STATE-OF-THE-ART OF DEVELOPMENT AND APPLICATION OF FLUX-CORED WIRES FOR WELDING OF CARBON AND LOW-ALLOYED STEELS

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State-of-the-art in development of flux-cored wires for welding carbon and low-alloyed steels is considered. Main characteristics of flux-cored welding wires developed by the E.O. Paton Electric Welding Institute over the recent years, as well as properties of metal of the welds and welded joints made with these wires are presented. Recommended application field for these wires are listed.

Keywords: *arc welding, flux-cored wire, low-carbon and low-alloyed steels, state-of-the-art in development, application fields*

Mechanized and automatic flux-cored wire welding has become in the recent decade the main alternative to manual electrode arc welding and mechanized gas-shielded solid wire welding. Increase in consumption of flux-cored welding wires in the developed countries is explained by their evident engineering-and-economic advantages, such as high efficiency, excellent operating characteristics, consistent quality and guaranteed mechanical properties of the welds in welding of different-purpose steels. According to estimations, generalized indices of the volumes of production and application of flux-cored welding wires are at a level of 11 % in the Western Europe countries, 19 % in the USA, 27 % in Japan and more than 36 % in the Republic of Korea. The main areas of their application are shipbuilding, erection of drilling platforms, fabrication of structures and bridge construction, manufacture of tanks and vessels, and industrial and transport machine building.

Experts give the following estimates concerning distribution of the volumes of wires consumption by strength grades of steels. The share of wires for welding steels with yield strength of up to 500 MPa is 92 %, low-alloyed steels with yield strength above 500 MPa — 4 %, and steels designed for operation under low temperatures — around 2 %. The balance is a share of steels resistant to atmospheric corrosion, as well as other specialized steels. Consumption of flux-cored wires for welding of stainless steels is developing at an evident rate.

Development of an advanced technology for manufacture of flux-cored wires, meeting requirements of international quality standards, promoted progress in and increased application of flux-cored wire welding. The aim of the present article is to present the latest developments of domestic flux-cored wires, as well as areas of their effective application.

Metallurgical, technical and engineering-and-economic characteristics of flux-cored welding wires. Flux-cored wires are usually subdivided into classes, depending on the fact whether it is necessary to provide additional gas shielding of molten metal (gas-shielded) or there is no need in it (self-shielding). Respectively, according to the core composition, flux-cored wires are subdivided into gas-shielded, i.e. rutile, basic and metal-core (with metal type of the core), and self-shielding ones, i.e. carbonate- fluorite, oxide-fluoride, etc. As to their intended use, flux-cored wires are classified into wires of general and specialized application (in particular, wires for welding with forced weld formation).

Metallurgical advantages of flux-cored wires consist in a relatively easy and flexible adaptation of wire properties to composition and properties of steel being welded, as well as in providing the possibility of controlling heat input during welding. Utilization of special treatment of components of the wire core, wire surface treatment and deposition of protective coatings allow obtaining an invariably low level of the content of diffusible hydrogen in the weld metal below 5 $cm^3/100$ g [1].

Technological advantages of flux-cored wires are provided by a high arcing stability, low spattering of electrode metal and a convenient shape of the welds during welding in different spatial positions. Application of self-shielding flux-cored wires under field and erection conditions provides an easy welding process and flexibility, which are determined by the absence of the need to arrange additional shielding of molten metal. Besides, owing to a special sheath design and core composition, self-shielding flux-cores wires feature a higher efficiency of shielding of the molten metal during welding in open-air sites under the action of wind flows, compared with gas-shielded ones.

Engineering-and-economic advantages of flux-cored wires mainly lie in a high fusion efficiency provided by a high current density and extra filler material of the core (iron powder). The efficiency of fusion of flux-cored wires with a metal core amounts to 7.2–9.6 kg/h. An additional aspect is saving of power and heat, which are estimated to be at a level of 0.5–0.9 kW·h/kg of the deposited metal (Figure 1), if flux-cored wire welding is compared with solid wire welding. A more uniform radial penetration of metal [2–4] can be achieved when using flux-cored wires.

Hygienic and sanitary properties of modern flux-cored wires are at a level of those of solid wires (this applies, in particular, to flux-cored wires of rutile type and wires of metal-core type).

Classification requirements and properties of flux-cored wires for welding of different steel classes, as well as technical requirements to the flux-cored wires are unified in international standards ISO 17632:2004, ISO 17633:2004, ISO 18276:2005 and European standard EN 758, and in national standards AWS, DIN, JIS, GOST, DSTU, etc.

Most of the world producers use a technology of manufacture of the flux-cored wires from cold-rolled strips. In fact, the manufacture of wire is performed in one production line. It includes device for formation of the wire sheath (different designs) from a steel strip by continuously filling the formed profile with a mixture of powders and a multiple draw bench, where reducing of a wire to a finished size is carried out.

Advantages of such a technology include a small number of equipment pieces and personnel, low power consumption, and possibility of manufacturing a very wide range of wires with quick readjustment to a different wire type (high production flexibility). This technology was realized using different methods of reducing of billets and finishing treatment of the formed wire. The manufacture of wire from a tubular billet (seamless) requires a greater number of technological operations, this accordingly increasing production costs.

The complete technological cycle of manufacture of flux-cored wire with all the schemes includes a range of preparatory, intermediate, auxiliary and final operations, playing an important role in providing a quality product. Finished flux-cored wire is supplied in accordance with standardized methods of winding and packing (layer winding on spools or wire formers, or in containers of «Marathon» type according to EN 759). The quality assurance system (ISO standards) provides for the use of through inspection with accurate documentation of the procedures. This determines a wide application of up-to-date control technique, involving a qualified personnel and good analytic tooling of production. In particular, SE «Pilot Plant for Welding Consumables of the E.O. Paton Electric Welding Institute» uses devices for continuous control and monitoring of wire filling to realize inspection functions and documentation (Figure 2).

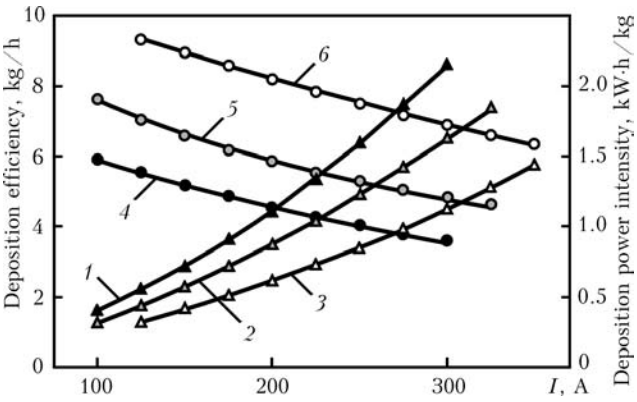

Figure 1. Typical indicators of deposition efficiency (*1–3*) and power intensity (*4–6*) in using flux-cored wires and solid wires 1.2 mm in diameter for mechanized welding: *1, 4* — flux-cored wire with metal core; *2, 5* — same with rutile core; *3, 6* — solid wire

Flux-cored wires for gas-shielded welding. New-generation flux-cored wires PP-AN59, PP-AN63 and PP-AN69 with a rutile core type, designed for welding of wide-application carbon and low-alloyed steels, and PP-AN61, PP-AN67 — for welding of high-strength low-alloyed steels were developed by the E.O. Paton Electric Welding Institute in the recent years according to European standard EN 758 and DSTU (GOST) 26271. These wires have a tubular design and are produced with diameters of 1.2 to 2.0 mm.

The wire world market is based on wires for CO_2 or Ar + CO_2 mixture welding of steels with yield strength of 400 to 500 MPa. Available are wires for welding of low-alloyed steels resistant to atmosphere corrosion and used at decreased temperatures. The scopes of application of wires for welding of steels

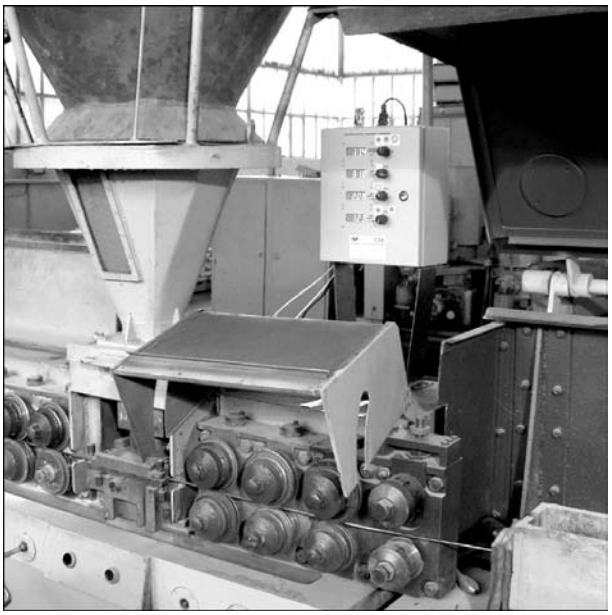

Figure 2. Device for monitoring of filling of the formed sheath of two-layer design flux-cored wire with a charge using a forming unit (SE «Pilot Plant for Welding Consumables of the E.O. Paton Electric Welding Institute»)

Table 1. Classification characteristics and properties of flux-cored wires for gas-shielded welding

Wire grade	Classification according to GOST 26271, EN 758 and AWS	Diameter, mm	Alloying system, wt.%	Guaranteed mechanical properties					
				σ_y, MPa	σ_t, MPa	δ, %	Correspondence to requirements for KCV_{min} = 35 J/cm^2 at temperature, °C		
							−20	−30	−40
PP-AN61	PG-49-A4U T46 4Z PCMI H5 E81T1-K2	1.2 1.4 1.6 2.0	0.06C 1.3Mn 0.4Si 1.6Ni	490	580	20			Yes
PP-AN63	PG-44-A2U T42 2PC1 H10 E71-T1	1.2 1.4 1.6 2.0	0.07C 1.3Mn 0.4Si	440	530	22	Yes		
PP-AN67	PG-59-A3V5 T59 3PC1 H5 E71-T1	1.2 1.4 1.6 2.0	0.08C 1.2Mn 0.4Si 1.2Ni 0.3Cr 0.3Mo	590	650	18		Yes	
PP-AN70M	PG-44-A3V T42 2MC3 H5 E71-T1	1.2 1.4 1.6 2.0	0.08C 1.4Mn 0.5Si	420	540	22	Yes		
PP-AN72	PG-48-A3V T48 5MC1 H5 E71-T1	1.2 1.4 1.6	0.08C 1.0Mn 0.3Si 2.2Ni	480	540	24			KCV_{min} = = 47 J/cm^2
PP-AN74	PG-59-A3V T59 5PC1 H10 E71-T1	1.2 1.4 1.6	0.06C 1.3Mn 0.4Si 2.5Ni 0.4Mo	590	680	24			Same

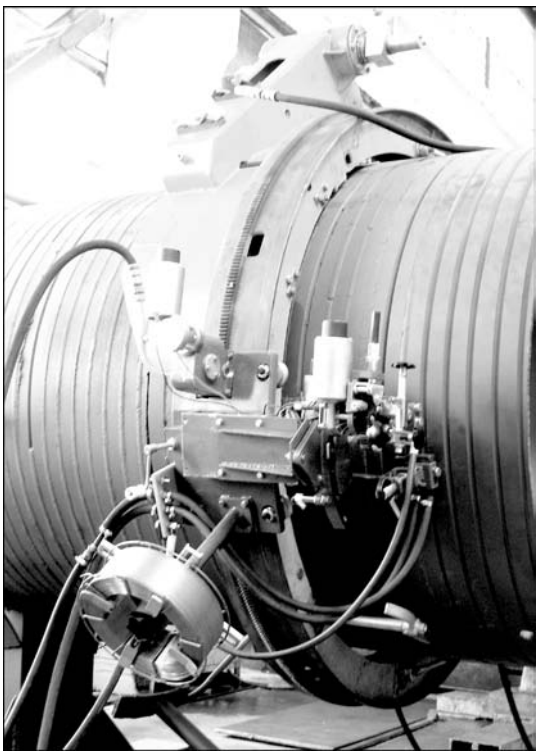

Figure 3. Welding machine of new-generation system «Styk» for automatic arc flux-cored wire position butt welding of large-diameter pipes with forced weld formation (manufacturer — OJSC «Kakhovka Plant of Electric Welding Equipment»)

with yield strength of up to 700 MPa increasing every year.

Widening of application of the metal-core wires relates to advancements in automated and robotic welding processes. The new wires providing good shape of the welds, low level of spattering and fumes can be used for welding in all spatial positions. Metal-core wires PP-AN70, PP-AN70M, PP-AN72 and PP-AN74, which demonstrate higher welding-technological properties than Sv-08G2S, were developed for automated and robotic welding in ship and machine building. Some characteristics of these flux-cored wires are given in Table 1. Manufacture of above flux-cored wires was mastered at SE «Pilot Plant for Welding Consumables of the E.O. Paton Electric Welding Institute».

Gas-shielded tubular-design flux-cored wires of the PP-AN61, PP-AN63, PP-AN72 and PP-AN74 grades are designed for semi-automatic welding, and the PP-AN70M grade wire, in addition, — for automatic (robotic) welding of low-carbon and low-alloyed steels. Wires of PP-AN70M, PP-AN72 and PP-AN74 grades are of a metal-core type. Ar + CO_2 (80 + + 20 %) gas mixture is recommended to for use as a shielding atmosphere for welding with these wires. CO_2 or Ar + CO_2 mixture can be used as a shielding

Table 2. Classification characteristics and properties of metal deposited with self-shielding flux-cored wires

Wire grade	Classification according to GOST 26271, EN 758 and AWS	Diameter, mm	Alloying system, wt.%	Guaranteed mechanical properties of deposited metal					
				σ_y, MPa	σ_t, MPa	δ, %	Correspondence to requirements of KCV_{min} = 35 J/cm^2 at temperature, °C		
							–20	–30	–40
PP-AN3	PS-44-A3N T42 3ZS3 H10 E70-TG	2.8 3.0	0.09C 1.2Mn 0.35Si	440	560	22		Yes	
PP-AN7	PS-44-A3V T42 3ZS3 H10 E71-TG	2.4	0.08C 1.1Mn 0.35Si	440	540	22		Same	
PP-AN60	PS-49-A3V T49 3ZS3 H10 E71-TG	1.2 1.4 1.6	0.08C 1.1Mn 1.3Ni 0.8Al	490	590	22			Yes

Table 3. Classification characteristics and properties of specialized self-shielding flux-cored wires

Wire grade	Classification according to GOST 26271, EN 758 and AWS	Diameter, mm	Alloying system, wt.%	Guaranteed mechanical properties of deposited metal					
				σ_y, MPa	σ_t, MPa	δ, %	Correspondence to requirements of KCV_{min} = 35 J/cm$_2$ at temperature, °C		
							–20	–30	–40
PP-AN19N	PS-39-A2(R)VP T42 2ZS3 H5 EG72-TG	2.4 3.0	0.09C 1.4Mn 0.4Si 0.5Ni	390	520	22	Yes		
PP-AN30	PS-54-AZUP — Corresponds to E81-TG	2.4	0.07C 1.7Mn 0.5Si 0.4Mo 0.07V	540	630	18			Yes
PP-AN30VS	PS-57-AZUP — Corresponds to E91-TG	2.0 2.4	0.07C 1.7Mn 0.5Si 0.6Ni 0.5Mo	570	690	18			KCV_{min} = = 47 J/cm^2

gas in welding with wires of the PP-AN61 and PP-AN63 grades.

The main areas of application of new-generation flux-cored wires for gas-shielded welding are as follows. The PP-AN61 grade wire is used in manufacture of railway cars, in machine building, manufacture of equipment designed for operation under conditions of high alternating loads and abrasive wear, welding of vessels and metal structures of different application, and in ship building; PP-AN63, PP-AN72 and PP-AN74 wires — for welding in all spatial positions in ship building, construction and fabrication of metal structures; PP-AN70M wire — for welding in flat position and on a horizontal plane in making filling welds for machine building and manufacture of vehicles and metal structures.

Self-shielding flux-cored wires. Primarily the USA and CIS countries were active in development and manufacture of flux-cored wires on commercial scales. The product line (quantity of grades) has been reduced in the last two decades as a result of decrease in output of wires with unreliable technological characteristics. An interest of the world market to this

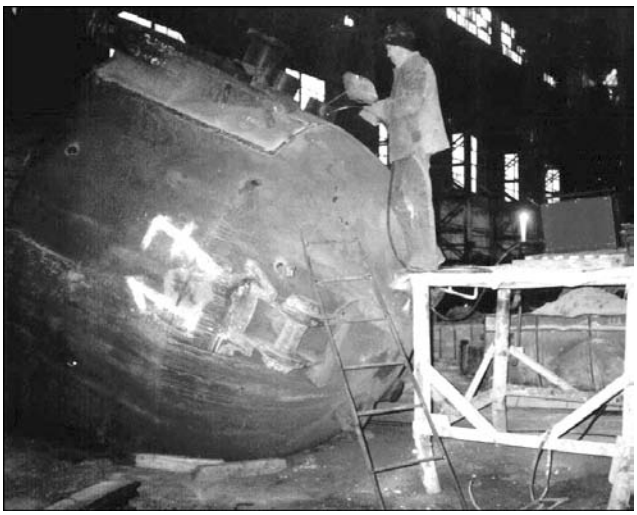

Figure 4. Repair welding of metallurgical equipment with flux-cored wire PP-AN7 at OJSC «F. Dzerzhinsky Dneprovsky Metallurgical Works, Dneprodzerzhinsk [5]

Figure 5. PP-AN9N flux-cored wire welding with forced formation of vertical butt joints on snap structures of Podolsko-Voskresensky Bridge over the Dnieper River in Kiev

class of the wires remains at a rather high level. In particular, this relates to building and erection operations (construction of pipelines, tanks, metallurgical units, bridges, industrial engineering and ship building). Wires for welding of steels with 400–500 MPa yield strength make the production basis. Wires for welding of pipelines make up a separate group. In addition to well-known wires of the two-layer design, self-shielding tubular flux-cored wires of small diameter with a core of fluoride-basic type were also developed by the E.O. Paton Electric Welding Institute. The core composition allows decreasing the silicon and aluminum content in the weld metal and provides the required value of impact toughness of welded joints at low temperatures.

Wires for welding with forced weld formation (electric gas welding) make an important subgroup of this class of wires. Growing demand for such wires in the CIS countries, in particular in Russia, is observed at present. The key customers are constructors of bridges, tanks and metallurgical facilities. Operation of new-generation pipe welding systems «Styk» (Figure 3) is being mastered.

Characteristics of some self-shielding flux-cored wires developed by the E.O. Paton Electric Welding Institute are given in Tables 2 and 3. PP-AN3 and PP-AN7 self-shielding flux-cored wires of a two-layer design are intended for semi-automatic welding of low-carbon and low-alloyed steels with thickness more than 5 mm. Wire PP-AN3 is applied for welding of road building machines, industrial equipment and building metal structures, and wire PP-AN7 — for welding of industrial equipment, in transport machine building, construction of off-shore structures and repair of industrial equipment (Figure 4).

Self-shielding tubular flux-cored wire PP-AN60 is recommended for semi-automatic welding in all spatial positions in manufacture of technological equipment, transport and hoisting devices, construction of drilling platforms and building structures.

PP-AN19N self-shielding flux-cored wire of a two-layer design is meant for automatic electric gas welding of low-carbon and low-alloyed steels with thickness of 8 up to 32 mm. It is mainly used with a process of welding of vertical butt joints by the downward method for construction of different metal structures, including vessels, ships, barges, span structures of bridges, tanks and bunkers (Figure 5).

PP-AN30 and PP-AN30VS self-shielding flux-cored wires of a two-layer design were developed for automatic erection welding of butt joints in pipes with 520 to 1420 mm diameter by using forced weld formation (electric gas process). Wire PP-AN30VS can be used for welding of butt joints in pipes of low-alloyed steels of the X80 strength class.

Ii should be noted in conclusion that rapid development of the market of consumption of flux-cored wires is an evidence of a high potential of arrangement of up-to-date productions for this type of welding consumables. Preference is given to production of wires with better operating characteristics, low metal losses for spattering and low emission of welding fumes. Structure of the world consumption, where small-diameter wires for welding of mass-application steels and increased-strength steels make the biggest shares, is to be taken into account in selection of production programs. Owing to successful accomplishment of the innovative project initiated by the National Academy of Sciences of Ukraine, SE «Pilot Plant for Welding Consumables of the E.O. Paton Electric Welding Institute» achieved the level of manufacture of flux-cored wires, which meets the up-to-date requirements for assurance of the quality of products, through upgrading of equipment and improvement of the technological process. Flux-cored wires of a new product line correspond to international standards and are competitive in the world market in their technical characteristics and quality. At the same time, the technology for their manufacture makes it possible to orient mainly to the raw materials base of Ukraine.

1. Pokhodnya, I.K. (2008) Metallurgy of arc welding of structural steels and welding consumables. *The Paton Welding J.*, **11**, 54–64.
2. Shlepakov, V.N. (2004) Current methods for investigation, prediction and estimation of properties of welding flux-cored wires. In: *Welding Consumables. Development. Technology. Manufacturing Quality:* Proc. of 3rd Int. Conf. on Welding Consumables of CIS countries. Dnepropetrovsk, 2004.
3. Shlepakov, V.N., Naumejko, S.M. (2005) Self-shielded flux-cored wires for welding low-alloy steels. *The Paton Welding J.*, **4**, 28–30.
4. Shlepakov, V.N., Kotelchuk, A.S., Naumejko, S.M. et al. (2005) Influence of the composition of flux-cored wire core and shielding gas on the stability of arc welding process. *Ibid.*, **6**, 16–20.
5. Shlepakov, V.M., Ignatyuk, V.M., Kotelchuk, O.S. et al. (2006) Mechanized repair flux-cored wire welding of units of metallurgical complex. In: *Problems of resource and safety service of structures, constructions and machines*. Kyiv: PWI.