

Tribological Properties of Coatings Obtained with Electrocontact Welding of Metal Powder Materials

R. Saifullina^a, L. Islamova^a, Yu. Kuznetsov^{b,*}, A. Kolomeichenko^c, R. Solov'yev^c, I. Kravchenko^d, K. Sovin^e, L. Kalashnikova^f

^aBashkir State Agrarian University, 50 years of October St. 34, 450001, Ufa, Russia,

^bOrel State Agrarian University named after N.V. Parakhin, General Rodin St. 69, 302019, Orel, Russia,

^cCenter of Agricultural Engineering of State Research Center of the Russian Federation, FSUE «NAMI», Avtomotornaya St. 2, 125438, Moscow, Russia,

^dRussian State Agrarian University – Moscow Agricultural Academy named after K.A. Timiryazev, Timiryazev St. 49, 127550, Moscow, Russia,

^eFederal Scientific Agroengineering Center VIM, 1 st Institut'sky proezd, 5, 109428, Moscow, Russia,

^fOrel State University named after I.S. Turgenev, Komsomolskaya St. 95, 302026, Orel, Russia.

Keywords:

Coatings
Wear resistance
Friction ratio
Powder materials
Powder coatings
Electrocontact welding

ABSTRACT

The investigations of tribo mechanical properties of coatings obtained with electrocontact welding of sintered powder materials and powder-polymer fillers of Russian manufacture are presented. It is proved that the introduction of antifriction components (powders of copper or tin) into filler material at a rate of 5-10 % increases the time to joints seizure by 1.5-2 and decreases by 1.5 the friction ratio. The application of powder-polymer and sintered fillers reinforced with metal grid produces a relief on the operating surface of the coating with the areas possessing minimum hardness. They are worn out more intensely and the forming herewith grooves help to keep lubricating oil on the friction surface. For the friction pair operating in abrasive wear conditions with adhesive wear elements, at welding it is recommended to use powder compositions (by weight): 80-90 % – PG-FBX6-2, 10-20 % of copper powder friction ratio (PMS-N); for wear conditions at adhesive wear: 90 % of iron powder (PZHR 3.200.28), 10 % of tin powder (PO-1); for abrasive wear conditions: 70-80 % – PG-FBX6-2, 30-20 % – VK8.

* Corresponding author:

Yury Kuznetsov 
E-mail: kentury@yandex.ru

Received: 10 January 2020

Revised: 7 February 2020

Accepted: 14 March 2020

© 2020 Published by Faculty of Engineering

1. INTRODUCTION

At current the deposition methods (gas flame, plasma, detonation and electro arc) are widely spread among various powder materials [1-13]. Methods of electro arc [14-16] and laser welding [17-21] of metal powders, cored wire and

sintered filler wires are well-known too. The method of application of metal powders – electrocontact welding is less known. Its essence is in current pulse gating via the circuit «electrode - adding material - part». As a result because of high electric resistance adding material is heated and welded to the metal

surface [22,23]. The advantages of the electrocontact welding of metal powders are the possibility of quenching of the deposited coating in the process of its welding, efficiency increase by 2-3 times in comparison with numerous coating techniques, reduction of the deposited material rate in comparison with the conventional welding by 3-4 times, the absence of considerable part heating, decrease of alloying elements burning out, low allowance for subsequent machining of the deposited reconditioning coating [24-27].

However, the method of the electrocontact welding of metal powder materials has some disadvantages, such as: a complicated and labour intensive nature of the deposition process of an even powder layer on the surfaces to be joined; the difficulty of holding the powder on curved surfaces; washing off some of the powder with a cooling liquid. Moreover, it is known from the powder metallurgy that the powder body is unstable because of abundant free energy. This is primarily caused by the presence of an extremely advanced internal phase interface between the solid body and pores [27-31]. Besides, the problems of wear resistance when using the fillers of powder compositions are underexplored, which allow to control the structure and physical mechanical properties of deposited reconditioning and / or hardening coating [24, 32-35].

In this regard, the main objective of the carried out investigations is the study of the tribotechnical characteristics, powder-polymer fillers deposited with electrocontact welding, and their composition optimization to obtain maximum wear resistance of the deposited reconditioning and /or hardening coating in the conditions of abrasive wear and adhesive wear.

2. MATERIALS AND METHODS

The installation of trade mark «BMU-1» (Fig. 1) was used for electrocontact welding of powder materials.

Depending on the trade mark of powder and the type of filler material, welding modes were varied in the following intervals: welding current – 4-7 kA, current pulse duration – 0.02-0.06 s, duration of pause between current pulses

– 0.04-0.08 s, pressure – 0.3 MPa, speed of rotation of the installation spindle – 3.5 min⁻¹.



Fig. 1. General view of installation for electrocontact welding.

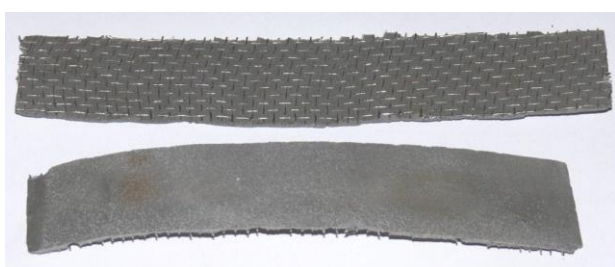
Metal powders (made in Russia) and their mixtures, of trade marks PG-FBX6-2, PG-S27M, PR-X11G4CR, chippings from cast iron SCH18, PZHR 3.200.28 + PMS-N, PZHR 3.200.28 + PO-1, PG-S27M + PMS-N, PZHR 3.200.28 + VK8, PZHR 3.200.28 + Sormite, PZHR 3.200.28 + VK8 were used for the investigation. The choice of these powders was determined by the objectives of the study, namely, increasing the wear resistance of powder coatings in the conditions of abrasive wear and adhesive wear. For example, solid (PG-FBX6-2, PG-S27M, PR-N11G4SR, Sormite) and high-hard (VK8) powders were studied for abrasive wear conditions. For example, solid (PG-FBX6-2, PG-S27M, PR-N11G4SR, Sormite) and high-hard (VK8) powders were studied for abrasive wear conditions. Antifriction powders (PMS-N, PO-1) were added to the powder composition for adhesive wear conditions. Since tin (PO-1), copper (PMS-N) and hard-alloy (VK8) powders are not sintered with powders from iron-carbon alloys, when welding in the studied modes (they are mechanically held in a matrix of steel powders), the PZHR 3.200.28 powder was used as a matrix for these powders. The chemical composition of the used powder materials is presented in Table 1.

The general view of the reinforced powder-polymer and sintered fillers used for welding is presented in Fig. 2. The general view of the coating on the part obtained by electrocontact welding is presented in Fig. 3.

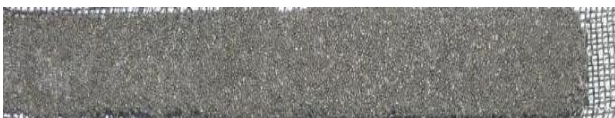
Table 1. Chemical composition of powders [29].

Powder trade mark	Mass fraction [%]															
	Fe	C	Si	Mn	S	P	O	Cu	Sn	Pb	Ni	Cr	B	W	Mo	Co
PZHR 3.200.28	99.4	0.04	0.06	0.14	0.02	0.02	0.32	-	-	-	-	-	-	-	-	-
PMS-N	0.08	-	-	-	-	-	0.03	99.5	-	-	-	-	-	-	-	-
PO-1	-	-	-	-	-	-	0.5	-	99.0	0.25	-	-	-	-	-	-
Sormite	60	2.8	3.5	1.5	-	-	-	-	-	-	4	28	-	-	-	-
PR-X11F4SR	82	0.8	3.0	-	-	-	-	-	-	-	-	11	2.7	-	-	-
SCH18	92.5	3.3	1.9	0.8	0.12	0.45	-	-	-	-	0.35	0.35	-	-	-	-
PG-FBX6-2	55	4.5	1.7	4	0.4	0.3	-	-	-	-	-	32	1.7	-	-	-
PG-S27M	63	4.0	1.5	1.2	-	-	-	-	-	-	1.7	26.5	-	0.3	1.2	-
VK8	0.3	0.6	-	-	-	-	0.4	-	-	-	-	-	-	91	-	7.6

Tribological studies of the samples were carried out on friction machine «SMC-2», which was completed with a heat exchanger to stabilize the oil temperature when the load in the friction pairs increased in order to accelerate the tests.



(a)



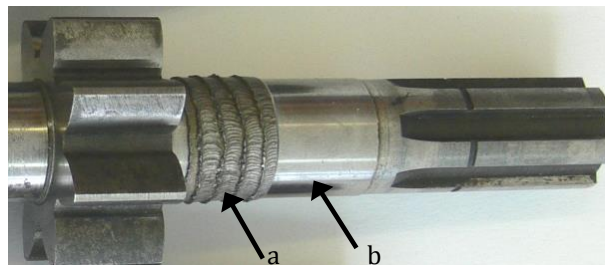
(b)

Fig. 2. Powder-polymer (a) and sintered (b) fillers reinforced with metal grid.

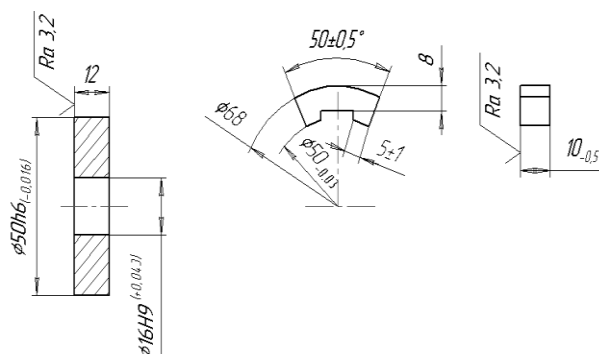
Friction pair wear was controlled with the artificial bases method. The artificial base in the form of a pyramid imprint with an angle 136° between edges was applied at 4 points of the sample circumferentially, via 90° it applied with Vickers hardness tester of model «TP-7r-1» at load on the diamond point 294.3 H. The wear was determined from the formula:

$$\Delta h = \frac{d_1 - d_2}{7} \quad (1)$$

where d_1 , d_2 – are the dimensions of projects diagonals of imprints at the beginning and at the end of tests correspondingly, mm;
7 – proportionality factor at the angle 136° between opposite edges of the square pyramid.

**Fig. 3.** General view of the coating on the part obtained by electrocontact welding: a – before grinding; b – after grinding.

The objects of the tribological investigations were the samples-rollers (Fig. 4), made of steel 45, on which the coatings of powder materials were welded by the electrocontact method.

**Fig. 4.** Sample and counterbody to carry out tests on wear.

The sample rotation frequency at the testing was 1000 min^{-1} . As a counterbody we used two blocks of gray cast iron of trade mark SCH10 (Fig. 4). Optimal load was selected according to load prior to research objects seizure. During running-in loading was increasing gradually after 1/6; 1/3 and 2/3 from optimal load. The oil temperature in the friction zone was maintained constant in the interval $70-80^\circ\text{C}$.

Extreme-pressure properties of the deposited coatings were estimated by measuring the time prior to friction pair seizure at pressure 44 MPa with the uncooled lubricating oil.

To speed-up the testings 5 % of grinding sludge was added to the lubricating oil. During the

friction pair replacement the lubricating oil was changed. Suspended abrasive particles were supported with impellar blades, mounted on an axis together with the tested sample.

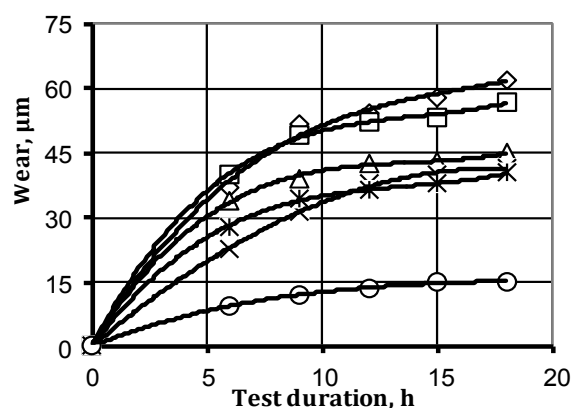
The surface roughness of the coatings was measured using profilometer-profilograph «ABRIS PM-7.2». Profilograms were recorded before and after each friction pair research. The track of strip-chart method was checked in according to the imprint in the center of the grid cell on the sample end. Each friction pair was measured in four mutually perpendicular surfaces.

3. RESULTS AND DISCUSSION

One of the directions of increase of the operating surface wear resistance in the conditions of abrasive wear is its hardness increase. Figure 5 presents the studies results of the test duration effect on the powder coatings wear. Figure 5 presents that the reference sample has the maximum (1-5 hours more in comparison with other samples) running-in duration. The reference sample wear insufficiently exceeds the coating wear, obtained from steel chip, which can be explained with its porousness. At the steady friction mode the coating of cast iron chip has the wear circa 26 % less, in comparison with the reference sample. This is connected with the increase of the operating surface hardness as a result of hardening at the electrocontact welding (hardness of SCH18 chip is not high and corresponds to HB 1700-2410), and also presence of antifriction graphite in the SCH 18 structure.

Wear rate of the powder coatings (except PZHR 3.200.28 + VK8 and PG-FBX6-2) at the steady mode is roughly the same. After 18 hours of testing the minimum wear of the coating of consistent powder was observed in PG-FBX6-2 and was 72 % from the reference sample wear. Among the powder composition coatings PZHR 3.200.28 + Sormite and PZHR 3.200.28 + VK8 have the minimum wear. However, during work with coating PZHR 3.200.28 + VK8 the counterbody has the extremely gross wear after 3 hours of testing, afterwards a new block is mounted. It is found that on testing of the powder composition coatings, containing highly rigid materials, the counterbody is worn out more intensively in comparison with the

consistent powder coatings. For this reason the usage of the powder composition coatings containing highly rigid materials, is irrational in the sliding friction conditions. It is reasonable to them for reconditioning or hardening of working elements of the road, building and agricultural machinery.



◇ – without coating (reference – steel 45, hardened to 40-45 HRC);
 □ – with coating from steel chip of steel 45 (chip size is 0.3-1.0 mm);
 △ – with coating from cast iron chip of trade mark SCH18;
 × – with coating from powder PG-FBX6-2;
 * – with coating from powder composition: PZHR 3.200.28 (80 %) + Sormite (20 %);
 o – with coating from powder composition: PZHR 3.200.28 (70 %) + VK8 (30 %)

Fig. 5. Influence of tests duration on coatings wear.

In the course of wear tests, it was found that the micro-relief of the surface of the sample taken as a reference standard was characterized by smoothing of micro-irregularities and an increase in the reference area of the working surface. At the same time, the working surface profile of the test sample with a coating obtained by electrocontact welding of sintered powder-polymer fillers reinforced with the metal grid gained a microrelief, which view was determined with the cell size of the reinforcing steel grid used in sintered powder fillers for reinforcing (Figs. 2 and 6).

Under friction the grid material with lower hardness is worn with the higher rate. Herewith formed grooves can keep some additional quantity of the lubricating oil, which positively influences on the wear resistance at boundary lubrication and increases the time to the moment of sticking (seizure) of the coworking surfaces. Analogical results are obtained at the electrocontact welding of cast iron chip and metal powder materials (Fig. 7).

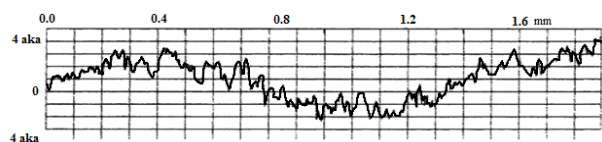


Fig. 6. Profilogram of the operating surface after 8 hours of testing by the friction machine.

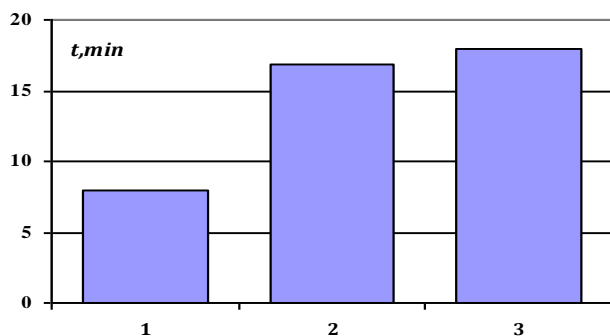


Fig. 7. Coatings seizure time: 1 – from steel 45 (reference); 2 – from cast iron chip SCH18; 3 – from powder PR-X11G4SR.

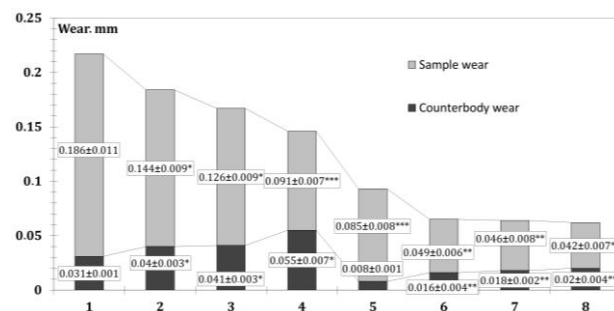
The sample with the metal powder material coating and cast iron counter-sample in the friction pair have the time to seizure on an average is 2 times more than, the reference friction pair has. This is explained with the presence of pores in the coating with oil absorbing capacity. When heated oil in the pores projects from them and lubricates flexible joint which in the boundary lubrication condition can endure higher temperatures before seizure of the interacting operating surfacers.

Another way to improve the wear resistance of coatings is to reduce their friction ratio by including antifriction materials in their composition. Copper and tin powders were used as these materials.

Investigations have shown (Fig. 8) that a powder coating with 10 % tin in its composition has the minimum wear, and a coating containing tin (5 %) and copper (5 %) has the maximum wear [29].

It should be stressed the simultaneous presence of tin and copper powders in the mixture influences negatively on the coating formation quality at the electrocontact welding, worsening its adhesion and also preventing qualitative sintering of iron particles caused by the effect of the factitious removal (exudation) of fusible metal. The coatings being obtained with the usage of tin or copper in the powder mixture, have the wear resistance exceeding the wear

resistance of the coating without these antifriction materials twice.



Polymer (bounding substance for metal powder), AFP – antifrictional powders (Cu – copper, Sn – tin).
*, **, *** – statistically significant difference in the corresponding values (with respect to Student's criterion) is absent.

Fig. 8. Wear of the coatings on the base of iron powder PZHR 3.200.28 and counterbody: 1 – 3 % Polymer, without AFP; 2 – 10 % Polymer, without AFP; 3 – 17 % Polymer, without AFP; 4 – 10 % Polymer, 5 % Sn, 5 % Cu; 5 – 10 % Polymer, 10 % Sn; 6 – 3 % Polymer, 20 % Cu, Reinforcing grid; 7 – 10 % Polymer, 10 % Cu; 8 – 10 % Polymer, 20 % Cu.

Estimating the effect of the coatings from metal powder materials with antifriction materials on the counterbody, it is established that blocks which were tested with the coating containing 20 % of copper had the minimum wear. The maximum wear of the counterbody was observed in the friction pair with the coating without antifriction material and with the minimum content (3 %) of cohesive polymer (polyvinylbutyral), which was used for powder particles adhesion at the electrocontact welding. The counterbody wear decreases at the increase of the adhesive component because of burning out of the last one at the electrocontact welding, which provides the increase of porousness and antifriction properties of the coating at the sake of lubrication oil keeping. Wear test of the reference sample was not carried out because of the extremely gross wear of the counterbody at the accepted test conditions.

The research showed that antifriction material content in the metal powder coating and its porousness produce considerable influence on the time prior to seizure of interactive operating surfaces. The most significant influence on the time prior to seizure of flexible joint (58 min), is done by the tin incorporated into the coating composition. It is established that the coatings from the metal powder materials with copper operate 1.5 less prior to seizure in comparison with tin [29].

The next experimental step was aimed at the investigation of the coatings from the metal powder materials with combination of antifriction and operating surface high hardness. It is reasonable to use these coatings in flexible joints with boundary lubrication, when counterpart also has high hardness of the operating surface (connections of type: «camshaft lobe - pusher», «fuel pump camshaft - plunger cam roller», «neck of gear-box input shaft - bearing rollers» etc., where sliding friction and combined rolling and friction are realized). The required resource of these flexible joints is provided only at the account of high surface hardness of the coworking surfaces. Thus, it is possible to suggest that the presence of the antifriction materials in the coating of metal powder materials, allows to increase wear resistance of flexible joints.

Together with the usage of the antifriction materials in the powder matrix with low hardness (HRC 12-18), the analogical coatings with the antifriction materials and the hard matrix (HRC 40-60) were tested. During the tribological investigations we determined the time prior to seizure and friction ratio of two hard composite coatings, obtained by the electrocontact welding from the powder mixtures of the following composition:

1. Hard powder PG-S27M – 90 % + antifriction filler (copper powder PMS-N) – 10 %.
2. Hard powder PG-FBX6-2 – 90 % + antifriction filler (copper powder PMS-N) – 10 %.

The above mentioned powder compositions were sintered into filler wires, according to the recommendations [36] and after the electrocontact welding were tested in the friction pair with steel 50, hardened to HRC 50-55. The results of the flexible joints tests were accepted as reference values: «hardened steel 50 – hardened steel 50»; «coating from powder PG-FBX6-2 - hardened steel 50».

It is established that the time prior to hardening of the powder compositions is by 3.5 times longer for PG-FBX6-2 + PMS-N and by 2.8 times – for PG-S27M + PMS-N, in comparison with hardened steel 50. The coating from metal powder material PG-FBX6-2 has the time prior to hardening twice shorter in comparison with the powder compositions with the hard matrix and antifriction material Fig. 9.

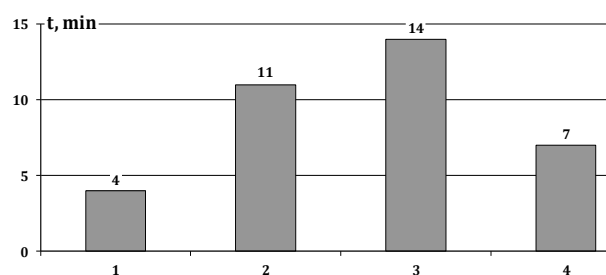


Fig. 9. Time prior to seizure in the tested friction pairs: 1 – Hardened steel 50; 2 – PG-S27M (90 %) + PMS-N (10 %); 3 – PG-FBX6-2 (90 %) + PMS-N (10 %); 4 – PG-FBX6-2.

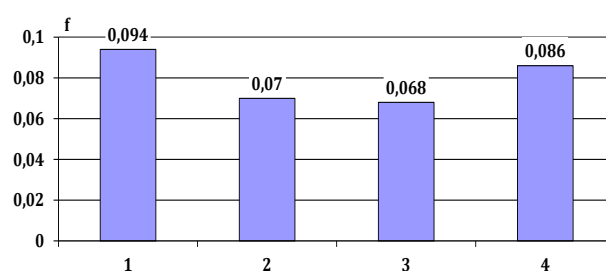


Fig. 10. Friction ratio in the tested friction pairs: 1 – Hardened steel 50; 2 – PG-S27M (90 %) + PMS-N (10 %); 3 – PG-FBX6-2 (90 %) + PMS-N (10 %); 4 – PG-FBX6-2.

The obtained values of friction ratios correlate well with the time prior to seizure in friction pair. Friction ratio (the most close value) for the coatings of powder compositions with copper in the friction pair with hardened steel 50 is about by 1.3 times lower than in the friction pair «hardened steel 50 - hardened steel 50», taken as a reference standard. Friction ratio of the coating of metal powder material PG-FBX6-2 without antifriction material is 8.5 % lower, in comparison with hardened steel 50 (Fig. 10).

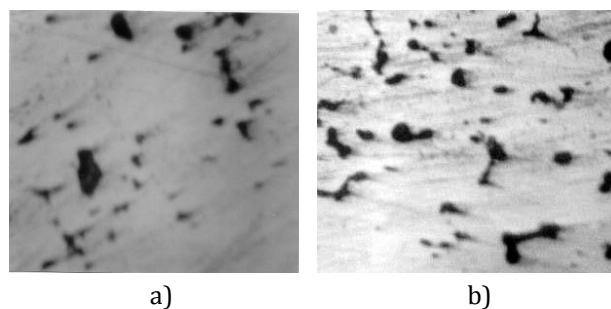


Fig. 11. Pores in powder coating with different polymer content (x400): a) 10 %; b) 20 %.

Figure 11 presents the microstructure of the coatings, obtained by the electrocontact welding of powder-polymer fillers. It is obvious that with an increase in the amount of adhesive polymer

that burns out during welding, the porosity of the coatings increases.

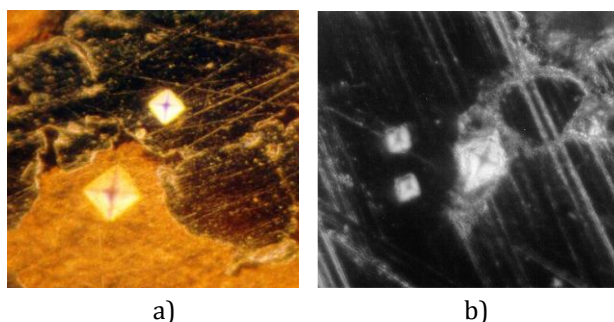


Fig. 12. Microstructure of the powder coating with copper (a) and tin (b) additives in powder matrix PZHR 3.200.28 (dark background) (x640).

Figure 12 presents the microstructure of the coatings, obtained from the powder materials, which composition was selected according to positions 5 and 6, indicated in Fig. 8. The powder particles of copper (micro-hardness – 650-710 MPa) and tin (micro-hardness – 144-156 MPa) and also their distribution through the coating depth were determined on a measurement basis of micro-hardness of structural constituents of powder coating. It was found that the bulk of copper powder particles, and especially of tin powder particles, after welding is located closer to the surface of the coating or to the border of fusion with the base metal of the part. This indicates that the temperature in the electrocontact welding zone is higher than the melting temperature of these elements, which causes a partial emission of liquid superheated metal to the surface and to the border of fusion with the metal base. After welding, the coatings are grinded and the surface layer with a high content of copper or tin particles is removed. This leads to a decrease in the number of antifriction additives in the coating compared to their initial content in the powder-polymer filler, which is a definite disadvantage.

4. CONCLUSIONS

1. The use of powders with high hardness (VK8) increases the wear of the counterbody, so to increase the wear resistance of the interface as a whole, it is necessary to select powder compositions according to the compatibility condition of the interacting surfaces. The presence of porosity in powder coatings increases the wear resistance and the time

before seizure, especially for boundary lubrication. The presence of porosity in powder coatings increases the wear resistance and the time before seizure, especially for boundary lubrication. When applying coatings, it is recommended to use the following powder compositions:

- for conditions of abrasive wear with wear elements at adhesive wear: 80-90 % (by weight) powder PG-FBX6-2, 10-20 % copper powder (PMS-N);
- for conditions of abrasive wear: 70-80 % (by weight) powder PG-FBX6-2, 30-20 % powder VK8;
- for conditions of adhesive wear: 90 % (by weight) iron powder (PZHR 3.200.28), 10 % tin powder (PO-1).

2. Introduction of antifriction materials (copper or tin powders) at a rate of 5-10 % by weight increases the time to seizure by 1.5-2 times and decreases the friction ratio by 1.5 times.
3. The use of sintered and powder-polymer fillers reinforced with metal grid for electrocontact welding contributes to the creation of a regular microrelief, the type of which is determined by the size of the grid cell and the ratio of the particle hardness of the powder components.

REFERENCES

- [1] V.N. Korenev, A.Ju. Rodichev, A.V. Semenov, *Methods of Reconditioning and Hardening of Parts by Gas Flame Spraying*, Welding Industry, no. 2, pp. 40-43, 2014.
- [2] Yu.S. Korobov, *Prolongation of Parts Service Life by Supersonic Flame Spraying*, Heavy Mechanical Engineering, vol. 7, pp. 34-38, 2006.
- [3] V.S. Goncharov, E.V. Vasilyev, A.N. Popov, *Hardening of Gas Flame Coatings*, International Science Popular Journal, no. 6-1, pp. 39-41, 2014.
- [4] M. Gupta, N. Markocsana, X.-H. Lib, B. Kjellmanc, *Development of Bondcoats for High Lifetime Suspension Plasma Sprayed Thermal Barrier Coatings*, Surface and Coatings Technology, vol. 371, pp. 366-377, 2019, doi: [10.1016/j.surfcoat.2018.11.013](https://doi.org/10.1016/j.surfcoat.2018.11.013)
- [5] E. Sánchez, E. Bannier, V. Cantavella, M.D. Salvador, E. Klyatskina, J. Morgiel, J. Grzonka, A.R. Boccaccini, *Deposition of Al₂O₃-TiO₂ Nanostructured Powders by Atmospheric Plasma*

- Spraying*, Journal of Thermal Spray Technology, vol. 17, no. 3, pp. 329-337, 2008, doi: [10.1007/s11666-008-9181-5](https://doi.org/10.1007/s11666-008-9181-5)
- [6] S.M. Muneer, M. Nadeera, *Wear Characterization and Microstructure Evaluation of Silicon Carbide Based Nano composite Coating Using Plasma Spraying*, Materials Today: Proceedings, vol. 5, iss. 11, pp. 23834-23843, 2018, doi: [10.1016/j.matpr.2018.10.175](https://doi.org/10.1016/j.matpr.2018.10.175)
- [7] V.P. Singh, A. Sil, R. Jayaganthan, *Wear of Plasma Sprayed Conventional and Nanostructured Al₂O₃ and Cr₂O₃ Based Coatings*, Transactions of the Indian Institute of Metals, vol. 65, no. 1, pp. 1-12, 2012, doi: [10.1007/s12666-011-0070-0](https://doi.org/10.1007/s12666-011-0070-0)
- [8] G. Mauer, M.O. Jarlago, D.E. Mack, R. Vaßen, *Plasma-sprayed thermal barrier coatings: new materials, processing issues, and solutions*, Journal of Thermal Spray Technology, vol. 22, no. 5, pp. 646-658, 2013, doi: [10.1007/s11666-013-9889-8](https://doi.org/10.1007/s11666-013-9889-8)
- [9] S.-W. Yao, J.-J. Tian, C.-J. Li, G.-J. Yang, C.-X. Li, *Understanding the Formation of Limited Interlamellar Bonding in Plasma Sprayed Ceramic Coatings Cased on the Concept of Intrinsic Bonding Temperature*, Journal of Thermal Spray Technology, vol. 25, no. 8, pp. 1617-1630, 2016, doi: [10.1007/s11666-016-0464-y](https://doi.org/10.1007/s11666-016-0464-y)
- [10] G. Sundarajan, G. Sivakumar, D. Sen, D. Srinivasa Rao, G. Ravichandra, *The Tribological Behaviour of Detonation Sprayed TiMo(CN) Based Cermet Coatings*, International Journal of Refractory Metals and Hard Materials, vol. 28, iss. 1, pp. 71-81, 2010, doi: [10.1016/j.ijrmhm.2009.07.007](https://doi.org/10.1016/j.ijrmhm.2009.07.007)
- [11] I.Ya. Movshovich, Yu.A. Chernay, G.I. Ischenko, *Effect of Physical and Mechanical Characteristics of the Detonation Coatings on the Wear Resistance of Work Items Re-adjustable Dies*, Forging and Stamping Production. Materials processing by pressure, no. 10, pp. 6-11, 2012.
- [12] A. Sova, D. Pervushin, I. Smurov, *Development of Multimaterial Coatings by Cold Spray and Gas Detonation Spraying*, Surface and Coatings Technology, vol. 205, iss. 4, pp. 1108-1114, 2010, doi: [10.1016/j.surfcoat.2010.07.092](https://doi.org/10.1016/j.surfcoat.2010.07.092)
- [13] A.V. Kolomeichenko, S.N. Sharifullin, V.N. Logachev, A.A. Izmalkov, *Investigation of Properties of Electro-metallized Coatings Deposited by Supersonic Air Stream with Aerosol Fluxing*, IOP Conference Series: Materials Science and Engineering, p. 012059, 2019, doi: [10.1088/1757-899X/570/1/012059](https://doi.org/10.1088/1757-899X/570/1/012059)
- [14] V.A. Erofeev, S.K. Zakharov, S.V. Zotova, *Influence of Parameters of Powder Material Arch Surfacing on Tool Surface Properties*, Bulletin of Tula State University, Technical Sciences, no. 1, pp. 117-124, 2017.
- [15] A.A. Sitnikov, *Structure and Properties of Deposited Electroarch Coatings from Powders of Mechanoactivated SHS-composites*, Metal Working (Technology, Equipment, Tools), vol. 52, no. 3, pp. 51-55, 2011.
- [16] Yu.N. Saraev, V.P. Bezborodov, M.V. Perovskay, K.A. Bolgaru, B.S. Braverman, *Enhancing Coating Properties by Application of Pulsed Arc Surfacing Method when Modifying the Molten Metal by Composite Powder Materials*, Journal of Physics: Conference Series, vol. 1115, iss. 4, p. 042035, 2018, doi: [10.1088/1742-6596/1115/4/042035](https://doi.org/10.1088/1742-6596/1115/4/042035)
- [17] S. Nowotny, S. Scharek, E. Beyer, K.H. Richter, *Laser Beam Build-up Welding: Precision in Repair, Surface Cladding, and Direct 3D Metal Deposition*, Journal of Thermal Spray Technology, vol. 16, no. 3, pp. 345-348, 2007.
- [18] R.K. Sidhu, O.F. Ojo, M.C. Chaturvedi, *Microstructural Analysis of Laser-beam-welded Directionally Solidified INCONEL 738*, Metallurgical and Materials Transactions A, vol. 38, no. 4, pp. 858-870, 2007.
- [19] Y.L. Huang, G.Y. Liang, J.Y. Su, J.G. Li, *Interaction Between Laser Beam and Powder Stream in the Process of Laser Cladding with Powder Feeding*, Modelling and Simulation in Materials Science and Engineering, vol. 13, no. 1, pp. 47-56, 2005, doi: [10.1088/0965-0393/13/1/004](https://doi.org/10.1088/0965-0393/13/1/004)
- [20] E.I. Tesker, V.A. Guryev, S.E. Tesker, *Microstructure and Properties of Laser Deposited Surface Layers*, Physics and Chemistry of Material Machining, no. 1, pp. 38-42, 2004.
- [21] V.P. Biryukov, *Increase of Work Endurance of Sliding Friction Pairs at Laser Welding of Powder Materials*, Heavy Mechanic Engineering, no. 9, pp. 14-17, 2013.
- [22] M.Z. Nafikov, *Reconditioning of Shafts By electric Resistance Welding of two Steel Wires*, Welding International, vol. 30, iss. 3, pp. 236-243, 2016, doi: [10.1080/09507116.2015.1044274](https://doi.org/10.1080/09507116.2015.1044274)
- [23] M.U. Rustamova, *Electrocontact Welding of Materials at Parts Reconditioning and Hardening*, Young Scientist, no. 7, pp. 164-165, 2016.
- [24] V.S. Natalenko, A.P. Pavlov, *Indicators of Hardness of Coating Obtained by Electrocontact Welding Composite Filler Materials*, Journal of Advanced Research in Technical Science, no. 14-2, pp. 153-156, 2019, doi: [10.26160/2474-5901-2019-14-153-156](https://doi.org/10.26160/2474-5901-2019-14-153-156)
- [25] I.R. Gaskarov, I.R. Maksyutov, V.V. Arslanov, A.V. Arslanov, *Investigation of Coatings Properties, Obtained by Electrocontact Welding of Steel*

- Wire, Bulletin of Bashkir State Agrarian University, no. 8, pp. 123-128, 2018.
- [26] M.N. Farkhshatov, K.V. Yuferov, *Cohesive Resistance of Coatings, Obtained by Electrocontact Welding of Wire from High-carbon Instrument Steel*, Materials of GOSNITI, vol. 118, pp. 206-209, 2015.
- [27] N. Yunusbaev, I. Gabitov, M. Farkhshatov, M. Nafikov, R. Saifullin, I. Zagirov, S. Insafuddinov, *Perspective Method of Restoration of Autotractor Parts by Electrocontact Welding of Powder Materials in the Magnetic Field*, Tribology in Industry, vol. 41, no. 1, pp. 115-125, 2019, doi: [10.24874/ti.2019.41.01.13](https://doi.org/10.24874/ti.2019.41.01.13)
- [28] M.Z. Nafikov, R.S. Aipov, A.Yu. Konnov, *Powder Metallurgy Reconditioning of Food and Processing Equipment Components*, Russian Metallurgy (Metally), vol. 2017, no. 12, pp. 1057-1062, 2015, doi: [10.1134/S0036029517120114](https://doi.org/10.1134/S0036029517120114)
- [29] R.N. Saifullin, *Improvement of Performance of Machine Parts by Electrocontact Welding of Composite Materials*, Journal of Friction and Wear, vol. 28, no. 2, pp. 206-211, 2007, doi: [10.3103/S1068366607020122](https://doi.org/10.3103/S1068366607020122)
- [30] S.V. Konovalov, V.E. Kormyshev, V.E. Gromov, Y.F. Ivanov, E.V. Kapralov, A.P. Semin, *Formation features of structure-phase states of Cr-Nb-C-V containing coatings on martensitic steel*, Journal of Surface Investigation, vol. 10, no. 5, pp. 1119-1124, 2016, doi: [10.1134/S1027451016050098](https://doi.org/10.1134/S1027451016050098)
- [31] X. Chen, C. Su, Y. Wang, A.N. Siddiquee, S. Konovalov, S. Jayalakshmi, R.A. Singh, *Cold Metal Transfer (CMT) Based Wire and Arc Additive Manufacture (WAAM) System*, Journal of Surface Investigation, vol. 12, no. 6, pp. 1278-1284, 2018, doi: [10.1134/S102745101901004X](https://doi.org/10.1134/S102745101901004X)
- [32] A.Yu. Konnov, M.V. Demchenko, A.V. Sisanbaev, M.Z. Nafikov, M.N. Farkhsatov, *Estimation of the Corrosion Resistance of the Metal Coatings Formed by Powder Metallurgy*, Russian Metallurgy (Metally), vol. 2019, no. 12, pp. 1285-1288, 2019, doi: [10.1134/S0036029519120097](https://doi.org/10.1134/S0036029519120097)
- [33] R.A. Latypov, P.I. Burak, G.R. Latypova, *Electrocontact Welding of Steel Wire on Cylindrical Parts via Intermedia Layer of Powder Material*, in 4-th International Research to Practice Conference, 17 April, 2014, Modern Innovations in Science and Technology, Kursk, ZAO University Book, pp. 362-367.
- [34] A.V. Serov, N.V. Serov, P.I. Burak, *Determination of Technological Parameters of Electrocontact Welding at Reconditioning and Hardening of Flat Surfaces*, Bulletin of Federal State Educational Institution of Higher Professional Education «Moscow State Agroengineering University named after V.P. Goryachkin», vol. 77, no. 1, pp. 35-40, 2017.
- [35] A.A. Boltenev, V.N. Chizhov, V.P. Sheryshev, *Modelling and Forecasting of Process Conditions of Electrocontact Sintering of Metal Powder Materials at Parts Reconditioning*, Welding Industry, no. 8, pp. 24-27, 2001.
- [36] R.N. Saifullin, *Electrocontact Welding of Powder Materials at Parts Reconditioning and Obtaining Protective Coatings*, Monograph, Ufa: BashSAU, 2008.