melt was formed at a temperature close to 1200 °C. This was accompanied by a marked exothermic effect reaching its maximum at the said temperature.

Discussion of results and conclusions. Investigations of physical-chemical properties of powder materials and their mixtures modelling the flux-cored wire core, which were carried out by the methods of complex thermal analysis and mass-spectroscopy of the gas phase in dynamic heating from 30 to 1500 °C, make it possible to establish the temperature ranges, extent of development and consumption of heat for the reactions of thermal destructions to evolve gases, oxidation of components, and melting of mixtures to form the primary melt of the metal and slag phases. Formation of the melts as early as at a stage of heating of the powder core up to melting of the wire sheath and evolution of the gaseous products (H_2O, CO_2, SiF_4) determine shielding functions of the electrode material and exert a substantial impact on the course of the metal to gas interaction reactions at the drop and pool stages. Temperature ranges of the thermochemical reactions (endothermic processes of removal of moisture, destruction and melting, and exothermic processes of oxidation and complex formation) accompanying the heating process overlap, and their thermal effects superimpose on one another, thus stimulating development of some processes and slowing down of the other ones. Therefore, control of these reactions by varying composition of a mixture allows regulation of the rate of melting of the core to achieve favourable characteristics of melting of the flux-cored wire and transfer of the electrode metal to the weld pool. Values of the heat flow in heating of powder composites enable estimation of the consumption of heat for their heating and melting, allowing for the mutual effect of the exothermic and endothermic reactions occurring in the material investigated.

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CONTROL OF PROPERTIES OF THE WELD METAL BY REGULATING THE LEVEL OF OXIDATION OF THE WELD POOL IN GAS-SHIELDED WELDING

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Activity of oxygen dissolved in the weld pool metal was determined directly in the process of welding of low-alloy steel in the oxidising shielding gas atmosphere by using the electrochemical method. Prediction of mechanical properties of the weld metal depending on the activity of oxygen in molten metal and welding heat input was substantiated.

Keywords: *arc welding, consumable electrode, oxidising shielding gases, weld pool, electrochemical method, oxygen activity, heat input, weld metal, structure and mechanical properties*

Structure and properties of the weld metal on low-alloy steels are known to depend to a considerable degree on its oxygen content [1, 2]. Oxygen contained in molten metal of the drops and weld pool in arc welding of steel in oxidising shielding gases may be in different states: in a dissolved or chemically combined state in the form of suspended particles of oxides and complex inclusions. Metal-soluble oxygen $[O]_s$ or oxygen activity a_o determines the course of the processes of deoxidation, refining and secondary oxidation and affects the final composition of the weld metal, its structure formation and properties.

The methods applied in practice for analysis of the oxygen content of the weld metal allow evaluation of its total concentration, i.e. the total content of oxygen $[O]_t$, both active and combined into chemical compounds. It takes several hours to perform this operation, including sampling, preparation of a sample, its transportation to a laboratory and analysis by the vacuum melting method.

At the same time, large-scale metallurgy uses to an increasing extent the method of evaluation of the activity of oxygen in iron-based melts, which consists in measuring the electromotive force (emf) generated in a concentration cell based on solid oxide electrolyte

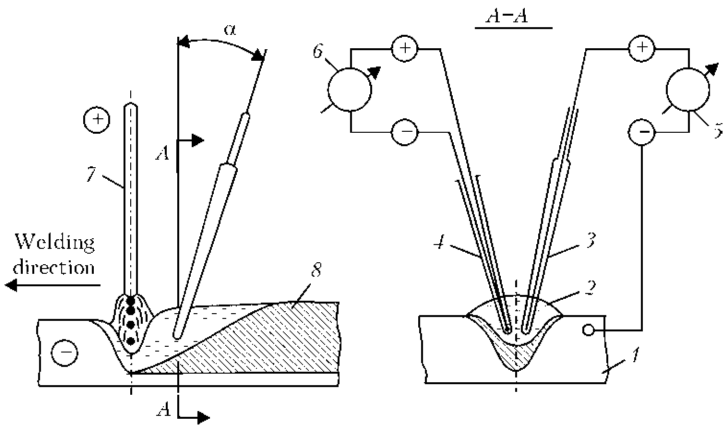

Figure 1. Schematic diagram of express monitoring of oxygen activity in weld pool metal: *1* — base metal; *2* — weld pool; *3* — oxidation sensor; *4* — thermocouple; *5*, *6* — measuring instruments; *7* — welding electrode; *8* — weld (α = 15–20° — angle of inclination of sensor and thermocouple)

[3]. An important feature of this method is that the oxide phase forming in molten metal as a result of its oxidation does not affect the level of the generated emf and, hence, the activity of oxygen in metal. Therefore, the measurements can be performed without any preliminary holding of sensor in the melt, which is usually applied to stabilise processes occurring in the galvanic cell circuit, this being of high importance for investigation of short-time fast processes taking place in the weld pool. The measured values of the oxygen activity range from 0.0001 to 0.2 wt.% [4].

The soluble oxygen content can be determined by the electrochemical method within 15–20 s by immersing the oxygen galvanic cell into the weld pool [5, 6]. Oxygen activity a_o (this directly measurable value is taken as a criterion of oxidation of the weld pool metal) and total oxygen content $[O]_t$ of the weld are the mutually complementary values, as their difference $\Delta[O] = [O]_t - a_o$ characterises the content of oxygen combined into chemical compounds, i.e. the content of oxide and complex inclusions in the metal [6].

Participating in metallurgical reactions during fusion welding, oxygen may have both positive and negative effect on the technological strength [7, 8], sensitivity to formation of pores [8] and mechanical properties of the welds [9], depending on its concentration in the melt.

The purpose of this study was to analyse mechanical properties and structure of the weld metal depending on the variations of the activity of oxygen in the weld pool metal directly in the process of welding of low-carbon steel in the oxidising shielding gas atmosphere.

The data on the content of soluble oxygen in the melt were obtained by using the electrochemical method. Figure 1 shows schematic diagram of the express method used to monitor oxygen activity a_o in the weld pool metal by measuring the emf generated in an oxygen concentration galvanic cell based on solid electrolyte. For this the use was made of a commercially produced oxidation sensor made from Y_2O_3-stabilised ZrO_2 and comprising the Mo–MoO_2 reference electrode, which was immersed into a low-temperature zone of the weld pool to a depth of 4–6 mm. The distance between the sensor, thermocouple and arc was 10–12 mm. The local measurement of temperature of the weld pool metal was made with tungsten-rhenium thermocouple VR 5/20. Digital voltmeters with a voltage measurement range of zero to 1000 mV were used to fix the emf induced in the sensor and thermocouple.

The oxygen activity was determined from the measured values of emf in the galvanic cell and temperature of the weld pool metal [4]:

$$\lg a_o = 2.685 - \frac{10.086E + 5661}{T},$$

where E is the emf generated in the concentration cell circuit, mV; and T is the temperature of the weld pool, K.

Experimental V-groove butt joints on steel VSt3sp (killed) were welded at a reverse polarity current by using 2 mm diameter wire Sv-08G2S in the CO_2 and Ar + 20 % CO_2 gas mixture atmospheres. Variations in oxygen activity a_o in the weld pool metal were studied depending on the arc voltage in a range of 28 to 36 V at fixed values of the welding current: 400, 450 and 500 A, and at welding heat input g/v ranging from 5 to 35 kJ/cm. Measured results are given in Figures 2 and 3.

As seen from Figure 2, in case of welding in the Ar + 20 % CO_2 mixture, oxygen activity a_o in the weld pool metal linearly increases with growth of the arc voltage, this being most pronounced at a current of 400 A. The sensitivity of a_o to variations in the arc voltage decreases with increase of the welding current. In welding at a current of 500 A, the oxygen activity remains almost unchanged over the entire range of the tested values of the arc voltage. The range of the welding conditions was determined, in which a change of the main process parameters (I_w, U_a, v_w) caused no substantial changes in the oxygen activity, i.e. the level of oxidation of molten metal, at the fixed compositions of the shielding gas and welding current. It can be seen from Figure 3 that with increase of welding

Mechanical properties of metal of the welds made in oxidising shielding gases on steel VSt3sp depending on the welding heat input and oxygen activity in the weld pool

Shielding gas	g/v, kJ/cm	$[O]_t$, wt.%	a_o, wt.%	$\Delta[O]$, wt.%	$\sigma_{0.2}$, MPa	σ_t, MPA	δ_5, %	ψ, %	KCV, J/cm^2, at T, °C		
									+20	−20	−40
CO_2	18.4	0.054	0.0056	0.0484	350	420	26.5	55.2	120	60	32
	28.8	0.061	0.0063	0.0547	335	380	25.2	53.4	98	42	16
Ar + 20 % CO_2	18.4	0.035	0.0034	0.0316	384	530	33.0	66.0	165	115	55
	28.8	0.046	0.0040	0.0420	353	465	29.3	58.6	136	91	43

Note. Given are the values averaged over the results of tests of three to five specimens.

heat input g/v the level of oxidation of the weld pool metal first grows almost linearly, then this growth slows down, and in a range of welding conditions with a heat input above 20 kJ/cm the value of a_o remains almost constant. This regularity shows up when welding is performed in the CO_2 and Ar + 20 % CO_2 gas mixture atmospheres having a different oxidising ability. This character of dependence of the oxygen activity on the welding parameters is attributable, first of all, to increase in the base metal content of the weld pool, as well as to increase in the content of iron vapours in the arc atmosphere causing decrease in a partial pressure of the oxidising gases and, hence, absorption of oxygen by the electrode metal drops.

Further investigations allowed evaluation of the effect of welding heat input on the oxygen activity in the melt, as well as of mechanical properties of the welds made on steel VSt3sp in the CO_2 and Ar + 20 % CO_2 gas mixture atmospheres (Table). The data of the Table show that the a_o values grow with increase in the oxidising ability of the shielding atmosphere. However, they are an order of magnitude lower than total oxygen content $[O]_t$ of the weld metal determined by the vacuum melting method.

Structure of metal of the experimental welds was examined by using the optical and electron microscopes, and character of the $\gamma \rightarrow \alpha$ transformation of this metal under conditions of continuous cooling was studied by using the high-sensitivity dilatometry instruments combined with the «Ala-Too» unit for high-temperature metallography. The Pt-Pt–10 % Rh thermocouple was employed for precise measurement of temperature. The dilatometer was evacuated to a pressure of $2 \cdot 10^{-4}$ Torr and then filled up with high-purity argon to prevent oxidation or decarburisation of samples. To investigate the effect of oxygen on peculiarities of decomposition of austenite in the weld metal, the samples were heated to a temperature of 1250 °C and held for 2 min at this temperature providing the identical grain sizes. Cooling from 800 to 500 °C was performed at a rate of 5 °C/s. The temperature versus time of elongation of a sample was recorded during this thermal cycle simulating the welding conditions by using a specially calibrated potentiometer KSP-4.

It was established that high values of impact toughness of the weld metal and a maximal amount of acicular ferrite in structure of the weld metal can be achieved at the content of combined oxygen $\Delta[O]$ in the weld ranging from 0.015 to 0.045 % (Figure 4, *a*) and at the following contents of alloying elements and impurities, wt.%: 0.08–0.11 C, 0.40–0.55 Si, 1.2–1.5 Mn, 0.015–

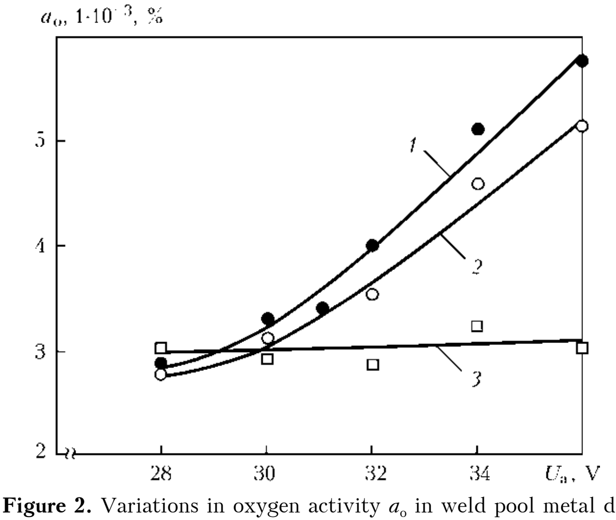

Figure 2. Variations in oxygen activity a_o in weld pool metal depending on the arc voltage in welding of steel in Ar + 20 % CO_2 gas mixture: *1* — I_w = 400; *2* — 450; *3* — 500 A

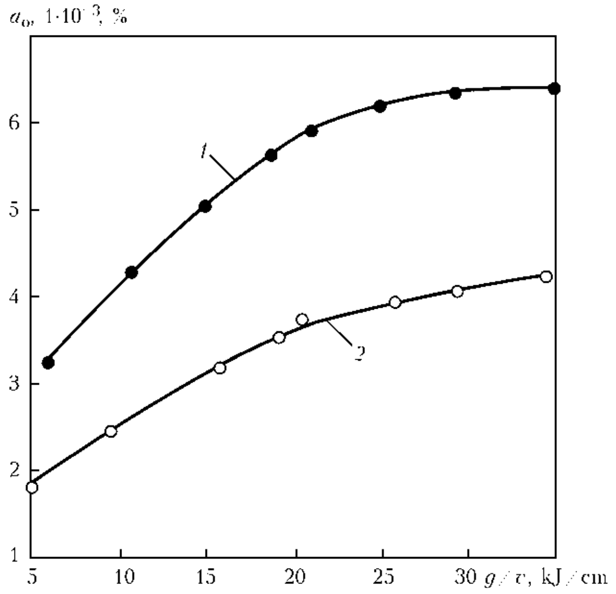

Figure 3. Variations in oxygen activity a_o in weld pool metal depending on the heat input in welding of steel in oxidising shielding gases: *1* — CO_2; *2* — Ar + 20 % CO_2

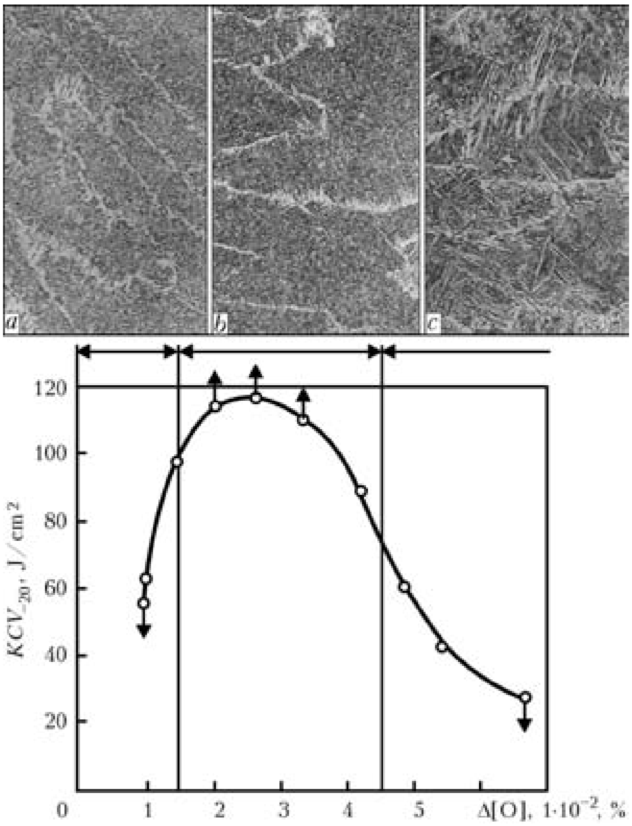

Figure 4. Effect of oxygen combined into chemical compounds, Δ[O], on impact toughness and microstructure (×200) of metal of the welds made in oxidising shielding gases: *a* — structure of acicular ferrite with bainite regions; *b* — structure with predominant acicular ferrite; *c* — grain-boundary ferrite and lamellar precipitates of Widmanstatten ferrite

0.020 S and P. Deviations of the oxygen concentration to higher or lower values from the said ranges were accompanied by decrease in the amount of acicular ferrite in structure of the weld metal.

The $\gamma \rightarrow \alpha$ transformation in the weld metal with a high oxygen content (0.06–0.07 %) occurred at higher temperatures of 720 to 680 °C, this being 20–30 °C higher than in the welds with the 0.045 % or lower oxygen content. Lowering of the transformation beginning temperature decelerated diffusion processes in the pearlitic transformation region. As a result, the major portion of austenite undergoes transformations by the shear mechanism to form finely dispersed acicular ferrite. It was found out that at an oxygen content of 0.015 to 0.045 % the structure of the weld metal contained 75–80 % of acicular ferrite (Figure 4, *b*). Electron microscopic examinations showed that the formed acicular phase was not bainite, as there were no characteristic precipitates of the carbide phase at the needle edges (Figure 5). The matrix surrounding a growing ferrite needle featured an increased density of dislocations.

Fine oxide particles with a size of less than 0.1 μm present in metal were nuclei of the ferrite phase in the bulk of austenitic grains, which was confirmed by the results of electron microscopic examinations (see Figure 5). Decrease in the acicular ferrite content of the welds with an oxygen concentration of less than 0.015 % (see Figure 4, *a*) can be explained by decrease in the quantity of the oxide particles, i.e. quantity of the ferritic phase nucleation centres. Depending on their quantity and size, such particles favour formation of this or other morphology of the ferritic phase [1] affecting the fine metal structure and, hence, its sensitivity to brittle fracture.

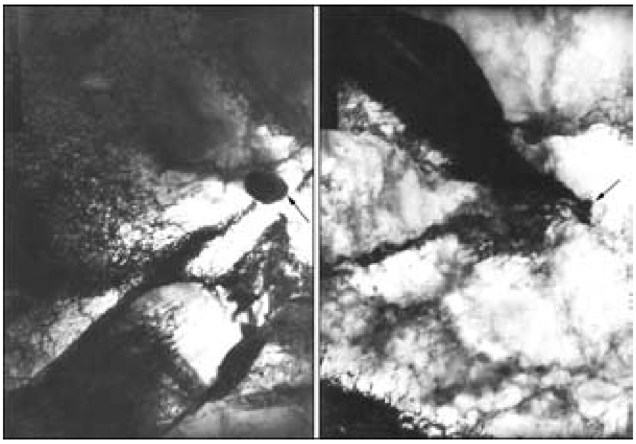

Figure 5. Microstructure (×13,200) of acicular ferrite in metal of the welds made in Ar + 20 % CO_2 mixture (arrows indicate to oxide inclusions connected to edge regions of ferrite needles)

Therefore, the quantitative data on the activity of oxygen in molten metal of the weld pool do not only make it possible to explain the phenomena taking place during welding, but also, which is more important, allow the scientifically substantiated planning of this or other effect. In particular, such data are extremely important for development of the schemes of alloying of new welding wires, selection of the optimal shielding gas–wire combinations, development of the technologies for welding of steels, and more reliable prediction of mechanical properties of the welds.

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