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DEVELOPMENT OF NEW GENERATION FLUX-CORED WIRES FOR GAS-SHIELDED ARC WELDING OF JOINTS OF LOW-ALLOY STEELS WITH ULTIMATE STRENGTH OF 640–940 MPa

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The results of studying the properties of flux-cored wires with a metal core are considered, which were used as a base for suggesting approaches to development of compositions of flux-cored wires for gas-shielded arc welding of joints of low-alloy steels of higher and high strength. Application of dynamic thermal analysis of powder mixtures that model the wire cores, enabled obtaining information on kinetics of the processes which develop at heating and melting of flux-cored wire compositions that allows optimizing the core compositions. Recommendations were elaborated on selection and application of flux-cored wires for welding low-alloy high-strength steels. 10 Ref., 2 Tables, 3 Figures.

Keywords: arc welding, flux-cored wire, low-alloy high-strength steel

A stable tendency to increase the scope of application of high-strength low-alloy steels for fabrication of welded metal structures of engineering constructions (such as, for instance, main systems of transportation of gaseous and liquid products) and other facilities, particularly those operating under complex climatic conditions, provided the impetus for expansion of research and development in the sphere of creating new electrode materials for arc welding [1, 2]. Research and development of electrode materials for welding high-strength steels from the very beginning were aimed at controlling the microstructure in terms of optimizing the combination of particles of the bainite, ferrite and martensite components. Reaching the specified level of property values is made more difficult by a strong dependence of the dynamics of formation of microstructural components on welding mode parameters [3, 4]. The works devoted to the role of the composition of nonmetallic inclusions, their morphology and distribution along the grain boundaries in formation of the microstructure and properties of weld metal became an important step in development of ideas about the ways to control the visco-plastic properties of weld metal in high-strength steel joints [5–9]. Development of flux-cored wire for gas-shielded arc welding of joints of high-strength low-alloy steels was based on the results of research and development of flux-cored wires with a metal core [7], typical samples of which ensure optimal welding-technological properties. Numerous studies on selection and optimization of weld metal alloying system for welding high-strength low-alloy steels (HSLA) of different strength level formed the base for generalization of the recommended compositions of electrode materials by alloying system in the form of an international standard [10].

Application of the process of flux-cored wire arc welding in gas mixtures based on argon and carbon dioxide gas allows ensuring the stability of the process of transfer of the wire sheath metal and powder core materials which melt, into the weld pool within the limits of application of parameter ranges of the mode, characterized by spray or spray-droplet transfer, and which minimizes the electrode metal losses. Here, the process of melting of flux-cored electrode wire and running of the reactions of interaction of molten metal with the gas shielding atmosphere can be regulated by oxidizing capacity in a rather wide range without deterioration of welding-technological properties.

The objective of this work is research analysis and preparing recommendations on development of flux-cored wires for gas-shielded arc welding of joints of higher and high strength low-alloy steels.

Main research results and their discussion. Experience of application of metal-core type wires, where the powder core includes a complex powder mixture of low-melting mineral components for metallurgical processing and refining of weld pool metal, formed the base of research and development of

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flux-cored wires for welding high-strength steels. The materials used for fluxing, were low-melting salts of alkali-earth metals (fluosilicates, carbonates, aluminates, fluorides, etc.) with low hygroscopicity, the slag melts of which assimilate inclusions, forming as sharp-angled particles, film precipitates, spinels, which significantly lower the grain-boundary strength. Melt treatment by a fluxing mixture is designed for adjustment of the composition of nonmetallic inclusions and forms of their precipitation along the grain boundaries, as well as for lowering hydrogen content in the weld metal due to running of the reactions of its binding by fluorides. The composition of the refining slag system, is optimized in terms of the characteristics of powder mixture of the wire core. At manufacture of flux-cored wire for welding steels of a certain strength level it is recommended to conduct special control of the conformity of the mixture to the requirements, taking into account the possible change of raw material composition.

The refining mixture structure is based on application of a composition of element compounds from IIA (Mg, Ca, Ba), IIIA (A1) and IVA (Si) groups of the periodic system of elements. Metal-powder mixture is part of the salt composition that forms low-melting slags for refining, capable of removing nonmetallic inclusions from the weld pool metal before its solidification.

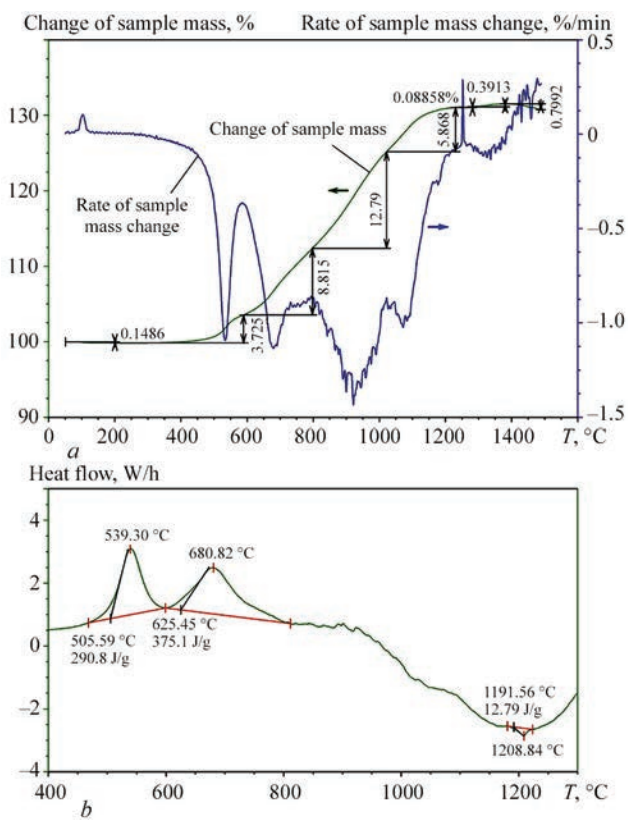

Figure 1. Results of thermogravimetric analysis (*a*) and analysis by the method of differential scanning calorimetry (*b*) of model core of flux-cored wire of oxide-fluoride type

Oxygen content in the weld metal is to a certain extent compensated by the total quantity of nonmetallic inclusions of oxide type, which affect the weld metal cold resistance. Oxygen content in weld metal within 0.25–0.35 wt.% is considered optimal. So, in welding with rutile type flux-cored wire in a mixture of Ar + CO_2, oxygen content decreases to 0.022–0.025 wt.%. Here, impact energy at –60 °C is equal to 50 J, compared to welding with the same wire in CO_2, when oxygen content can reach 0.05–0.06 wt.%, while impact energy values decrease and are close to 27 J at –40 °C.

Refining mixture compositions were designed proceeding from the results of dynamic thermal analysis of experimental powder mixtures, the composition of which was selected, taking into account the basic principles of weld metal alloying in welding high-strength steels of certain strength category. Complex thermogravimetric analysis in combination with differential scanning calorimetry allows determination of temperature ranges of formation of metal and slag melts, performing quantitative evaluation of the degree of development of thermochemical reactions of interaction of the studied compositions with the gas environment during dynamic heating (in particular, thermal destruction and evaporation of the components, as well as oxidation of metal components). Figure 1, *a* shows the results of thermogravimetric analysis of the model core of flux-cored wire of oxide-fluoride type, that contains Al-based master alloys (in particular, Al-Li and Al-Mg master alloys), and Figure 1, *b* presents the results of analysis of the same sample of flux-cored wire core by the method of differential scanning calorimetry together with calculation of total thermal effects of the reactions. The process of heating of the charge of flux-cored wires of oxide-fluoride type is characterized by exothermal effects of a high intensity at temperatures of about 600 and 800 °C, which are accompanied by increase of sample mass and lowering of oxygen content in the gas phase of the heating chamber, that is indicative of intensification of the processes of oxidation of powders of Al and Mg master alloys, iron powder and ferroalloys, respectively. The slag melt forms in the temperature range of 1190–1220 °C that is characterized by a respective endothermic effect, which reaches a maximum at the temperature close to 1200 °C.

Melt formation already at the stage of heating of the powder core in electrode wire extension, before melting of the wire sheath and evolution of gaseous products (CO, CO_2, SiF_4, etc.) determines the protec-

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tive functions of the flux-cored wire and essentially influences the progress of the reactions of metal interaction with the gases at the drop and pool stages. Temperature ranges of thermochemical reactions (for instance, endothermic processes of moisture removal, destruction, melting and exothermic processes of oxidation and formation of complex compounds), which accompany the heating process, overlap, and their thermal effects are superposed one over the other, stimulating development of some processes and inhibiting other processes. Thus, control of these thermochemical reactions through correction of the core composition, allows regulation of its melting rate, achieving favourable characteristics of flux-cored wire melting, as a whole, as well as electrode metal transfer into the weld pool. Specific data on the heat flow magnitude at heating of powder compositions, enable assessment of heat losses for their heating and melting, allowing for mutual influence of exo- and endothermic reactions that develop in the flux-cored wire core.

Low-alloy welding consumables developed for welding high-strength steels, should satisfy higher requirements as regards their composition to ensure a low hydrogen content in the weld metal. High concentration of diffusible hydrogen in the welded joint can lead to formation of cold cracks. That is why, in welding of high-strength steels the quantity of hydrogen, penetrating into the weld pool, should be minimized. This is achieved due to initially low hydrogen content in the filler material and shielding gas, as well as due to ensuring welding conditions, preventing ingress of moisture and other hydrogen compounds into the welding zone from the environment.

In welding steels with the yield limit of up to 520 MPa, the admissible level of hydrogen content in the weld metal is limited by 5 cm^3/100 g of deposited metal, and in welding steels with the yield limit of 620 MPa and higher it can be up to 3 cm^3/100 g of deposited metal.

In order to manufacture flux-cored wires designed for welding high-strength steels, it is necessary to not only use initial raw materials with a low hydrogen content, but also ensure continuous monitoring of moisture content in all the raw materials and the ready charge during their storage and during wire manufacturing, and provide such conditions of storage and application of these consumables, which prevent their moisturizing. This is achieved by application of thermostatic containers at all the stages of flux-cored wire manufacturing. Cleaning of the steel strip should guarantee absence of moisture and remnants of conservation lubrication on the strip surface directly before its feeding for wire sheath forming and filling with the charge.

Flux-cored wire for high-strength steel welding is supplied to the user in hermetically sealed packing from aluminium foil, sealed under low vacuum. The term of use of flux-cored wire taken out of the sealed packing is limited by the documentation on producing welded joints of higher and high-strength steels.

Control of diffusible hydrogen content in raw materials which are used as components of flux-cored wire core and in charges for flux-cored wire core allows separating the components and compositions, application of which in the core of flux-cored wires for welding high-strength steels without special treatment should be limited. Thermal analysis of such materials combined with mass-spectrometry of the gas phase, is useful for achievement of this purpose. Considering possible oxidation of metal powders at heating up to high temperatures (700–1000 °C), thermal analysis is conducted in the flow of inert gas (usually, argon) for assessment of internal oxidation without the influence of air atmosphere.

Flux-cored metal materials (Fe·Mn, Mo, Fe·Si, Al, Al·Mg, Al·Ca) lose the adsorped moisture at heating in the temperature range of 110–240 °C. At further heating the structurally bound moisture is removed. This process is accompanied by development of internal oxidation processes. Results of thermal analysis allow determination of optimal conditions, under which the internal oxidation does not have any significant influence on removal of hydrogen and its compounds. It is rational to conduct heat treatment of the majority of materials in the temperature range of 200–400 °C, depending on the type of manufactured wire. A more complete removal of hydrogen and its compounds can be achieved by heat treatment of individual powders in a shielding atmosphere or in vacuum. However, even heat treatment of powder mixtures under regular conditions allows lowering the potential hydrogen content in the flux-cored wire core by 85 %.

Influence of strip cleaning and treatment of flux-cored wire surface to lower the diffusible hydrogen content in the weld metal was experimentally verified on test samples of flux-cored wires of carbonate-fluorite and metal-core types with comparable content of the core alloying part. Cold-rolled steel strip of 08Yu type of 0.8×12 mm dimensions was used for manufacturing such experimental flux-cored wires. The strip was cleaned from remains of conservation lubrication that is one of the greatest sources of diffusible hydrogen in flux-cored wires by two methods: mechanical

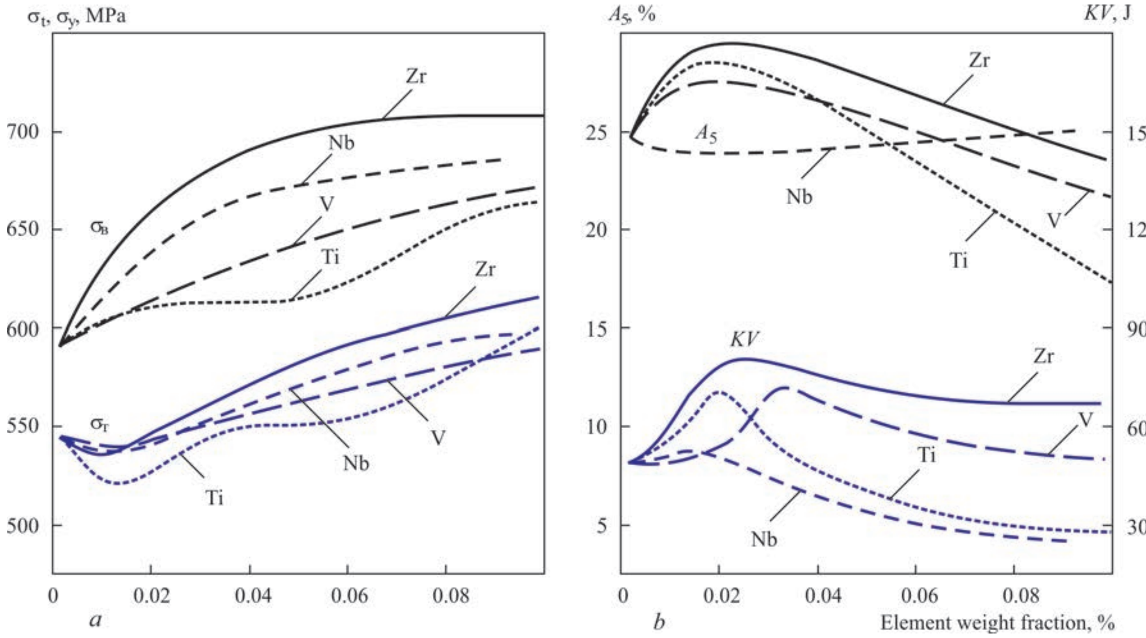

Figure 2. Mechanical properties of weld metal at microalloying by V, Ti, Nb and Zr: yield limit σ_y and ultimate tensile strength σ_t (*a*) and relative elongation A_5 and impact energy *KV* at testing temperature of –40 °C (*b*)

and rinsing in a degreasing solution. The results of analysis of diffusible hydrogen content in the strips cleaned by the first and second methods, turned out to be close and equal to approximately 1.2 cm^3/100 g of metal.

To prevent increase of hydrogen content in the flux-cored wire, it turned out to be useful to deposit an inhibiting coating on the wire surface after its cleaning. Wire packing in high-capacity containers of Marathon type is undesirable, because of the difficulties of ensuring the required sealing and the need to use the wire as soon as possible after opening the packing.

Development of core compositions of flux-cored wire for welding steels of different strength classes. Research and development of flux-cored wires for welding low-alloy high-strength steels in shielding gas atmosphere were conducted, taking into account the experience of producing steels of the respective strength class. In production of such steels the operations of refining and ladle treatment at the pouring stage, as well as heat treatment (hardening, tempering) at rolling are applied, as a result of which the rolled stock (steel) acquires a uniform microstructure of predominantly bainitic-martensitic class.

Regulation of the values of physico-mechanical properties of steels and electrode materials for their welding is achieved through microalloying by carbide- and nitride-forming elements (vanadium, niobi-

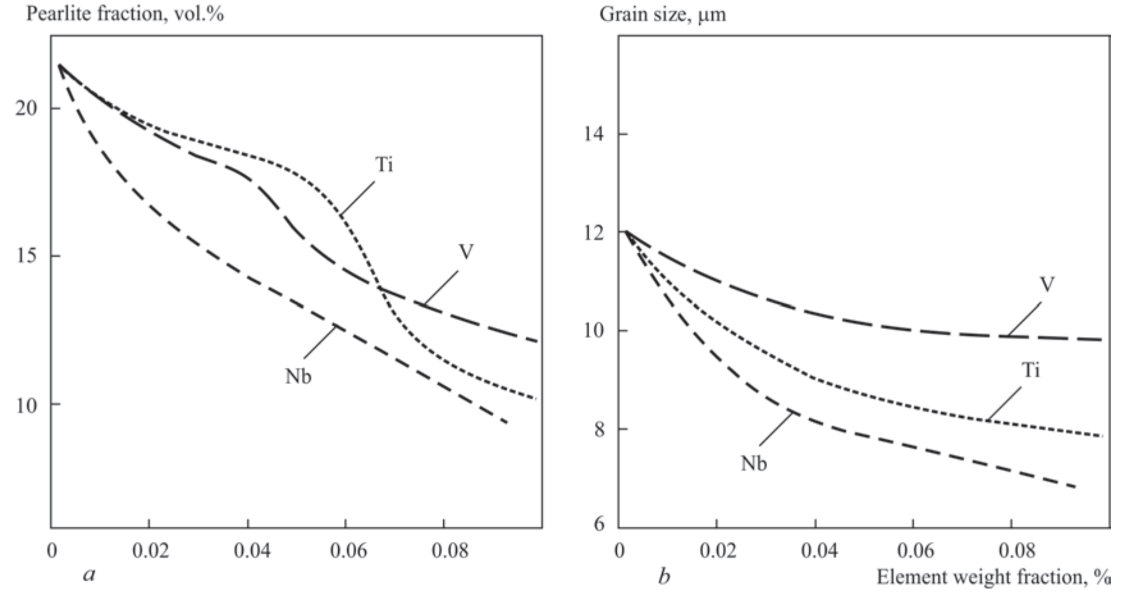

Figure 3. Influence of microalloying by V, Ti and Nb on metal microstructure: fraction of pearlite microstructural component in metal structure (*a*) and grain dimensions (*b*)

Table 1. Mechanical properties of weld metal of HSLA steels of different strength classes

Classification of flux-cored wire by EN ISO 18276 standard	Minimum value of yield limit of steel being welded, MPa	Values of properties of metal of the weld and welded joint			
		Yield limit, MPa	Ultimate tensile strength, MPa	Elongation, A_5, %	Impact energy ISO – V (J) at testing temperature
EN ISO 18276-A: T 55 5 Z M M 1 H5	550	> 550	640–820	> 22	> 47; –50 °C
EN ISO 18276-A: T 55 41 NiMo B M 2 H5 EN ISO 18276-A: T 55 61 NiMo B C 2 H5	–	> 550	640–760	> 23	> 60; –40 °C
EN ISO 18276-A: T 62 41 NiMo P M 1 H5	620	> 620	700–800	> 20	> 47; –40 °C
EN ISO 18276-A: T 62 5 Mn2.5Ni P M 1 H5	–	> 620	700–890	> 18	> 62; –40 °C > 47; –50 °C
EN ISO 18276-A: T 69 4 Z P M 1 H5	690	> 690	770–940	> 17	> 50; –40 °C

Table 2. Chemical analysis of the composition of weld metal of HSLA steels of different strength classes (typical values in wt.%)

Flux-cored wire classification by EN ISO 18276 standard	C	Mn	Si	P	S	Cr	Ni	Mo
EN ISO 18276-A: T 55 5 Z M M 1 H5	0.06	1.7	0.6	< 0.015	< 0.015	–	0.6	0.3
EN ISO 18276-A: T 55 41 NiMo B M 2 H5 EN ISO 18276-A: T 55 61 NiMo B C 2 H5	0.07	1.3	0.4	0.01	0.01	–	1.1	0.4
EN ISO 18276-A: T 62 41 NiMo P M 1 H5	0.07	1.40	0.40	< 0.015	< 0.015	–	0.9	0.4
EN ISO 18276-A: T 62 5 Mn2.5Ni P M 1 H5	0.08	1.35	0.35	< 0.015	< 0.015	–	2.2	–
EN ISO 18276-A: T 69 4 Z P M 1 H5	0.06	1.4	0.4	< 0.010	< 0.010	–	2.9	0.35
EN ISO 18276-A: T 69 4 Mn2NiCrMo M M 1 H5	0.05	1.5	0.5	0.01	0.01	0.4	2	0.4

um, zirconium, titanium) at lowering of carbon content and base alloying by manganese, silicon, nickel, molybdenum and chromium.

Analysis of the known systems of microalloying by vanadium, titanium, niobium and zirconium allowed selecting the system of microalloying through the flux-cored wire core, which is the most suitable for the tasks of welding high-strength low-alloyed steels and determining the optimum limits of such microalloying. The optimum is achieved (Figures 2 and 3) for microalloying by V — up to 0.08; Ti — up to 0.05; Nb — up to 0.02; Zr — up to 0.09 wt.%. Lowering of ductility (values A_5 and *KV*) is due to embrittlement of the grain boundaries. V, Ti and Nb are capable of forming film type carbonitrides.

Optimization of the composition of complex microalloying of weld metal through the flux-cored wire core was performed, allowing for adsorption activity of carbo- and nitride-forming and alkali-earth elements, and the influence of microalloying on the structurally-sensitive mechanical properties of the welded joint was experimentally assessed.

The main requirements to the properties of the metal of welds and welded joints of high-strength steels, made by gas-shielded arc fusion welding, are specified by international standard EN ISO 18276 «Flux-cored wires for gas-shielded welding of high-strength steels» [10]. As regards chemical composition, the limits were determined for weld metal alloying by the content of Mn, Ni, Cr and Mo, in keeping with the level of strength values; by impurity content: for carbon — 0.03–0.1 wt.%, sulphur — not more than 0.020 wt.% and phosphorus — not more than 0.020 wt.%; and by alloying elements — in keeping with the specified strength level. Recommended limiting of hydrogen content in the deposited metal is not more than 5 cm^3/100 g of deposited metal.

The compositions of flux-cored wires for gas-shielded welding were developed, taking into account the main requirements of the standard, in keeping with the flux-cored wire category by strength values.

Tables 1 and 2 give the values of the properties of flux-cored wires for arc welding of HSLA steels in shielding gases (82 % Ar + 18 % CO_2).

Conclusions

Obtained results were the base for development of flux-cored wires for welding HSLA steels and allowed formulating the main stages of such development:

- development of core compositions of flux-cored wires for welding high-strength steels in the shielding gas atmosphere of M21 type (Ar + CO_2 mixture), taking into account the strength class from 600 up to 800 MPa, which provide spray or spray-droplet transfer of electrode metal at 1.2 mm base diameter of the wire and when maintaining the recommended parameters of the welding mode;
- calculations of chemical composition of the deposited metal for welds, produced in arc fusion welding proceeding from the basic recommendations, included into EN ISO 18276 standard for welding steels

of the appropriate strength level that determines the fraction of disperse bainite component of weld microstructure, which forms at austenite-ferrite transformation during weld metal cooling;

• experimental confirmation of the conformity of microstructural composition of weld metal to the requirements made at maintenance of the recommended parameters of the welding process;

• conducting the full testing cycle, and verifying the compliance of these test results with technical requirements, made of the property values for joints of steels of the respective strength level.

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