Journal of Engineering Physics and Thermophysics, Vol. 77, No. 3, 2004

ON THE PROBLEM OF DEPOSITION OF WEAR- AND HEAT-RESISTANT COATINGS ON MACHINE PARTS

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UDC 621.793.72:533

The content of doping elements as a function of the flow rate of the working gas (pressure), the wear resistance (the dopant is flux-cored wire), the thermal conductivity, the strength, the thermal stability, and the structure (the dopant is aluminum and Ni–Cr-alloy wires) have been investigated in coatings produced by the method of electric-arc metallization.

The economic expediency of reclamation of worn-out surfaces of parts of machines and mechanisms has stimulated work on creating a technology and improving equipment for these purposes. Numerous methods of reclamation and deposition of strengthening coatings depending on the conditions of operation of the products reclaimed have been developed at present. Work is being carried out in this direction at some institutes of the National Academy of Sciences and other institutions of Belarus. However, problems on the reclamation of bulk (the most expensive, as a rule) products, for example, the crankshafts of heavy-loaded diesel engines of the SMD-60, YaMZ-238, and other types, are the least understood. The reason is that they are deformed in heating (facing technologies), cracks appear because of the thermal loads, and one is unable to ensure the necessary adhesion of the sprayed layer to the base and the necessary porosity of the coating in gas-thermal spraying.

Work on creation of the technology of reclamation of heavy-loaded parts of machines and mechanisms, in particular, crankshafts of 100–250 kW diesel engines, by the method of electric-arc metallization has been carried out at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus (Minsk) since 1993; this method is economical, efficient, and relatively simple and does not lead to an overheating of the parts and the formation of cracks in the coating.

With the aim of improving the quality of the coating one activates the process of metallization by different methods: introducing dopants into the material sprayed, varying the chemical composition of the working gas, spraying with the use of a supersonic flow, etc. We followed the path of increasing the pressure and flow rate of the working gas, as a result of which the molten metal is sprayed by a supersonic air jet and further acceleration of particles is also carried out in a supersonic air flow formed by the second nozzle.

The technology of reclamation of more than 50 kinds of parts for various purposes has been developed at present. These include the crankshafts of diesel engines of heavy-duty motors and tractors — D-240 (Belarus tractor), 4VD, 6VD, Ikarus and Neoplan buses, YaMZ-740 (Kama Automobile Plant), YaMZ-236 (Minsk Automobile Plant), Mercedes 401, 403, and 441, Volvo, grain harvesters, and others — the crankshafts of heavy-duty compressors, the bearing journals and mounting seats for the rolling bearings of camshafts, electric motors, and wheel hubs, the brake shafts of trailers and semitrailers, the spindle of a grinding machine and the tail spindle of a coordinate machine, rollers for subways, and others.

In carrying out this work, we have placed particular emphasis on the selection of a dopant (filler material) the coating from which would meet the basic operating characteristics as far as strength, adhesion, and wear resistance are concerned. For this purpose we have investigated a large number of coatings from various materials (solid and flux-cored wires) and their combinations [1, 2]. Based on the investigation results, we recommend PP-MM-2 (V0), PP-MM-2S (V1), PP-MM-63 (V2), and PP-TP1 (V3) flux-cored wires as the dopants. The employment of the indicated materials enables one to deposit a coating without a sublayer to control the chemical composition of the coating and hence its operating properties over a wide range due to the technological parameters and the combination of materials, for example, V0 + V3 [1–3]. However, when air is used as the working gas, the doping elements burn away due to

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A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, 15 P. Brovka Str., Minsk, 220072, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 77, No. 3, pp. 103–107, May–June, 2004. Original article submitted June 4, 2003.

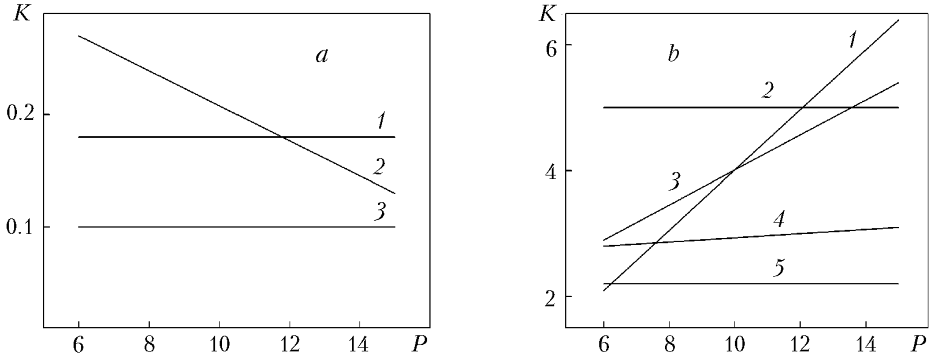


Fig. 1. Content of the doping elements K in a V3 flux-cored-wire coating vs. pressure of the working gas P: a) 1) Si; 2) C; 3) Mn; b) 1) O (200 A); 2) Cr; 3) O (250 A); 4) Ni; 5) Al. P, 10^5 N/m^2; K, %.

the high temperature of the arc discharge (≈6000 K). Thus, for example, in the case of employment of PP-TP1 (V3) flux-cored wire as the dopant, the content of manganese in the coating decreased to 0.1% for its concentration of 0.4 in the wire; the content of silicon decreased from 0.27 to 0.18 and that of carbon decreased from 0.67 to 0.13 (Fig. 1a). It is noteworthy that the content of carbon in the coating drops with increase in the flow rate of air, whereas the content of the bound oxygen increases (it increases to a much larger extent for lower arc-discharge currents (Fig. 1b)).

The high temperature of particles and the release of heat in their hardening lead to a considerable heating of the surface layer, which generates thermal stresses in it; the value of the thermal stresses depends on the difference of the coefficients of thermal expansion of the base and the coating, the temperature gradient in the layer, the geometry of the part, etc. As a result, in continuous spraying of a layer nearly 0.5 mm thick, we have its cracking; therefore; spraying is carried out with breaks; the average temperature of the crankpin does not exceed 60–70^{o}C. Rough calculations of the temperature stresses show that cracking of the layer is possible even in its heating to 100^{o}C; it also depends on the strength of the material sprayed. Rupture tests have shown that the strength attains 180 to 190 MPa [1].

Structural stresses arise in the coating in addition to the temperature stresses. We have noted cases where the appearance of a crack and its closing occurred within a day after the spraying. In this connection, one must carry out mechanical treatment of the coating no earlier than within two days after the spraying.

In normal operation of the friction pair shell–crankpin, the hardness of the crankpin surface exerts no influence on the operating characteristics of the crankshaft. Thus, the crankshafts reclaimed by us in 1993 had hardness at a level of 25–28 HRC and were used for several years. However, under actual conditions, motor oil is contaminated by pulverized particles leading to the erosion of contacting surfaces. Penetration of particles into both the shell and the relatively soft porous coating occurred. In the latter case, the "soft" coating on the crankshaft did not wear out, whereas the shells intensely failed. Improvement in the hardness of the coating in the presence of the contaminants in oil leads to a deterioration of its characteristics: an ever increasing number of foreign particles penetrate into the shell and abrasive wear of the crankshaft occurs. When the filtration of the oil is good, of primary importance is the compatibility of the metals on the friction surface.

However, it is necessary to improve the hardness of the coating for another reason. Normal wear of the metal of the crankpin is mainly caused by the fatigue processes in the surface layer (if we disregard the fact that about half the wear occurs at the instant the engine is started). The intensity of fatigue failure is in inverse proportion to the rupture strength of the material, which is related to its hardness in direct proportion. Investigations carried out by the Brinell–Haworth method in friction of a rubber disk against a plane specimen through an abrasive interlayer have shown that wear resistance is improved with hardness of the coating (Fig. 2a). As a result of testing the specimens on MT-1 (friction against a plane specimen without lubrication of a counterbody) and SMT-1 (friction according to the crankshaft–block scheme in the presence of lubrication) friction machines, it has been established that the rate of wear of a number of coatings (depending on the technological parameters) is at a level of 1–1.5 of that of the 45 steel hardened to 58 HRC (Fig. 2b and c).

Under the actual conditions of operation of Ikarus buses, the rate of wear of the reclaimed crankpins is 0.12 to 0.30 μm per 1000 km of the bus's run, which corresponds to the wear resistance of new crankshafts, whereas the

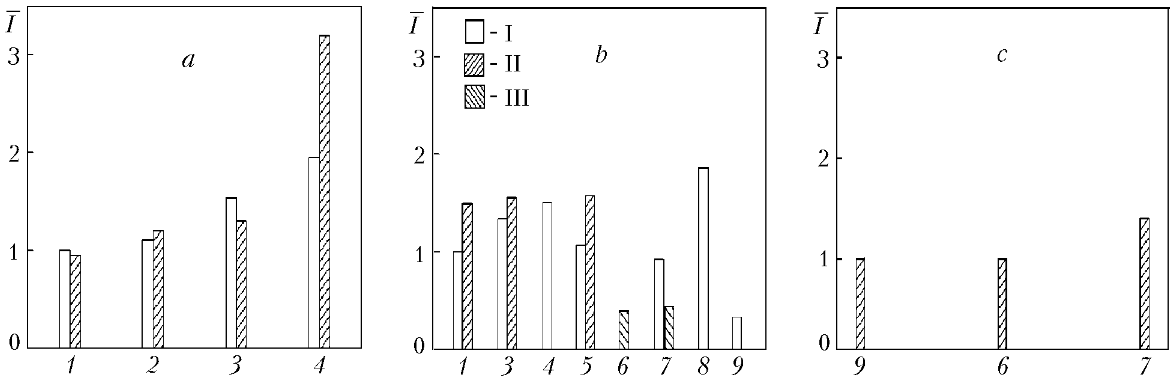


Fig. 2. Relative rate of wear of the coatings $\bar{I}$ from different materials on a laboratory setup: a) by the Brinell–Haworth method; b) MT-1; c) SMT-1 (working medium: I, products of combustion of butane and propane; II, air; III, heated air): 1) 40Kh13; 2) PP-FMI-2; 3) PP-MM-2S; 4) PP-MM-2; 5) PP-MM-2S+PP-TP1; 6) PP-MM-2+PP-TP1; 7) PP-TP1; 8) 65G; 9) 45 steel.

rate of wear of the reclaimed rollers of the suspension of subway cars with a hardness of the coating of 43–45 HRC is lower than that of new rollers with a cemented surface of hardness 54–55 HRC.

Selection of a wear-resistance coating does not mean that the investigations are completed. Whereas a 0.5–1.0-mm layer is sprayed for manufacture of specimens, under actual conditions one has to deposit coatings of thickness 1.5–2.0 mm or more on crankpins. Cracks appear on such coatings in the absence of a good cohesion to the base. High adhesion improves heat removal from the coating into the crankshaft, i.e., decreases temperature stresses and crack formation. In our experiments, the cohesive strength (without deposition of a sublayer) attained 60–90 MPa for different wires; stripping of the sprayed layer with an area of nearly 20 cm^2 on the bearing journal of the crankshaft of an Ikarus engine (192 hp) was observed only once (over a period of more than seven years of operation) due to the welding of the shell.

In connection with the low thermal conductivity of the layer sprayed, we must take into account that burns of the coating are possible in grinding of the crankshaft. It is also not improbable that as a result of the reduction in heat removal, the temperature in the friction zone changes, changing the viscosity of the oil and the temperature of the shells. The shell temperature also sharply increases if a foreign particle arrives at the shell–crankpin gap, which leads to a deformed shell [4]. According to the data of [4], 70 to 80% of the emergency failures of YaMZ augmented engines is connected with the arrival of mechanical particles at this gap.

However the technology of reclamation of crankshafts goes beyond spraying. One must primarily maintain technological discipline at all steps of the process. Different plugs must be taken out of the crankshafts before spraying, and counterweights, bearings, and gears must be removed; the crankshafts must be flushed, which is not always done because of the high cost (flushing of a KamAZ crankshaft costs ≈15 dollars). Thereafter one pregrinds the crankshafts, burns out oil in furnaces, closes oil galleries, covers surfaces not to be sprayed, and carries out shot-blast treatment of the crankpin and its spraying. Then one performs cleaning of the crankshaft and its grinding, polishing, balancing, and conservation.

It is necessary to thoroughly flush both the crankshaft and the engine in the process of installation of the crankshaft into the engine. When the flushing of the engine's oil galleries is of low quality, abrasive particles are transferred by the oil line most frequently to the last bearing journals, as a result of which marks are formed on them and we have increased abrasive wear in addition to the effects described above. An analogous process occurs in the case of starting of a cold engine when the relief valve lets raw oil pass into the oil line, bypassing the filter. Furthermore, each filtering system passes particles having a size smaller than a certain size. Thus, this limit is at a level of 20 μm for paper filters and of 5 μm for cardboard filters. The data of [4] point to the linear dependence of the rate of wear of the crankshaft on the particle size.

Two more important points are abundant pre-oiling of the coating before installing the crankshaft and direct filling of the oil line with oil before running-in the engine. The fulfillment of the latter condition is necessary in con-

TABLE 1. Thickness of the Coating on the Specimens, mm

Side	Specimen No.			
	1	2	3	4
A	0.5–0.6	0.3–0.35	0.4–0.45	0.7–0.8
B	0.2–0.3	0.15–0.25	0.2–0.3	0.25–0.35

nection with the porosity of the layer sprayed, since oil is absorbed into the coating over the period of assembly and is absent on the friction surface at the instant the engine is started. It takes a certain time to fill the volume of the oil line and the filter with oil. When the oil temperature is low and the capacity of the oil pump is insufficient, this time can attain tens of seconds for certain engines.

Subsequently, the porosity of the coating ensures the necessary wetting of the friction surface by oil. The coatings sprayed have a porosity of 5–7% for a pore size of 1–2 μm (the measurements have been performed with an electron microscope using an automatic image analyzer). Such parameters are ensured due to the high velocity of particles, which is nearly 350 m/sec.

The investigations of the dependence of the physicochemical properties of coatings on different factors and the analysis of the actual conditions of assembly and operation of the engines have enabled us to create a technology of reclamation of the crankshafts of 100–250 kW diesel engines and other parts of machines and mechanisms.

Improvement in wear resistance because of the change in operating conditions is contributed to by deposition of heat-resistant coatings on the working surface of the parts of the engines of the sleeve-piston group, which results in a decrease in the heat loss from the working body to the cooling system, a reduction in the influence of high temperatures on their efficiency, etc. The use of ceramics and pearlites for creation of heat-resistant coatings leads to a substantial improvement in the operating characteristics of an engine [5]:

(a) we have a more efficient and complete combustion of the fuel, which results in a reduction of nearly 3–9 g/(kW·h) in its flow rate and a decrease in the amount of unsaturated hydrocarbons and hydrogen in exhaust gases;

(b) the character of combustion of the fuel changes, which leads to a reduction in the maximum pressure in the combustion chamber and, as a consequence, in vibration and noise; the "milder" regime of operation decreases the wear of the bushings of the cylinder and connecting-rod shells;

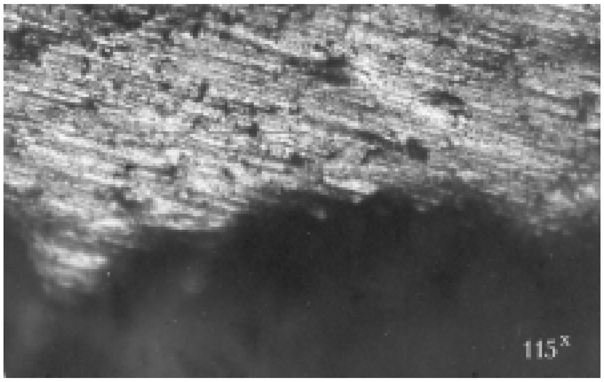
(c) the rate of accumulation of the products of polymerization and condensation of hydrocarbons in the oil is reduced, which results in a decreased carbon and varnish deposition;

(d) thermal stresses in the piston are reduced, which leads to an increase of no less than 1.5 times in its service life.

Metal wires are sprayed in electric-arc metallization, and the thermal conductivity of the coatings is fairly high. However, one can select operating regimes of the unit in which the deposited coating can contain up to 60% of the oxides, i.e., the layer sprayed consists of metal ceramics, in practice [6]. Furthermore, a metal coating, for example, of aluminum, can subsequently be electrochemically treated to form an Al_2O_3 layer. As a result, a multilayer coating with a metal sublayer and a ceramic surface is formed.

In this connection, we have investigated the possibility of producing metal-wire coatings with the aim of employing them subsequently for protection of the parts of the engine's combustion chamber. We employed 1.8–2.2-mm aluminum and Ni–Cr-alloy (nichrome) wires as the dopant. We determined the thermal conductivity, hardness, thermal stability, and structure of the coatings. Specimens of thickness 2.5–5 mm were sprayed to determine the thermal-conductivity coefficient. The thermal-conductivity coefficient of "aluminum" coatings with a density of $(2.1–2.15)\cdot10^3$ kg/m^3 was 49 W/(m·K) in the temperature range 25–125^{o}C, which is nearly four times smaller that that of pure aluminum (210 W/(m·K)). The thermal-conductivity coefficient of nichrome coatings was equal to 4 W/(m·K) in the range 25–150^{o}C, which is 3–5 times lower than that of monolithic material (12–22 W/(m·K)). For the sake of comparison, we note that the thermal conductivity of partially stabilized zirconium dioxide (it is assumed to be one of the most promising materials for protection of the working surface of the combustion chamber) is at a level of 1 W/(m·K) [7].

Depending on the operating regime of the metallizer, the microhardness of the aluminum layer was $(80–150)\cdot10^7$ N·m^{-2}, which is twice as high as in the case indicated in [5] and is much higher than the hardness of annealed aluminum ($18\cdot10^7$ N·m^{-2}).



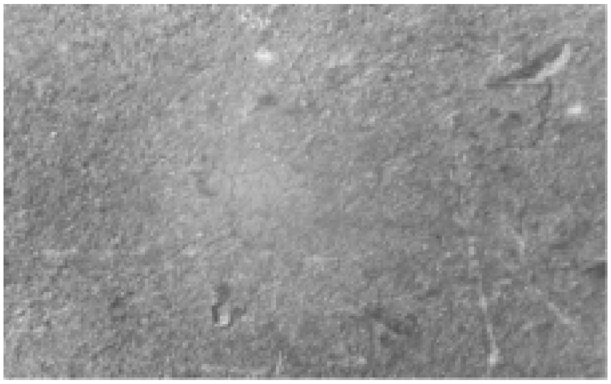


Fig. 3. Coating after 348 tests (side A).

Fig. 4. Structure of the base–coating transition zone.

A thermal-shock test was carried out on specially manufactured specimens. A coating whose thickness is indicated in Table 1 was deposited on both sides (A and B) of a 160 × 30 × 5 mm plate of 20 rimming steel.

The procedure of the tests involved heating of the specimens in the furnace from a cold state, holding at a temperature of 600°C for 20 min, and cooling in water at a temperature of 18°C.

It has been established that cracks appeared on side A of all four specimens after 348 tests (Fig. 3, the thickness of the coating on side A is nearly 2 to 3 times larger than that on side B). Thereafter the number of tests was increased to 446; however no cracks were formed in the coating on side B of all four specimens and no mechanical damage (peeling, increase in the number of cracks, etc.) was detected on side A of all four specimens.

An analysis of the metallographic investigations shows that cracks and peeling of the coating off the base are absent in the transition zone material of the base–coating of the pore. The cracks observed in the coating after the thermal-shock tests do not cause the coatings to "flake" and do not reduce the adhesion of the coating to the base (Fig. 4).

In closing, we must note that a technology of reclamation of parts of different machines and mechanisms by the method of electric-arc metallization (crankshafts, camshafts, and others) has been developed as a result of the investigations performed. We recommend PP-TP1 flux-cored wire or a PP-TP-1+PP-MM-2(S) combination as the dopants for spraying in an air medium without a sublayer.

The investigations performed on deposition of coatings with a low thermal conductivity as applied to thermal protection of the parts of the combustion chambers of engines show that work carried out in this direction is promising and is being continued at present together with the Central Laboratory of the Minsk Motor Plant.

REFERENCES

1. M. S. Tret'yak and V. V. Chuprasov, Strength characteristics of coatings in electric-arc metallization, *Inzh.-Fiz. Zh.*, **72**, No. 1, 121–125 (1999).
2. M. S. Tret'yak and V. V. Chuprasov, Hardness of coatings of various filler materials in electric-arc metallization, *Inzh.-Fiz. Zh.*, **72**, No. 5, 983–987 (1999).
3. *Report on Scientific-Research Work*, No. GR 19961118, A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, Minsk (1996).
4. M. A. Grigor'ev, V. G. Novikov, and S. R. Kolosova, Abrasive wear of the shells of crankshaft bearings, *Avtomobil'naya Promyshlennost'*, No. 1, 19–21 (1995).
5. M. D. Nikitin, A. Ya. Kulik, and I. I. Zakharov, *Heat- and Wear-Resistant Coatings of Diesel Engine Parts* [in Russian], Mashinostroenie, Leningrad (1977).
6. A. Hasui, *Deposition Technology* [Russian translation], Mashinostroenie, Moscow (1975).
7. A. F. Il'yushchenko, V. S. Ivashko, V. A. Okovityi, et al., *Heat-Resistant Coatings Based on* ZrO_2, NII PM OP, Minsk (1998).