of the specimen destruction.

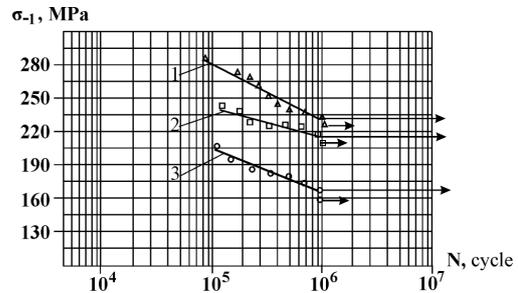


Fig. 10. The results of fatigue strength tests of the coated specimens: coating obtained by the combined technology (1); sprayed coating (2); without coating (3)

It can be concluded from comparison of the curves that fatigue limit of the coatings obtained by the combined technology was 20 % higher than that of the sprayed coatings and 50 % higher in comparison with the specimens without coating. In the case of insufficient cohesive and adhesive fatigue strength of the coating, the surface heat-affected zone should be considered the factor increasing the fatigue limit of the base material.

6. Discussion of results of studying the properties obtained by the application of the combined technology

The features of compaction and heating of the sprayed coating during its subsequent electro-contact strengthening ensure coatings with a uniform distribution of physical and mechanical properties throughout their surface.

Figs. 11, 12 show physical and mechanical properties of the coatings obtained by spraying and the combined technology and their comparison.

It is clear from the comparative analysis that the ECS makes it possible to obtain practically pore-free sprayed coatings with high bond strength.

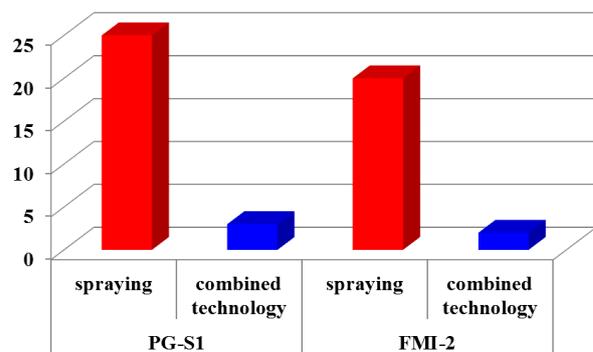


Fig. 11. Comparison of porosity of the coatings obtained by different technologies, %

Such results were achieved due to the fact that the re-hardening of the surface layer takes place in the process of electro-contact strengthening which leads to an increase in its microhardness. High-temperature temper

of the subsurface metal layers contributes to softening of the surface layer.

In the process of electro-contact strengthening, decomposition of residual austenite and growth of microhardness have occurred in deep layers. This is explained by high carbon concentration in the layer and martensitic transformation of residual austenite in the coating.

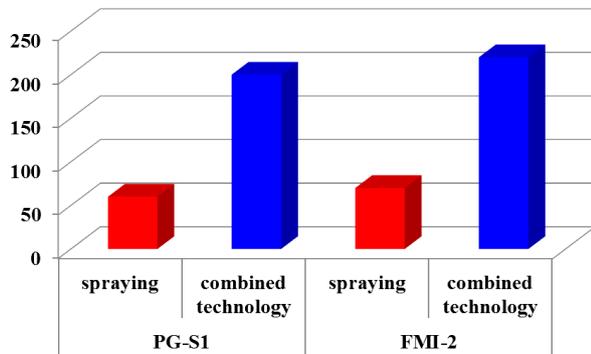


Fig. 12. Comparison of the bond strength of the coatings obtained by different technologies, MPa

Quality of protection and operation of equipment with strengthened parts show that industrial introduction of this technology will significantly reduce duration and complexity of repair works. In addition, this will extend equipment life and improve efficiency and profitability of production.

The positive effect of the combined action of temperature and power factors enables application of this technology for restoration of parts in various industries.

This study advantage consists in the fact that application of the combined technology will make it possible to restore shaft parts of agricultural machinery with a degree of wear more than 1 mm. In addition, this technology can be applied to any materials including brittle materials and materials with low heat resistance.

However, there are objective difficulties connected with the need to use diverse equipment. Therefore, there are many technological parameters which determine physical, mechanical and operation properties of the restored machine part surfaces.

Further studies may be aimed at determination of optimal modes of electro-contact strengthening when restoring parts with pre-determined physical, mechanical, and operational properties. Application of the combined part recovery technology will enable transfer of the results obtained to the parts working in various process media.

7. Conclusions

1. The technology of electro-contact strengthening of sprayed coatings, its features and influence of the process parameters on properties of the wear resistant coatings have been studied. It was established that with an increase in the strengthening pressure to 30–40 MPa and current up to 14–16 kA, the bond strength of the sprayed coating increased and amounted to 180...220 MPa. The reverse dependence was observed for porosity of the sprayed coatings. With an increase in pressure, porosity of the selected materials decreased and made up 2...5 %.

2. Wear resistance of the coatings obtained by the combined technology throughout the range of the studied loads and speeds was higher than that obtained by the classical spraying technology.

3. Electro-contact strengthening has allowed us to increase the fatigue limit of sprayed coatings by 20 %.

4. Comparison of results of the studies on application of coatings by the classical and the combined technologies of application of wear resistant coatings has allowed us to assert that physical-mechanical and operational properties of the applied coatings have considerably increased at a pressure of 20...40 MPa, current of 11...16 kA, duration of current pulses and pauses of 0.02...0.04 s.

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