According to estimations of specialists, a great number of structures, constructions and machine in operation in Ukraine have exhausted their designed service life. In this connection, of special current importance are the issues related to control of operating reliability and durability of critical facilities by determining their technical state, residual life and scientifically grounded safe operation life.

Below we give a selection of articles based on the results of studies completed in 2007–2009 under targeted integrated program RESOURCE of the National Academy of Sciences of Ukraine by involving scientists and specialists from 26 institutions of 8 departments of the Academy.

Editorial Board

SUBSTANTIATION OF THE SYSTEM OF DEOXIDATION AND MICROALLOYING OF DEPOSITED METAL WITH ELECTRODES FOR WELDING AND REPAIR OF BRIDGE AND TRANSPORT STRUCTURES

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The paper provides substantiation of the system of deoxidation and microalloying of weld metal produced with electrodes that are designed for welding and repair of bridge and transport structures. The main characteristics of the electrodes developed by using this system are described.

Keywords: *arc welding, structural low-alloy steels, covered electrodes, welding and repair of structures, microalloying system*

The Second Pan-European Transport Conference held in 1994 passed the program of development of the continental transport network, according to which nine main transcontinental cargo transportation directions, called «Crete Corridors», were to be built. Four of them are to pass through the territory of Ukraine. Taking a central place in Europe in this way, i.e. having the highest transit traffic factor among the neighbouring European countries, Ukraine should become a peculiar bridge between Europe and Asia to substantially reduce traffic expenses and delivery time in the system of international goods exchange. The program was approved for building and functioning of the national network of international transport corridors in Ukraine [1].

To implement this program, it will be necessary to upgrade railways, so that they meet modern requirements for speed, length and weight of the passed-through trains, build new highways of the international level, construct many bridges, tunnels and crossroads, as well as 26 unique transport-storehouse terminals.

Transport problems have to be solved also because of the European Football Championship to be held in Ukraine in 2012. City and belt highways are reconstructed in Kiev and other cities of Ukraine. Bridges across the Dnieper River, over- and underpasses, as well as junctions at most intensive traffic crossroads are built. This will require involvement of metalwork and transport engineering factories, as well as building and assembly organisations that intensively employ welding technologies. For factory conditions, these are mostly mechanised welding processes. However, part of the operations, which are associated, as a rule, with welding of the most critical structures and repair of defects are traditionally performed under factory conditions by using covered electrodes. In field, the major part of spatial welds, which for technical reasons cannot be made by the mechanised welding methods, are usually produced by manual covered-electrode arc welding.

Operation of bridge and transport structures, which were built earlier, is accompanied by current repairs and overhauls to maintain them in an appropriate condition. After liquidation of the united national economy system of the USSR, condition of basic assets of the key industries and inter-industry manufacturing infrastructure in Ukraine and other CIS countries is constantly deteriorating.

To prevent probable man-caused crises, the supervision authorities and Public Committee «2005» formed at the initiative of the Ukrainian Government have been performing for a number of years a careful monitoring of safety of structures, constructions and related machines. The above monitoring covers railway and motor transport bridges, offshore and pipeline transport facilities, transport infrastructure in the form of inter- and multi-modal, as well as terminal systems, which under no circumstances must be weak points of the «Crete Corridors», etc. All of the above facilities are built, maintained in a working condition and repaired by using welding technologies.

Steel for bridge and transport structures. Evolution of chemical composition and properties of rolled stock of structural steels is shown in Figure 1 [2, 3]. Low-alloy silicon-manganese steels of the 09G2S (class S345) and 12G2S (class S375) grades according to GOST 19281–89, low-alloy (with chromium and nickel) steels of the 10KhSND and 12KhSND grades (class S390) according to GOST 6713–91, medium-alloy (with molybdenum) steels of the 14G2AF (class S390), 16G2AF (class S440) and 12GN2MFAYu (class S590) grades according to GOST 19281–89 are used to construct and repair the bridge and transport structures.

At present the metallurgical industry produces grades 09G2S and 12G2S from steels, the requirements to which are specified by inter-state standards. Production of steels classed as S390, S440 and S590 has been practically ceased, as GOST 19281–89 permitted a high content of harmful impurities in them, which made them susceptible to brittle fracture.

Steels 15KhSND and 10KhSND turned out to be too expensive. In addition, as found out, they no longer corresponded to modern requirements for purity, performance and weldability imposed by bridge constructors. In this connection, consumption of these steels had been dramatically reduced by the beginning of the 1990s. Now Ukraine produces only a limited volume of rolled products from them. The Russian Federation continues using them in bridge construction. Structures fabricated earlier from the said steels are still in operation, and this fact should be taken into account when choosing welding consumables to repair them.

Factories of the South of Ukraine managed production of other grades of this class of steels using their own specifications. The Mariupol Institute of Structural Materials «Prometey» developed niobium-containing steels of the 06GB and 06G2B grades, which meet requirements to strength classes S355–S490. They are produced according to TU U 14-16-150–99 and supplied in the form of 8 to 50 mm thick plates. Different modes of heat treatment of the rolled stock provide four level of its strength ($\sigma_t \geq 450$, 490, 540 and 590 MPa, and $\sigma_y \geq 355$, 440 and 490 MPa, respectively) at almost identical values of ductility and impact toughness. The required Z-properties and continuity at a level of class 0 are guaranteed.

Steel of the 09G2SYuch grade is supplied according to TU U 322-16-127–97 in 8 to 40 mm plates. Its mechanical properties are provided within the following ranges, depending upon the plate thickness and heat treatment method: $\sigma_y = 325$–450 MPa, $\sigma_t = 480$–570 MPa, $\delta_5 = 19$ %, $KCU \geq 29$ J/cm^2 and $KCV \geq 29$ J/cm^2 at a temperature of −40 to −70 °C.

The said steel grades have different weldability. Steel 06G2B has the lowest value of carbon equivalent calculated by the IIW formula, and steels 09G2SYuch

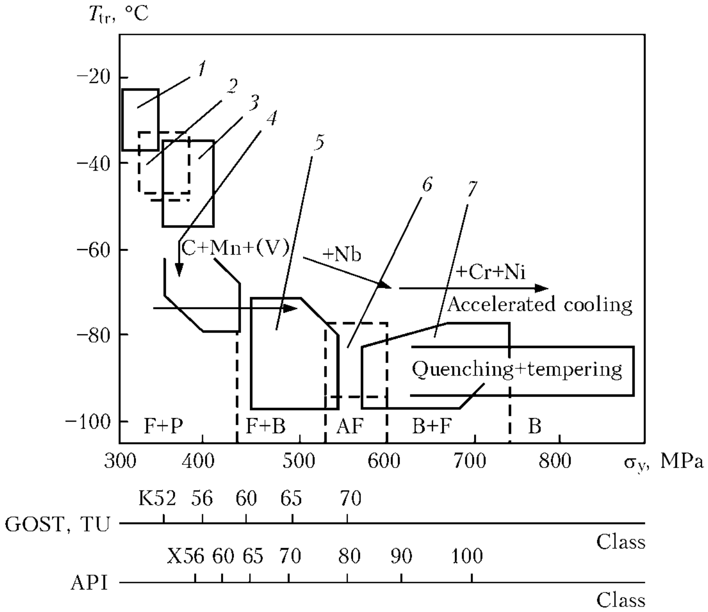


Figure 1. Evolution of properties of rolled stock of structural steels depending on chemical composition and manufacturing technology: *1* — steel St3 (1950s); *2* — steel St3 + Ti (1960s); *3* — steel 09G2 (1960s); *4* — steel 13G1 + (Si, Ti) (1965–1970); *5* — steel 10G2 + + (V, Nb, Ti) (1970s); *6* — steel 09G2 + (Nb, Ti, B) (1980s); *7* — steel 09G2 + (Cr, Ni, V, Nb); F — ferrite; B — bainite; AF — acicular ferrite; P — pearlite

and 10KhSND have the highest value. Indeed, the latter used to fabricate welded structures involves technological problems, which are noted by the authors of study [4]. When welding steel 06G2B, one might expect the weldability problems related to niobium contained in it. The above considerations are proved by the results of investigation of weldability of steels 10KhSND and 09G2SYuch, compared with molybdenum-containing steel 06G2B [5]. It was established that steel 06G2B is characterised by the highest resistance to delayed fracture. In the rest two steel grades the required value of resistance to delayed fracture is provided only at a concentration of hydrogen in the deposited metal that is not in excess of 7 ml/100 g. Steel 10KhSND reacts more intensively to increase in the concentration of hydrogen. Based on the investigation results, steel of the 06G2B grade is recommended for application in bridge construction [6].

Manufacture of transport structures is traditionally oriented to application of rolled stock of low-alloy steels 09G2S with thickness of no more than 20 mm.

Welding electrodes. Bridge and transport welded structures operate under very unfavourable service (impact, dynamic and vibration loads, atmospheric corrosion) and climatic conditions (negative temperatures in winter go down to −40 °C in Ukraine, and even lower outside Ukraine). Emergency failure of these structures may lead to substantial technical, economic and environmental losses. Therefore, the quality of welds and reliability of welded joints should meet sufficiently high requirements.

According to the regulatory documents, electrodes of the low-hydrogen class, types E42A and E50A (GOST 9467–75), are recommended for construction and repair of bridge and transport structures. To avoid technological defects, welding should be performed with electrodes having high welding-operational properties.

Table 1. Consumables for manual arc welding of bridge structures [7]

Steel grade (strength class)	Type and grade of electrodes for manual arc welding
T-, fillet and overlap joints	
15KhSND 15KhSNDA 09G2SD 12G2SBD (345)	E46A – UONI-13/45 E50A – UONI-13/55 E50A – MTG-02
10KhSND 10KhSNDA (390)	E46A – UONI-13/45 E50A – UONI-13/55 E50A – MTG-02
Butt joints	
15KhSND 15KhSNDA 09G2SD (345)	E50A UONI-13/55 MTG-01K MTG-02 MTG-03

Russian regulatory documents provide for the use of electrodes UONI-13/45 and UONI-13/55, as well as electrodes of the MTG grade, which were initially developed for construction of pipelines. They are manufactured under licenses of European companies by the Sychevsky Electrode Factory (RF). Types and grades of electrodes are given in Table 1.

In the national practice, electrodes UONI-13/45 and UONI-13/55, which were developed 70 years ago and no longer meet the up-to-date requirements, are mainly used for welding of bridge and transport structures from carbon and low-alloy steels. The key drawbacks of the UONI-13 type electrodes are as follows:

- inconsistency of mechanical properties of the weld metal, primarily impact toughness at low temperatures. The cold-shortness threshold of the weld metal obtained by using these electrodes is −30 to −40 °C;
- low welding-operational properties (welds are formed with reinforcement, poor slag crust detachability, increased spattering, possibility of performing welding only at direct current);
- low manufacturability showing up in susceptibility of the covering mixture to solidification and non-uniform outflow from the head of the electrode-covering press in deposition of covering on the rod;
- increased hygroscopicity of the covering.

The task posed for development of new electrodes for welding bridge and transport structures was to eliminate drawbacks peculiar to electrodes of the UONI-13 type. One of the main tasks was to ensure high impact toughness of the weld metal at negative temperatures, down to −60 °C.

Selection and experimental substantiation of weld metal deoxidation system. Gas- and slag-forming system $CaCO_3$–CaF_2–SiO_2–TiO_2 is used in the majority of grades of low-hydrogen electrodes. Welding-operating properties of electrodes and efficiency of molten metal shielding are regulated with this system by the $CaCO_3/CaF_2$ ratio and covering thickness.

Domestic developments of low-hydrogen electrodes of the E42A and E50A types according to GOST 9467–75 are traditionally oriented to a complex system of deoxidation of weld metal with manganese, silicon, titanium and aluminium, which is contained in the form of a concurrent element in ferrotitanium (up to 8 %). In the opinion of developers of the electrodes, titanium and partially aluminium, characterised by high affinity for oxygen, combined with manganese and silicon should provide high mechanical properties because of deep deoxidation of the weld metal, as well as its favourable structure-phase composition, which is formed under conditions of welding thermal cycle.

It is a known fact that structure of the weld metal in low-alloy welds includes ferrite of a different morphology (xenomorphic in the form of interlayers along the prior austenite grain boundaries, polygonal, lamellar, acicular and lath) with regions of the second phase, which consists of carbides, martensite, bainite, retained austenite or their mixture [8–10].

Boundaries of disoriented individual lamellae and laths of ferrite are low-angle. Structural elements of acicular ferrite, fine and uniformly distributed within each grain, form high-angle boundaries, which are more favourable in terms of brittle fracture resistance [10–12]. In fracture, a crack in such a structure has to change its propagation direction more frequently, this leading to a considerable increase in fracture resistance. For this reason, the weld metal with acicular ferrite dominating in its structure is characterised by higher values of impact toughness, including at low temperature.

High cold resistance of the weld metal can be achieved if the second phase, which forms simultaneously with acicular ferrite, is of a ductile nature, rather than of the brittle one.

The effect of alloying elements on structure and properties of the weld metal can be explained as follows. Manganese provides the high values of strength and impact toughness of the welds. The 1.4–1.6 wt.% manganese content is considered optimal [13–15]. In this case, the highest yield of acicular ferrite is achieved in structure of the weld metal.

Increasing the silicon content from 0.2 to 0.9 wt.% leads to growth of the volume content of acicular ferrite in the deposited metal. But this increases the amount and deteriorates the morphology of the second phase, i.e. cementite films and bainite and pearlite islands are replaced by martensite and austenite [16], which leads to decrease in the level of impact toughness. The optimal values of impact toughness of metal deoxidised with silicon and manganese are provided at a manganese content of 1.4–1.6 wt.% and silicon content of 0.2–0.4 wt.%.

The effect of titanium on structure and mechanical properties of the weld metal is considered in studies [17–19] etc. Their authors note a positive effect of titanium on impact toughness of metal of the welds made with low-hydrogen electrodes. However, the optimal content of titanium in the weld metal, reported by different authors, varies over wide ranges, depending upon the presence and proportion of other alloying elements. It is unclear why titanium fails to always provide the expected high toughness of the welds made with electrodes UONI-13, and does not provide it, as a rule, if welding is performed using electrodes with a covering, which greatly differs in proportion of main slag-forming materials from electrodes of the UONI-13 type.

Most of the above-quoted results of metal science research were obtained under conditions of metallurgical welding systems reliably «closed» from ambient air. Ideal deoxidisers (titanium instead of ferrotitanium, metal manganese instead of ferromanganese), which do not occur in real industrial conditions, were used in the electrode covering applied for research. It is hard to understand from the publications how high the degree of robustness of the found balance of microalloying elements is with respect to variation in material composition of the covering, including its ability to efficiently shield the molten metal from the ambient air.

The authors conducted experimental studies of the system of deoxidation and microalloying of the weld metal based on manganese, silicon and titanium in coverings of low-hydrogen electrodes for welding of bridge and transport structures. For this, experimental electrodes based on marble, fluorspar and rutile (or quartz sand) were manufactured and tested. Total contents of main gas- and slag-forming ($CaCO_3$ and CaF_2), as well as metal components of the coverings (ferroalloys with iron powder), and their proportions are given in Table 2.

Commercial ferroalloys were used as deoxidisers: electric-furnace low-carbon ferromanganese (88 wt.% Mn), ferrosilicium (granulated with 15 wt.% Si, or lumpy with 45 wt.% Si) and ferrotitanium (35 wt.% Ti, 5 wt.% Si, and 8 wt.% Al). The total content of ferroalloys and iron powder in a covering varied from 22 to 44 wt.%.

The contents of ferroalloys, ritule or quartz sand in coverings of electrodes of series 2M, 3M, 2T and 3T were regulated so that the planned increase of the titanium content of the deposited metal did not change, if possible, the content of manganese and silicon within each series of the electrodes. At the same time, the assigned content of ferromanganese in cov-

Table 2. Base of coverings, dimensional and technological parameters of experimental electrodes

Electrode series	Content in covering, wt.%				Parameters of electrodes			
	$CaCO_3$	CaF_2	$CaCO_3/CaF_2$	Metal components	D/d	$K_{c.w}$, %	$K_{s.sh}$, %	$\tau_{s.c}$, ms
2M	51.0	18.0	3/1	22–24	1.50	35	25	7.5
3M	51.0	18.0	3/1	24–28	1.50	–	–	–
2T	26.0	26.0	1/1	35–46	1.55–1.60	45	22	14.5
3T	26.0	26.0	1/1	39–46	1.55–1.60	–	–	–
R	26.5	22.5	1.2/1.0	44–46	1.65	55	25	10.5

Note. $K_{c.w}$ – covering weight factor; $K_{s.sh}$ – slag shielding factor; $\tau_{s.c}$ – short circuit duration.

Table 3. Chemical composition of metal deposited with experimental electrodes

Electrode series	C	Mn	Si	O	N	Ti
2M	0.05–0.07	0.67–0.84	0.20–0.32	370–530	110–160	0–330
3M	0.07–0.09	1.38–1.73	0.37–0.52	280–500	110–150	0–420
2T	0.04–0.06	0.87–1.32	0.28–0.41	270–390	130–360	10–640
3T	0.06–0.07	1.17–1.34	0.33–0.42	260–320	130–240	20–700
R	0.04–0.06	0.75–1.75	0.25–0.90	240–360	70–130	80–520
Note. Contents of C, Mn and Si is given in wt.%, and contents of other elements is given in ppm.						

erings of electrodes of series 3M and 3T was deliberately made higher than in series 2M and 2T.

The content of ferroalloys in coverings of electrodes of series R was calculated by the method of active experimental design using the D-optimal plan.

The iron powder in all series of experimental electrodes was used as a balance compensator. Diameter of the electrodes was 4 mm. Other dimensional and technological parameters of the electrodes are given in Table 2, and chemical composition of the deposited metal is given in Table 3.

As follows from Tables 2 and 3, coverings of series M reproduce the gas- and slag-forming base, as well as dimensional and technological parameters of coverings of electrodes UONI-13. The $CaCO_3/CaF_2$ ratio in them is 3/1. Hence, they feature a high oxidation potential, sufficiently effective shielding of molten metal from air, and spray transfer of electrode metal. Coverings of electrodes of series T model similar parameters of electrodes ANO-7, «Garant», as well as many grades of electrodes of ESAB, «Thyssen» etc. The $CaCO_3/CaF_2$ ratio in their covering is 1/1. Hence, its oxidation potential is much lower, and the ability of metal shielding from air is also lower, in view of its nitrogen content. The electrode metal transfer is globular. In covering of electrodes of series R the $CaCO_3/CaF_2$ ratio is 1.2/1.0. Compared to electrodes of series T, their metallurgical and technological characteristics are much better, and shielding function of the covering is at a high level because of its large thickness.

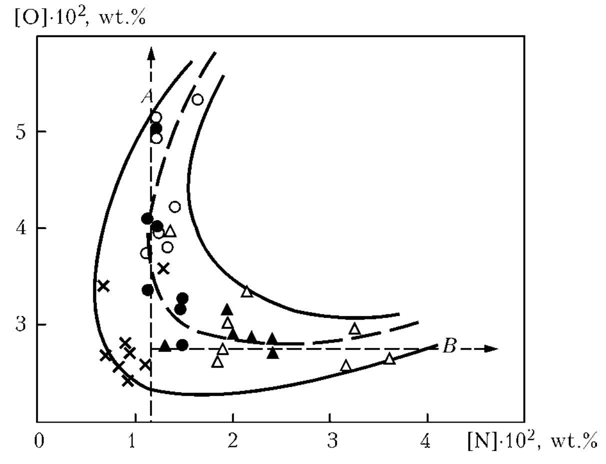


Figure 2. Comparison of oxygen and nitrogen contents of metal deposited with experimental electrodes having coverings of series 2M (○), 3M (●, 2T (Δ), 3T (▲ and R (×)

The content of titanium in the deposited metal was varied from 0 to 700 ppm, that of oxygen — from 240 to 530, and nitrogen — from 70 to 360 ppm (see Table 3), i.e. oxygen and nitrogen, along with manganese, silicon and titanium, should be regarded as elements that actively affect mechanical properties, including ductility of the weld metal.

The values of strength (σ_y and σ_t) and ductility (δ and KCV_T) of multilayer weld metal were investigated on 18 mm thick low-carbon steel. Below we analyse only the KCV_{+20} values obtained by testing specimens with a notch passing through all the layers of the weld.

Limits of variations in the contents of oxygen and nitrogen are shown in Figure 2. It can be seen from the Figure that the weight content of nitrogen is of the same order of magnitude as the equilibrium concentration of nitrogen in iron containing titanium and oxygen. However, as proved by our analysis, in contrast to the equilibrium concentration, it grows with increase in the titanium content of the weld, rather than decreases. This is an indirect confirmation that the source of nitrogen is air, from which it is absorbed by titanium. The weight content of oxygen is an order of magnitude higher than the equilibrium concentration of oxygen in iron deoxidised with titanium, which is characteristic of metal deposited by fusion arc welding. In this case, non-metallic inclusions, which form at a stage of solidification of the weld pool and have no time to go to the slag, are the main source of oxygen. The points located along vertical A in Figure 2 reflect results obtained mainly with electrodes of series M ($[O]_{var}$ at $[N]$ = const), and those along horizontal B — results obtained mainly with electrodes of series T ($[N]_{var}$ at $[O]$ = const). The data given confirm a differing oxidation and shielding ability of coverings of the compared experimental series of electrodes. Electrodes of series R provide a low content of both oxygen and nitrogen in the deposited metal, i.e. they are characterised by a low oxidation ability of their covering (like electrodes of series T) and its sufficiently effective ability to shield from air (like electrodes of series M).

Metal deposited with the experimental electrodes can be classed in chemical composition with the Fe–Mn–Si–Ti–O–N system. In this case, titanium acts as deoxidiser, like silicon and manganese, and, at the same time, as a nitride-forming element. Depending upon the conditions of shielding the electrode metal from air, part of titanium can be combined to form nitrides, and other part — to form oxides.

Consequences of the above double role of titanium revealed by analysing results on KCV_{+20} were determined by using the following experimental results processing approaches.

The system of deoxidation of welds with silicon and manganese is based on the following chemical reaction:

$$[Si] + 2(MnO) = 2[Mn] + (SiO_2). \tag{1}$$

The equilibrium content of oxygen in the deposited metal can be calculated from equation [20, 21]:

$$[O] = K_{Si-Mn}\,([Mn]\cdot[Si])^{-0.25}. \tag{2}$$

The temperature dependence of the equilibrium constant of chemical reaction (1) has the following form:

$$\lg K_{Si-Mn} = -\frac{15518}{T} + 6.01. \tag{3}$$

Deoxidation parameter $([Mn]\cdot[Si])^{-0.25}$ is complex, as it reflects the effect of the total content of manganese and silicon, as well as their ratio on residual oxygen in the deposited metal, which has the form of non-metallic inclusions formed at a stage of cooling and solidification of the weld pool. A low value of negative exponent in the deoxidation parameter means that control of oxygen in the metal by changing manganese and silicon in it is very limited, compared, for example, to the operating welding parameters, and is indicative of the presence of other deoxidisers, etc. Nevertheless, it permits evaluating the oxygen content component that is caused by complex deoxidation of the weld metal with silicon and manganese. By giving our results on KCV_{+20} depending on the deoxidation parameter, we thus relate them to the content of oxygen that remained in the weld as a result reaction (1), and consider the entire revealed situation to be a consequence of the effect of other factors (e.g. titanium and oxygen that do not participate in reaction (1), and nitrogen).

The Fe–Ti–O–N system, which we arrive at as a result of excluding oxygen that remains in the deposited metal after it has been deoxidised with silicon and manganese, can be described by three equations:

$$Ti_xO_y(s) = x[Ti] + y[O]; \tag{4}$$

$$TiN(s) = [Ti] + [N]; \tag{5}$$

$$xTiN(s) + y[O] = Ti_xO_y(s) + x[N], \tag{6}$$

where (s) is the solid state of an ingredient [22, 23]. Note that equation (6) was derived by subtracting (5) from (4).

To describe conditions of formation (decomposition) of nitride in iron alloys containing, as in our case, less than 0.05 % Ti, the use is made of equations (4) and (6), which characterise affinity of titanium and its nitride for oxygen. Equation (6) in its explicit form reflects relationship between the equilibrium concentrations of nitrogen and oxygen in iron in the presence of titanium. In view of a very low concentration of the above components, thermodynamic calculations of constants are made by using their concentration instead of activity, and, based on the form of oxide Ti_2O_3 revealed in the experiments, it is suggested that temperature dependence of the constants should be evaluated from the following equations [22, 23]:

$$\lg K_4 = -\frac{55200}{T} + 16.4; \tag{7}$$

$$\lg K_5 = -\frac{19000}{T} + 6.48; \tag{8}$$

$$\lg K_6 = \lg [N]^x/[O]^y = \frac{14200}{T} - 3.44. \tag{9}$$

Equation (6) shows that TiN in the melts reliably shielded from air, like titanium in reaction (4), may act as deoxidiser of molten steel. The $[N]^x/[O]^y$ ratio is, in fact, an equilibrium constant of reaction (6) that depends upon the total concentration of nitrogen and oxygen, as well as stoichiometric coefficients, which, in turn, are determined by the composition of the forming titanium oxides (TiO_2, Ti_2O_3 or TiO) depending on the deoxidation conditions and on the contribution to this process made by manganese, along with titanium, as well as by silicon and aluminium contained in ferrotitanium.

Finally, we used the coefficient of imbalance of nitrogen caused by titanium, B_N, for consideration of the Fe–Ti–O–N system. Its values are calculated from the actual composition of the deposited metal as a content of nitrogen that is not fixed into titanium nitrides, using the following formula [24, 25]:

$$B_N = 14/48[Ti] - [N]. \tag{10}$$

Aluminium was not taken into account in this case, as it is a weaker nitride-former, compared to titanium, and better shields it from oxidation than from interaction with nitrogen.

As follows from Figure 3, *a*, the impact toughness values depending on the deoxidation parameter can be distributed into three groups. For groups of series *V*1 and *V*2, which include results of testing the electrodes of series 3M, 2T and 3T (in Figure 2, they are located mostly along vertical *A* and horizontal *B*, respectively), impact toughness of the weld metal changes for some reasons that are not related to the deoxidation parameter ($([Mn]\cdot[Si])^{-0.25}$) and, hence,

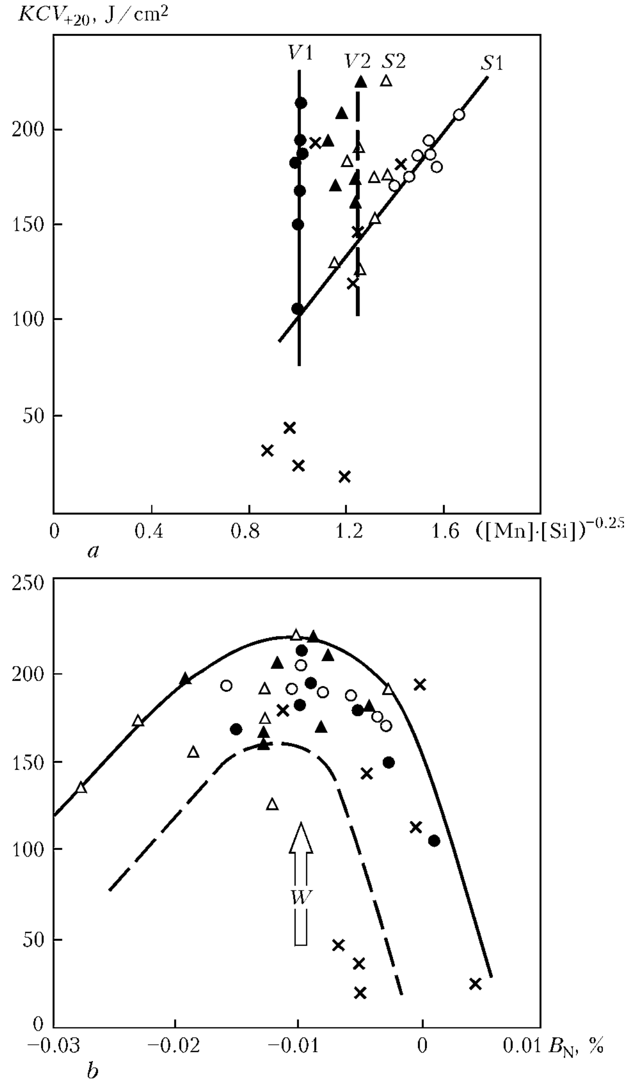


Figure 3. KCV_{+20} versus parameter of complex deoxidation of deposited metal with manganese and silicon, $([Mn]\cdot[Si])^{-0.25}$ (*a*), and versus coefficient of imbalance of titanium and nitrogen contents of deposited metal, B_N (*b*): ○ — electrodes of series 2M; ● — 3M; Δ — 2T; ▲ — 3T; × — R

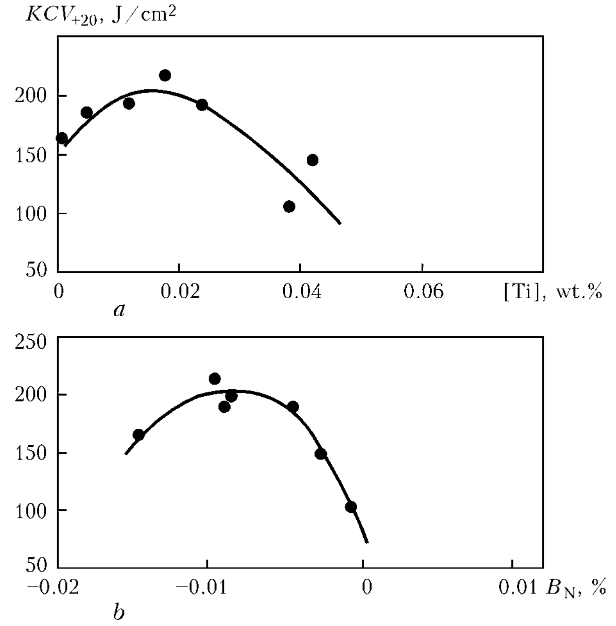


Figure 4. KCV_{+20} versus titanium content (*a*) and B_N (*b*) in metal of the welds made with electrodes of experimental series *V*1

to oxygen of manganese silicates, the content of which for each of these groups is constant, as it was planned by the experimental design. The said reasons of changes in impact toughness are analysed below. For group *S*1, which includes mostly the results of testing the electrodes of series 2M and 2T, impact toughness of the weld grows with increase in the deoxidation parameter and, hence, with increase in the weight content of oxygen fixed into manganese silicates. The reasons of this dependence are not considered in this publication.

The values of impact toughness of the weld versus the coefficient of imbalance of nitrogen caused by titanium, which are shown in Figure 3, form an extreme region with maximum at $B_N \approx -0.01$ %. To the left of maximum of KCV_{+20}, its decrease should be considered a consequence of increase in the weight content of nitrogen not fixed into titanium nitrides in the weld metal, while that to the right — a consequence of increase in the weight content of redundant titanium not fixed into nitrides. A change in impact toughness of the weld in a range of maximum amounts to a factor of one and a half. The causes of this are not related to the Ti–N balance described by equation (10). They will also be considered below.

Seemingly, the results of experiments on series *V*1 can be explained by fully excluding from consideration the effect of nitrogen on impact toughness because of its low content. Deoxidation of the weld metal with titanium occurs by reaction (4), i.e. it is enough to allow for the effect on KCV_{+20} by changes in the concentration of titanium and oxygen remained in the weld metal in quasi-equilibrium with silicon and manganese. As follows from literature data, non-metallic inclusions must form at an optimal proportion of titanium and oxygen. These inclusions facilitate initiation and provide the highest yield of acicular ferrite, which is a structural component responsible for high impact toughness of the low-alloy weld. It follows from Figure 4, *a* that the maximal value of KCV_{+20} takes place at 0.018–0.020 wt.% Ti, which is in good agreement with the data published by other authors. This optimum is implemented in all modern developments of electrodes close to electrodes UONI-13/55 in their covering composition. It is likely that the effect of this favourable factor is suppressed to the right of maximal KCV_{+20}, in addition, by a too high level of strengthening of the metal by titanium.

At the same time, imbalance coefficient B_N can also be used as an argument for representing results on experimental series *V*1 (Figure 4, *b*), as at such a low concentration of nitrogen B_N is equivalent to the content of titanium not fixed into nitrides in the deposited metal.

The results on experimental series *V*2, which is represented by electrodes of series 2T and 3T, are more difficult to interpret by this scheme, as titanium acts here mainly as a nitride-former. It can be seen from Figure 5 that the extreme character of variations in impact toughness takes place when it is considered depending on B_N. In this case, a substantial change in KCV_{+20} at $B_N \approx$ const is observed in maximum, like in Figure 3, *b*, and the cause of it remains unclear so far.

Assume that in experimental series *V*2 the process of deoxidation of the weld metal occurs by reaction (6). Show results on KCV_{+20} scattered in maximum in Figure 5 depending on the [N]/[O] ratio, which is a particular case of equilibrium constant of chemical reaction (6), where stoichiometric coefficients are assumed to be equal to $x = y = 1$, as the real form of deoxidation products is unknown to us. As follows from Figure 6, *a*, dependence $KCV_{+20} = f([N]/[O])$ is described by an inclined line showing that in the case of insufficient shielding of the molten metal from ambient air, which takes place when using electrodes of series 2T and 3T, involvement of titanium into the nitride formation reaction leads to substantial deterioration of impact toughness of the weld metal. The highest value of KCV_{+20} is observed when such a reaction is eliminated.

Figure 6, *b* shows the same interpretation of the results on experimental series *W* scattered in maximum of $KCV_{+20} = f(B_N)$ in Figure 3, *b* at $B_N \approx -0.01$. It can be seen that the values of KCV_{+20} are distributed in two levels, each corresponding to its peculiar contents of oxygen and nitrogen. Although we compare electrodes that are different in their metallurgical nature, the lines are parallel to each other and have a slope identical to that of the curve in Figure 5, when the concentration of oxygen in the deposited metal was kept constant. The data presented show that variation in KCV_{+20} in maximum in Figure 3, like in Figure 5, is also caused by growth of the [N]/[O] ratio.

Both titanium oxides and nitrides forming at a stage of solidification of the weld pool are considered in a number of references to be the centres of nucleation of acicular ferrite in γ–α transformation taking place in cooling of the weld metal. The results presented showed that titanium nitrides could hardly act as such nucleators of acicular ferrite. As evidenced by the results of a number of studies, titanium nitrides forming at the last stages of solidification, in particular as well as sulphides, precipitate on the surface of titanium oxide inclusions and suppress their ability to act as centres of nucleation of acicular ferrite. This point of view seems fairly plausible, although requiring a more painstaking substantiation.

Therefore, our results suggest that the favourable role of titanium in increasing impact toughness of the weld metal produced by using low-hydrogen electrodes can be enhanced by improving the efficiency of shielding the molten metal from air through increasing thickness of the electrode covering.

Under the efficient shielding conditions, the said role of titanium can be increased by using it in a combination with boron. When present in metal in a concentration that is an order of magnitude lower than that of titanium, boron concentrates along the austenite grain boundaries and, in opinion of some specialists, blocks the mechanism of nucleation of grain-boundary ferrite, thus creating conditions for increasing formation of acicular ferrite on titanium oxide inclusions inside grains. As shown by our investigations, this leads to a substantial increase in impact toughness not only at room temperature, but also at negative temperatures down to −60 °C [26].

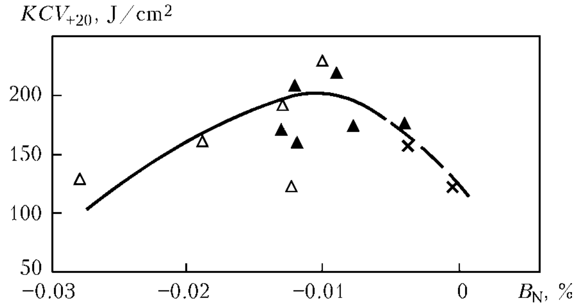


Figure 5. KCV_{+20} versus B_N in metal of the weld made with electrodes of experimental series *V*2

Main characteristics of the developed electrodes. The slag-forming system of covering, consisting of marble, fluorite, rutile and feldspar ($CaCO_3:CaF_2 \approx$ $\approx 1:1$), was used to achieve good welding-operating

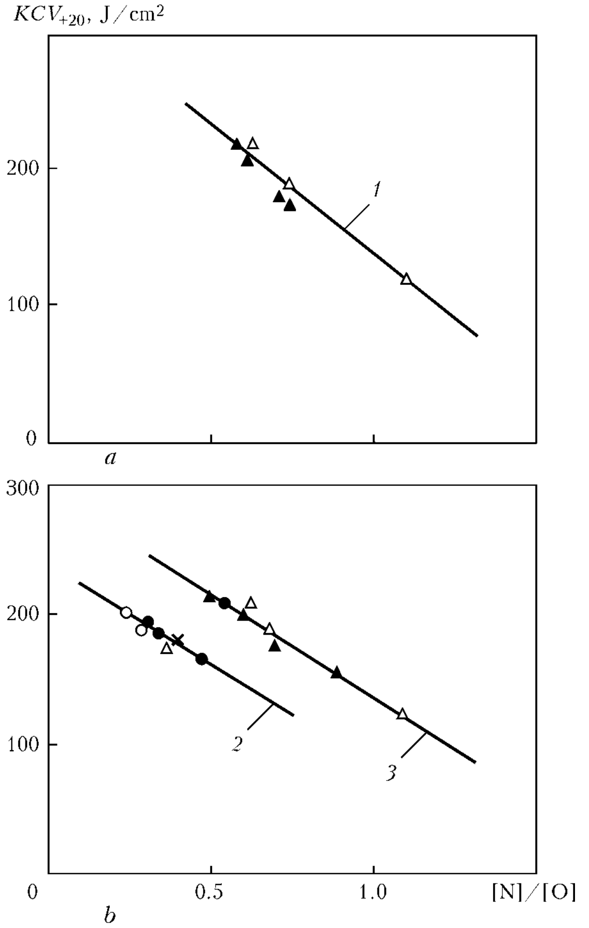
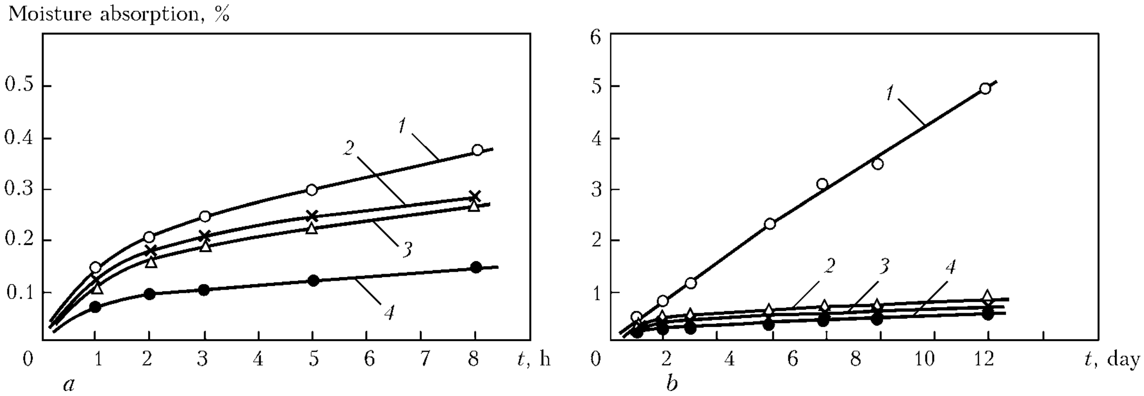


Figure 6. Curve $KCV_{+20} = f([N]/[O])$ plotted in experimental series *V*2 (*a*) and *W* (*b*): *1* — B_N = 0.0105 %; *2* — $[N]_{mean}$ = = 0.013 %, [O] = 0.04 %; *3* — $[N]_{mean}$ = 0.02 %, $[O]_{mean}$ = 0.03 %

Table 4. Mechanical properties of weld and deposited metals produced by using developed electrodes

Electrode diameter, mm	Steel		σ_y, MPa	σ_t, MPa	δ_5, %	KCV, J/cm^2, at temperature, °C			
	Grade	δ, mm				20	−20	−40	−60
3.0	St3*	20	584	641	23	160	95	53	35
4.0	St3*	20	510	579	28	180	175	170	55
5.0	St3*	20	494	581	26	168	150	112	42
4.0	09G2S	14	477	593	28	200	133	70	35
4.0	09G2	14	513	606	27	187	133	113	98

*Deposited metal (variant *A* acc. to GOST 9466–75), the rest of the specimens — weld metal (variant *B* acc. to GOST 9466–75).



a *b*

Figure 7. Kinetics of sorption of atmospheric moisture by covering of experimental electrodes observed for time *t* in hours (*a*) and in days (*b*) without (*1*) and with (*2–4*) different technological anti-hygrosorption additions

properties of electrodes. This system provides good formation of the weld metal, high detachability of the slag crust and negligible metal spattering.

The Ti + B microalloying system (Ti = 250–350 ppm, and B = 40–60 ppm) was selected, the optimal content of Mn being 1.2–1.6 wt.%, and that of Si = 0.2–0.4 wt.%. This provides the weld metal with a sufficiently high cold resistance. A relatively high basicity of the gas-slag system of the covering, and the use of complex deoxidation and alloying of the electrode metal (Mn–Si–Ti) decrease transfer of harmful sulphur and phosphorus impurities from the covering to the weld metal.

The decreased content of marble in the covering (51 wt.% $CaCO_3$ in UONI-13, and 28 wt.% $CaCO_3$ in a new electrode) provided improvement of operating properties of the covering mixtures due to suppression of the process of interaction of marble with liquid glass and solidification of the covering mixture in the press head.

Mechanical properties of the deposited and weld metals produced by using the developed electrodes are given in Table 4.

Figure 7 compares the hygrosorption resistance of the electrode covering with and without technological anti-hygrosorption additions. It can be seen that resistance of the coverings to absorption of the atmospheric moisture under the effect of the technological additions grows to a level that meets requirements to electrodes having an index of high hygrosorption resistance of their coverings (HMR).

CONCLUSIONS

1. In welding with covered electrodes, the welding zone is not shielded from the ambient air as reliably as in the case of using other welding consumables. Under such conditions, titanium exhibits not only deoxidising properties (like manganese and silicon), but also nitride-forming ones. This double role of titanium does not allow using it to the full extent as a microalloying element to efficiently regulate impact toughness of the weld metal.

2. Based on analysis of literature sources and results of own investigations, conditions are suggested for using the systems of Mn–Si–Ti alloying and microalloying of the weld metal produced with low-hydrogen electrodes having a different gas-slag base of the covering, which promote increase in impact toughness of the weld metal. It was established that this can be achieved by improving the efficiency of shielding of the welding zone from interaction with air through increasing the $CaCO_3/CaF_2$ ratio in the covering and its thickness. This leads to reduction of the probability of formation of titanium nitrides with nitrogen that gets into the welding zone from the ambient air.

3. The concentration of Mn–Si–Ti in metal deposited with low-hydrogen electrodes having a different

$CaCO_3/CaF_2$ ratio in the covering was selected, providing good welding-operating properties of the electrodes and high impact toughness of the weld metal.

4. Under conditions of efficient shielding of molten metal from air, impact toughness of the weld metal can be additionally increased not only at room temperature, but also at negative temperatures down to −60 °C by combining titanium as a microalloying element with boron.

5. Hygroscopicity of the electrode coverings with technological anti-hygrosorption additions was studied. As established, they substantially increase resistance of the electrode coverings to absorption of the atmospheric moisture.

6. The investigation results were used for the development of low-hydrogen electrodes intended to replace electrodes UONI-13/15 for welding of carbon and low-alloy steels and repair of bridge and transport structures.

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