FLUX-CORED WIRES OF FMI SERIES FOR COATING DEPOSITION BY ELECTRIC ARC SPRAYING (Review)

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The paper gives a brief review of flux-cored wires developed by the H.V. Karpenko Physico-Mechanical Institute of the NAS of Ukraine for electric arc spraying. It is shown that development and utilisation of special flux-cored wires as electrode materials widened the application fields for electric arc metallising and allowed, in many cases, deposition of coatings with properties at a level of the best plasma and other thermal spraying ones at lower costs.

Keywords: *electric arc metallization, coating deposition by spraying, flux-cored wire, repair of worn surfaces, coating structure, properties*

Electric arc metallization is one of the thermal processes of coating deposition. In terms of technology it is the simplest and most efficient method, not requiring any expensive equipment, which is readily introduced into production. One of the essential disadvantages of this process is a limited range of applied consumables, namely solid wires. Therefore, application of flux-cored wires as electrode materials for coating deposition by electric-arc spraying allowed a broad variation of coating composition, dramatic expansion of their applications, and in many cases also producing coatings with the properties on the level of the best plasma and supersonic thermal coatings, but at 5 to 10 times lower cost. At present flux-cored wires for electric arc spraying are batch-produced both abroad (Metco, Castolin, TAFA, Nanosteel), and in Ukraine. The greatest contribution into development and introduction of electric-arc coatings from flux-cored wires was made by the specialists of the E.O. Paton Electric Welding Institute (PWI) [1–8], H.V. Karpenko Physico-Mechanical Institute (FMI) [9–25], and Priazovsky State Technical University [26]. Coatings deposited with flux-cored wires are used in many fields of technology for reconditioning and protection from abrasive and gas-abrasive wear at room and elevated temperatures right up to 700 °C, for repair of various parts of machines and units operating under the conditions of boundary friction.

FMI developed flux-cored wires of 1.8 mm diameter for electric-arc metallization (Table), pilot-production batches of which were manufactured at PWI. Results of investigations devoted to flux-cored wire development, studying structure formation and service properties of various-purpose electric-arc coatings are set forth in [1–10, 26], and developed flux-cored wire compositions are protected by patents of Ukraine [21–25].

Flux-cored wires and their purpose

Wire grade	Alloying system	*HRC*, *HV*, σ_t, σ_{coh}	Applications
FMI-2	Kh6Yu8R3	*HRC* 40 *HV* 650 σ_t = 130 MPa σ_{coh} = 40 MPa	Reconditioning of medium-loaded crankshafts, cam shafts, abrasive wear protection of printing equipment
FMI-5	50Kh6Yu3G2M2S2	*HV* 350 σ_t = 180 MPa σ_{coh} = 40 MPa	Reconditioning of bearing seats of parts
FMI-6	Kh6Yu6R3N4	*HRC* 40 *HV* 1000 σ_t = 60 MPa σ_{coh} = 45 MPa	Protection from gas corrosion and gas-abrasive wear at high temperatures (up to 700 °C)
FMI-7	70Kh6Yu6R3W4	*HRC* 40 *HV* 1150 σ_t = 120 MPa σ_{coh} = 45 MPa	Protection from gas corrosion at high temperatures (up to 600 °C)
FMI-8	50Kh6Yu2G2T2M2	*HV* 500 σ_t = 180 MPa σ_{coh} = 40 MPa	Reconditioning of journals of medium-loaded crank shafts, cam shafts

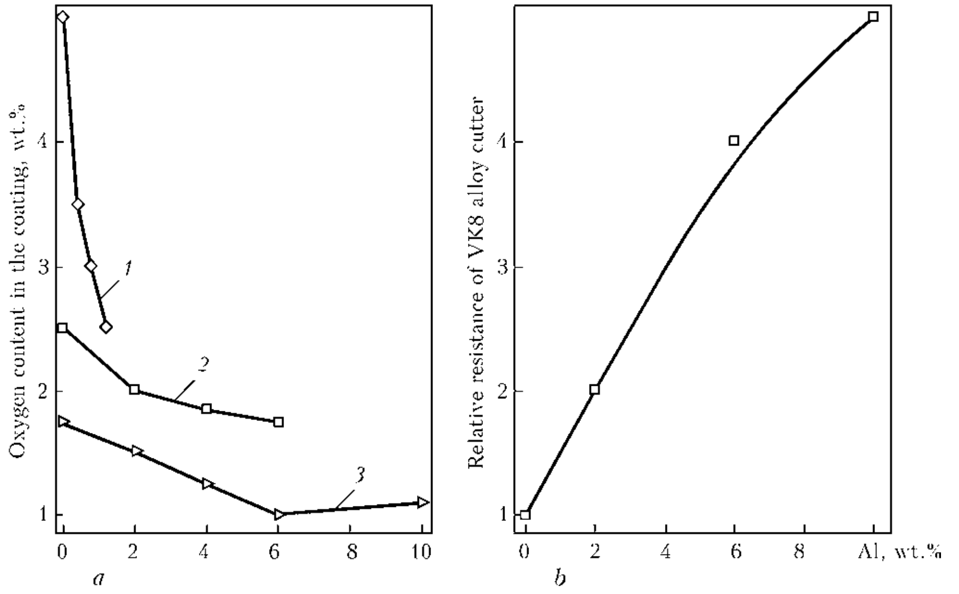

Figure 1. Influence of the quantity of carbon (*1*), chromium (PP 80Kh (0–6) (*2*) and aluminium (PP 80Kh6Yu (0–10)) (*3*) in flux-cored wire charge on the quantity of oxygen in the coatings (*a*) and relative resistance of the cutter from VK8 alloy (*b*) at treatment of coatings from PP 80Kh6Yu (0–10 Al) flux-cored wires

Repair coatings are used for repair of worn surfaces of shaft-type parts with subsequent mechanical treatment of coatings predominantly by machining tools. Therefore, the most important feature for such coatings is their high wear resistance and efficiency at machining. These conditions are ensured at formation of coatings with hardness *HV* 300–400, the structure of which contains a minimum quantity of the oxide phase.

Minimum amount of oxygen in the coatings on the level of 2 wt.% is provided in the presence of 0.8 % C, 6 % Cr and 6 % Al in the flux-cored wire charge (Figure 1).

With increase of aluminium content the quantity of martensite decreases, but ferrite content in the coating rises. Here, coating hardness decreases at simultaneous increase of its adhesion strength. Optimum coating hardness in the range of *HV* 300–400 is achieved in the presence of 6–12 wt.% Al in the wire. Matrix phase of such coatings is ferrite, alloyed by chromium and aluminium. Flux-cored wires with an increased content of aluminium are applied in power engineering for reconditioning the seats of shafts of electric motor rotors, brake drums of lorries, etc. (Figure 2).

The following requirements are made of coatings applied for parts operating under the conditions of abrasive wear: high hardness, low level of stresses of the first kind, and high wear resistance. It is established that with increase of coating hardness up to *HV* 700–800 their wear resistance rises, and above *HV* 800 it decreases, which is related to initiation of microcracks in the coatings. Coating wear results from growth of the already formed cracks along the lamella boundaries with their subsequent spallation. It is found that high wear resistance of coatings at testing by fixed abrasive is ensured by harder lamels and hard aluminium oxides on lamel boundaries. Therefore, in this case coatings should be formed, first, with a high microheterogeneity, so as to provide in them a low level of tensile stresses, and secondly, with thin lamels (high dispersity of the coating), so as to increase oxide content on interlamellar boundaries. At testing for wear by unfixed abrasive the weak links of the coatings are lamels with the lowest hardness and interlamellar boundaries. In this case, a coating with a low microheterogeneity and maximum thickness of the lamels should be formed, so as to minimize the number of boundaries between the lamels. Coatings of Fe–Cr–B–Al system of FMI grades became widely accepted for protection from abrasive wear in printing industry (Figure 3).

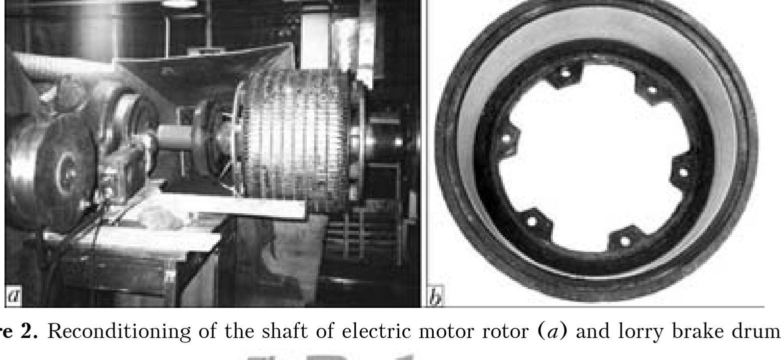

Figure 2. Reconditioning of the shaft of electric motor rotor (*a*) and lorry brake drum (*b*)

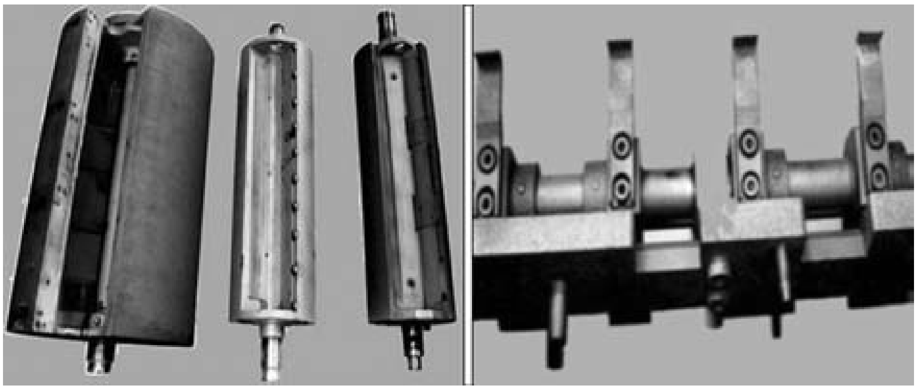

Figure 3. Reconditioned parts of sheet-drawing system of printing machine

Coating hardness for parts operating under the conditions of boundary friction should be not lower than *HV* 600. Machining of such coatings is performed by grinding to the required size. Here the coating structure often develops microcracks, which may lead to coating fracture in operation. To ensure the required coating characteristics, chromium, carbon, boron and aluminium are added to the composition of flux-cored wire charge in such amounts that martensite were the coating matrix phase. Such a structure provides a minimum level of tensile stresses in the coating not higher than 50 MPa.

At specific loads above 14 MPa catastrophic wear of the rider occurs in the coating — rider friction pair. Metallographic, spectral and X-ray structural analyses revealed that this is due to the presence of cracks on the coating ground surface, the open edges of which act as cutters, up to 0.3 μm high protrusions formed by aluminium oxides and carbides. Protrusions from carbides above the ground surface of the coatings form as a result of incomplete dissolution of coarse carbides from the charge in the flux-cored wire melt.

To remove intensive wear of the rider in the friction pair with the coating, methods of coating optimization were proposed, which consist in the following:

• provision of conditions for complete dissolution of carbides in flux-cored wire melt, using for this purpose finer carbide particles in the flux-cored wire charge or application of increased arc voltage (34–38 V) at spraying;

• reduction of air content in flux-cored wire charge by its compaction and addition of powder containing titanium compounds to it, which interacts with oxygen in the vapour phase in the melt zone, forming finer titanium oxides, which are by 1–2 orders of magnitude smaller than Al_2O_3 particles.

The ground surface of the coating, produced from flux-cored wire with an optimized charge composition, does not have any microprotrusions, and its roughness is essentially lower. More over, titanium and magnesium in the composition of flux-cored wire charge promote absorption of 2–3 wt.% N from the air, contained in the charge pores, that leads to formation of titanium nitride particles of 200–500 nm in the coating.

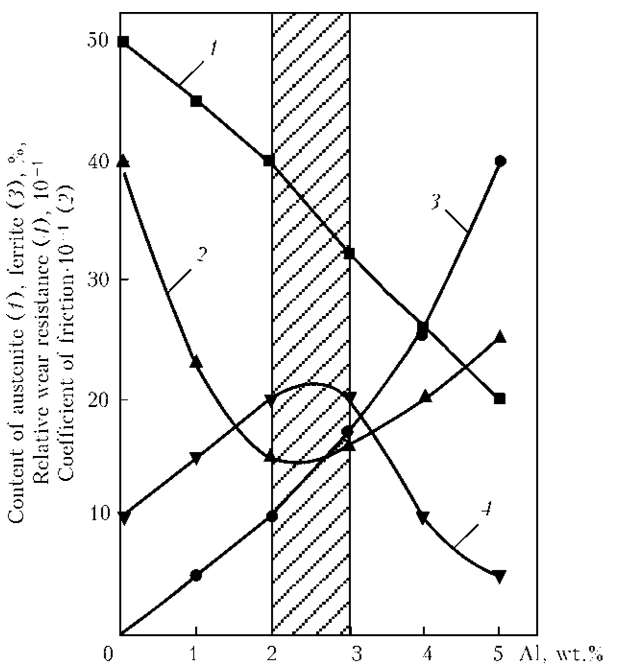

Figure 4. Influence of aluminium content in PP 50Kh6T2M2Yu2 flux-cored wire on tribological characteristics of coatings with a three-phase structure at boundary friction at specific load P = 7 MPa

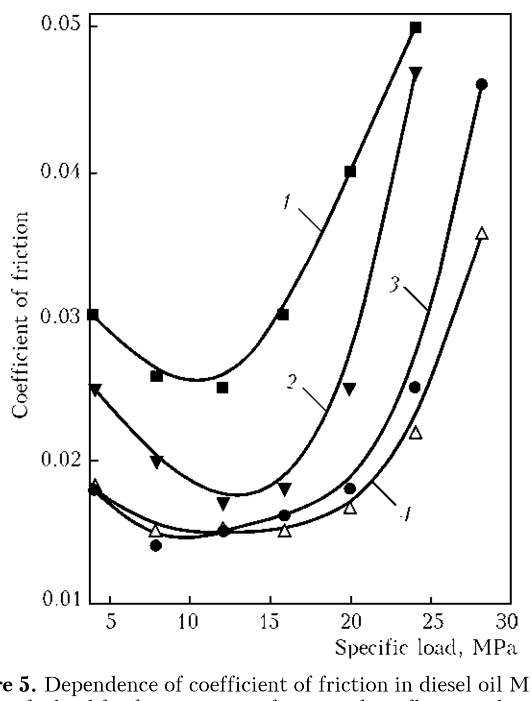

Figure 5. Dependence of coefficient of friction in diesel oil M14V2 on specific load for friction pairs of coating from flux-cored wire — bronze BrS-30: *1* — Kh6Yu6R3; *2* — ShKh15 steel (*HRC* 62); *3* — 50Kh6G2T2M2 + Kh6R3Yu6T2; *4* — 50Kh6T2M2Yu2

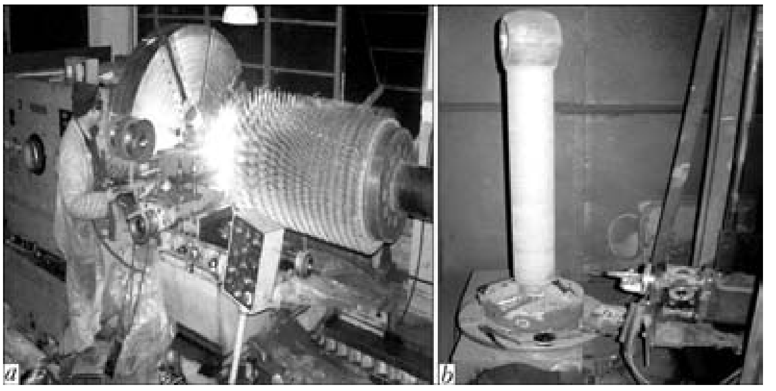

Figure 6. Spray-deposition of coating on supporting journal of turbine shaft (*a*) and hydraulic cylinder rod (*b*)

As a result of non-equilibrium of the coating structure and phase composition of coatings at friction, conditions can be in place in them, which are favorable for self-organizing of the surface layer.

Methods of small-angle roentgenography of the coating revealed that optimum conditions for self-organization of the surface develop in a three-phase coating with the matrix phase of martensite (~50 %), austenite (~30 %) and ferrite (~20 %). At high specific loads (Fe, Cr)$_{23}$C$_6$ carbides precipitate from austenite, and part of it transforms into tempered martensite with heat absorption.

It is supposed that nanosized graphite particles (10–20 nm) precipitate in ferrite. At friction carbon diffuses to the friction surface and forms a continuous graphite film on it. Optimum ferrite content in the coating structure is equal to 10–20 %. Coefficient of friction and wear of the friction pair are minimum (Figures 4 and 5). Such a content of ferrite in the coating is provided in the presence of 2–3 wt.% Al in it.

Wires of FMI series became accepted for reconditioning of support journals of rotors and shafts of compressor turbines for gas pumping in repair enterprises of «Ukrenergoservis», and rods of hydraulic cylinders of shaft equipment (Figure 6).

For coatings from flux-cored wire of Fe–Cr–B–Al system for spray-deposition of coatings operating under the conditions of higher temperatures in the case of gas-abrasive wear, a stable high hardness at long-term operation (several years) at high temperature is important. To ensure a high hardness and high-temperature resistance of coatings, such elements as chromium, boron, aluminium, magnesium, nickel and tungsten, which can initiate dispersion hardening at higher temperature, were added to the composition of flux-cored wire charge. Phase and spectral analyses determined that dispersion hardening of the coatings is provided by precipitation of (FeCr)$_2$B borides, CrN and AlN nitrides, as well as FeAl$_3$, Ni$_3$Al and Fe$_7$W$_6$ intermetallics in their structure. At up to 550 °C operating temperature the greatest hardening effect is provided by precipitation of Fe$_7$W$_6$ intermetallics, and above 550 °C — precipitation of Ni$_3$Al.

Coatings from flux-cored wire increase the wear resistance of 12Kh1MF steel by 30 times. Unlike monolithic materials, coatings are prone to both outer from the surface and internal interlamellar oxidation. Oxygen can penetrate along the lamel boundaries and along the microcracks to the steel base and form oxide

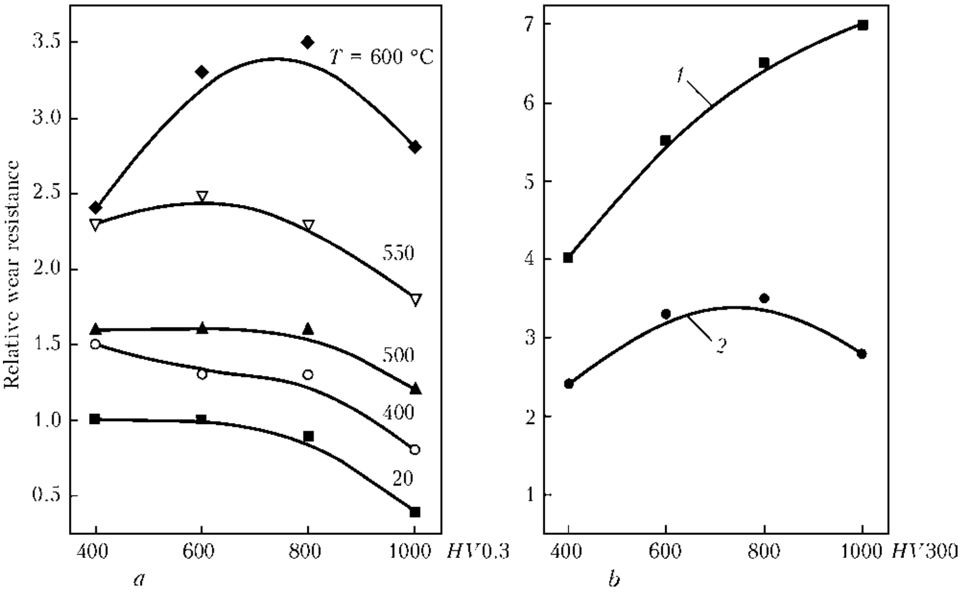

Figure 7. Relative wear resistance of coatings from flux-cored wires of Fe–Cr–B–Al system (filled signs) and reference samples from 12Kh1MF steel at different temperatures (preliminary soaking of samples for 50 h at testing temperature) (*a*) and relative wear resistance of coatings from the same materials at testing temperature of 600 °C (*b*) and duration of preliminary soaking of samples for 100 (*1*) and 50 (*2*) h

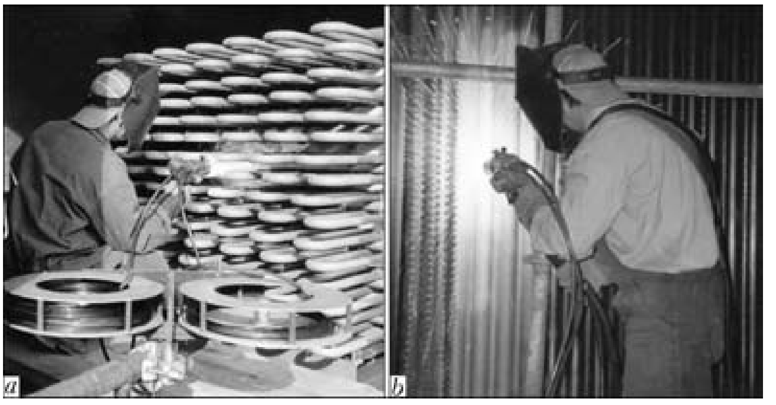

Figure 8. Spray-deposition of coatings from flux-cored wire on economizer pipe (*a*) and water-wall tubes (*b*) of TP-100 boiler for protection from gas abrasive wear at higher temperatures

films there. Intensity of gas-abrasive wear depends on coating hardness and level of stresses in them.

At room temperature coating wear resistance decreases with increase of its hardness and becomes lower than hardness of the standard — 12Kh1MF steel. With temperature rise, coating wear resistance increases, and the longer the high-temperature exposure, the higher the coating wear resistance (Figure 7). This is due to stresses of the first kind, forming in the coating. At long-term exposures at 500–600 °C temperatures two opposite processes proceed in the coating. First, disperse phases precipitate in the coating, which results in a rapid reduction of its volume and tensile stresses in it grow, while, at the same time, internal oxidation takes place in the coating and its volume increases, whereas tensile stresses decrease. As a result, at the exposure of about 1000 h, tensile stresses in the coatings are replaced by compressive stresses.

Coatings, in the structure of which dispersion hardening occurs, are applied for TPS boiler heating elements for protection from gas-abrasive wear (Figure 8).

Thus, flux-cored wires developed by H.V. Karpenko Physico-Mechanical Institute of NASU can become accepted for electric arc spraying for various purposes.

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