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INFLUENCE OF OXYGEN CONCENTRATION IN ARGON OF THE PROTECTIVE NOZZLE ON THE PROPERTIES AND COLOUR OF WELD SURFACE IN TIG WELDING OF TITANIUM

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The paper presents the results of investigations of the process of formation of a gas-saturated layer on the weld surface at accidental violation of the conditions of argon protection (under the nozzle) in TIG welding of VT1-0 titanium. It was found that the change of oxygen content in argon of the protective nozzle in the range from 0.024 to 1.18 vol.% leads to a change of the colour of a region of forming weld surface. It is shown that each colour corresponds to a certain depth of the gas-saturated layer that can be up to 0.25 mm. A correlation dependence of weld surface colour–gas-saturated layer thickness–oxygen content in the protective nozzle was established. Results of gas analysis and mechanical testing of the welds show that oxygen and nitrogen from the air in the argon of the protective nozzle practically do not interact with the molten metal of the weld pool during welding. Therefore, the quantitative characteristics of the metal of welds are on the level of those of the welds produced under standard conditions. To increase the operational reliability of welded assemblies with a coloured surface of a weld region, it is proposed to remove it, depending on its colour, to the depth in the range from 0.10 up to 0.25 mm. 9 Ref., 2 Tables, 6 Figures.

Keywords: argon-arc welding (TIG), VT1-0 titanium alloy, weld surface colour, violation of argon protection, weld metal properties

Tungsten electrode inert-gas (TIG) welding became widely accepted in industry for fabrication of titanium structures. The activity of titanium interaction with atmospheric gases, namely oxygen, nitrogen, carbon dioxide gas, moisture vapours, which are harmful impurities for titanium, becomes higher with increase of temperature. Noticeable absorption of oxygen by titanium begins already at the temperature of 300 °C, that of nitrogen — at 800 °C [1]. Oxygen solubility in α-phase can reach 34 at.%, that of nitrogen — 0.75 at.%, here the speed of titanium interaction with oxygen is 50 times higher than that of interaction with nitrogen [2]. High-temperature interaction of titanium with the air environment is accompanied by oxygen diffusion in-depth of the matrix and formation of solid solution of oxygen and nitrogen in titanium, which leads to pronounced distortion of the crystalline lattice and, as a result, to deterioration of mechanical characteristics of metal. The oxide layer which formed on the surface as a coarse acicular α′-phase, has higher hardness and brittleness [3]. Note that interstitial impurities not only have the strongest influence on titanium alloy weldability, but also promote delayed fracture of welded structures, in connection with formation of cold cracks in the welds and heat-effect zone (HAZ) [4, 5]. Therefore, in TIG welding special attention is given to reliable protection from contact with air not only of the weld pool molten metal, but also of the cooling welded joint [6]. To eliminate weld metal contamination by harmful impurities, in addition to application of high-purity argon, also welding torches and protective devices are used, which provide high-quality protection of the entire welded joint zone by inert gas. Correct selection of the ratio of argon flow rate to the welding torch and protective nozzle is important here. However, despite the high-quality protection, accidental violations of argon protection may occur during welding, both in the arc burning zone under the torch orifice, and in the zone of the cooling welded joint. Work [7] describes a method that allows revealing the violations of argon protection in the arc burning zone during welding and determining the degree of the influence of this violation on the weld mechanical properties. However, it is practically impossible to establish a violation of argon protection of the cooling weld surface, using such a procedure. Such a violation can be revealed only when the weld moves out from under the protective nozzle. When all the technological requirements to the welding process are followed, the weld surface has a silvery colour, while the change of the conditions of argon protection under the nozzle leads to a change of the weld surface colour, as a result of formation

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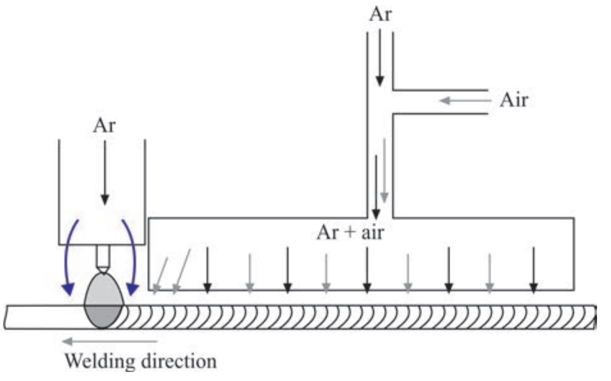


Figure 1. Scheme of air feeding into the protective nozzle

of an oxide-nitride layer of titanium on it. Such an effect is currently considered as a characteristic of the properties and performance of the welded joint. Thus, a standard was proposed, according to which the weld surface colour is the only characteristic for assessment of fitness for service of structures with such welds [8]. There is no information in publications on substantiation of quantitative assessment of the properties of the region of weld metal with a coloured surface. Therefore, investigation of the influence of random increase of oxygen content in the protective nozzle argon on the properties of weld metal at the change of its surface colour is an urgent problem. Its solution will allow creation of a data base: weld surface colour–weld metal properties, the objective of which is increasing the operational reliability of welded structure components, where coloured regions were revealed on the weld surface.

Procedure and materials. A package of methods was used for quantitative assessment of the influence of the concentration of interstitial impurities (oxygen and nitrogen) in the protective nozzle argon on weld metal properties, depending on the colour of their surface:

- spectral analysis;
- photographing the colour of weld surface;
- metallographic analysis;
- measurement of weld metal microhardness;
- determination of gas content in weld metal;
- mechanical tests of weld metal.

Table 1. Content of air (oxygen and nitrogen) in the protective nozzle argon, vol.%

Sample index	Air content	Oxygen content	Nitrogen content
1	0.12	0.024	0.09
2	0.19	0.038	0.14
3	0.37	0.074	0.28
4	0.48	0.096	0.37
5	0.60	0.120	0.46
6	1.10	0.220	0.85
7	1.60	0.320	1.24
8	2.24	0.440	1.74
9	5.90	1.180	4.60

Spectral analysis. Oxygen presence in the arc gap was determined by the intensity of radiation of oxygen atomic lines by the procedure, described in work [7]. A dosed amount of air was added to argon, coming to the protective nozzle. Air was fed to argon by the scheme shown in Figure 1.

An optimum ratio between argon flow rate to the torch and nozzle that ensures the required quality, was determined experimentally, trying to obtain the silver colour of the weld. Welding modes were as follows: welding current of 160 A, welding speed of 12 m/h, arc gap length of 1.5 mm. Argon flow rate to the torch was 12 l/min, to protective nozzle — 27 l/min. Air content in argon of the protective nozzle was varied in the range of 0.12–5.9 vol.%, here oxygen content changed in the range of 0.024–1.18 vol.% (Table 1). Welding was performed on 3 mm sheets of titanium alloy of VT1-0 grade. To ensure high-quality protection of the cooling HAZ metal, the distance from the protective nozzle plane to sheet surface was within 1.0–1.5 mm. Not less than three samples were welded at each value of air concentration, and the average value of radiation intensity of oxygen atomic lines was determined.

Photographing of weld surface was performed with digital camera of CANON model. Filming conditions (exposure, lighting, distance to weld surface) were the same for all the welded samples. After welding with each variant of oxygen concentration in argon of the protective nozzle, the weld surface was photographed to obtain the following correlation dependence: weld surface colour–weld metal properties.

Metallographic analysis. Increase of air content in argon of the protective nozzle leads to formation of oxide-nitride superfine films of different colour on the weld surface. The thickness of such films can be assessed by interference coloration [9]. Located under the colour film is metal with higher oxygen and nitrogen content, where the crystalline lattice is distorted and coarse acicular α′-phase is formed. Investigation of changes in microstructure in the surface layer of the metal of welds, made at fixed values of oxygen concentration in argon of the protective nozzle was performed in NEOPHOT-2 microscope.

Microhardness of the surface layer of weld metal was measured layer-by-layer by PMT-3 instrument at 50 g load. On the microsections a layer of a certain thickness was removed from the surface of weld made at each concentration of air in the protective nozzle, and not less than 10 measurements were taken in several regions of the microsection. Then the process was repeated, removing the metal layer with the measured hardness and hardness was measured again on the metal surface. Such a process was repeated until the values of weld metal hardness in the next layers practically did not change. For comparison, the same measurements were taken for the metal of welds made without air addition to the protective nozzle. The thus obtained data were used for plotting the following dependence: hardness of weld metal surface layer–distance from weld surface.

Content of gases (oxygen and nitrogen) was determined in the metal of welds at each concentration of air in the protective nozzle argon and without adding air to it. At assessment of the content of gases in the weld metal graphs were plotted by average values of the results for oxygen $[O]_{(Ar)}$ and nitrogen $[N]_{(Ar)}$ content in welds made in pure argon and welded at different concentrations of oxygen $[O]_{(Ar+air)}$ and nitrogen $[N]_{(Ar+air)}$ in the protective nozzle argon.

Mechanical testing of weld metal. To determine the ultimate strength and relative elongation of weld metal, samples for mechanical testing were cut out of the welds. A criterion for assessment of the properties of the metal of welds, made at addition of dosed air concentrations to argon, the values of ultimate strength and relative elongation in these welds were compared with the respective values of the metal of welds, produced at welding in argon without air addition. The results of mechanical testing and gas content in the metal of welds made without air addition in the protective nozzle, are given in work [7].

For static bend tests (10 mm width) samples were cut out across the weld, in keeping with Designation ASTM B265. Mandrel diameter D was selected from the condition $D = 5b$, where b is the sheet thickness ($b = 3$ mm). Before sample testing, grinding was used to remove the metal from the bead reverse side. Testing was followed by measuring the bend angle, as well as analyzing the weld surface for microcracks.

Investigation results. Oxygen presence in the arc gap was determined at the change of oxygen concentration in argon of the protective nozzle, in keeping with Table 1. As shown by investigations, despite an increase in oxygen content in argon of the protective nozzle (from 0.024 to 1.180 vol.%), no radiation of oxygen lines was found in the arc gap. It can be assumed that a certain part of the mixture of argon and air added to argon of the protective nozzle, is entrained due to injection by the peripheral part of the argon flow from the torch and is carried out without penetrating into the arc column. Another part is absorbed by the cooling solid surface of the forming weld and HAZ. It is also possible that part of oxygen molecules penetrates into the low-temperature regions of the arc, insufficiently dissociates and, that is why, no radiation of oxygen lines was registered in the arc.

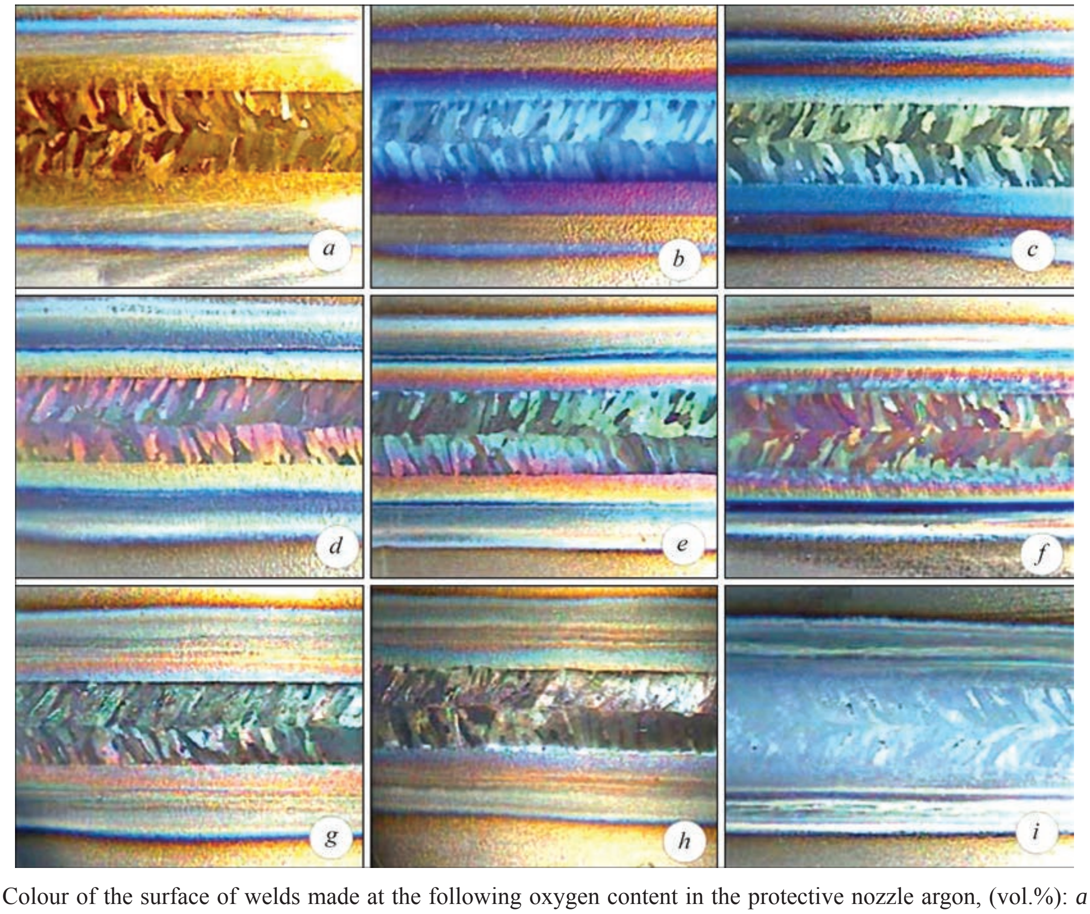


Figure 2. Colour of the surface of welds made at the following oxygen content in the protective nozzle argon, (vol.%): *a* — 0.024; *b* — 0.038; *c* — 0.074; *d* — 0.096; *e* — 0.120; *f* — 0.220; *g* — 0.320; *h* — 0.440; *i* — 1.180

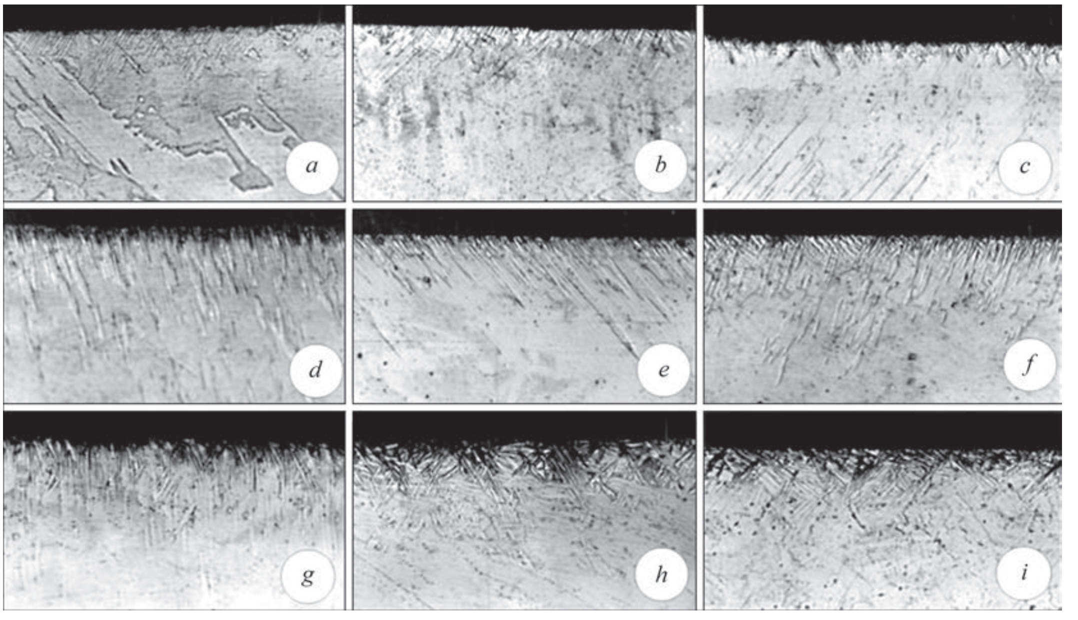


Figure 3. Microstructures (×250) of the surface layer of welds made at the following oxygen content in the protective nozzle argon (vol.%): *a* — 0.024; *b* — 0.038; *c* — 0.074; *d* — 0.096; *e* — 0.120; *f* — 0.220; *g* — 0.320; *h* — 0.440; *i* — 1.180

Analysis of the colour spectrum of the surface of weld metal led to the following conclusion. At increase of oxygen content in argon of the protective nozzle the weld surface colour changes from golden (0.024 vol.% oxygen) to grey-light blue (1.180 vol.% oxygen). Figure 2 shows the colours of weld surface, characteristic for each concentration value of air, which was added to the protective nozzle.

Microstructural analysis of surface layers of welds showed that at oxygen content of 0.024 vol.% in argon of the protective nozzle, a layer with thin acicular precipitates of not more than 0.012 mm depth forms on the weld metal surface (Figure 3, *a*). Such precipitates alternate with a structure typical for the metal of weld made in pure argon. At oxygen content of 0.038 vol.% in argon (Figure 3, *b*), a continuous layer with acicular structure of not more than 0.02 mm depth forms. Here, the needles have both the same and different direction relative to the surface. Such structural changes are associated with intensive absorption of oxygen and nitrogen in these regions of the metal. At further increase of oxygen content in argon up to 0.074 vol.% (Figure 3, *c*) the thickness of metal layer with an acicular structure also increases up to 0.05 mm. At 0.096 vol.% oxygen content in argon (Figure 3, *d*), the structure of the layer with an acicular morphology becomes inhomogeneous by the arrangement and size of the needles. Individual needles grow to the depth of 0.16 mm. Average depth of the layer is up to 0.07 mm. Further analysis of the microstructures shows that increase of oxygen content to 1.180 vol.% leads to increase of the depth of the layer with an acicular structure to 0.18–0.25 mm (Figure 3, *i*).

As a result of metallographic studies it was found that at air addition to the protective nozzle argon the surface layer of weld metal undergoes structural changes, associated with oxygen and nitrogen absorption. These changes occur to the depth of approximately 0.25 mm. No such structural changes were found in deeper lying regions of the weld.

The result of layer-by-layer measurement of weld metal microhardness for each value of oxygen concentration in the protective nozzle argon is shown in Figure 4. Comparison of the data given in Figures 3 and 4 leads to the conclusion that with increase of the quantity of air in the protective nozzle argon to 5.9 vol.% (1.18 vol.% oxygen) the depth of the metal surface layer with increased impurity content reaches approximately 0.20–0.25 mm.

Bending tests of the samples cut out across the weld without removing the surface layer, showed that bend angle is 180° for all the samples. It characterizes the metal as rather ductile. However, microcracks are found in the surface layer metal of all the samples (Figure 5).

Appearance of microcracks on the surface loaded by a tensile force, is attributable to low ductility of the metal surface layer, associated with increase of gas impurities in it. To assess the probable entrapment of air by the torch argon from protective nozzle argon and its absorption by weld pool metal, gas analysis of the weld metal was performed, and oxygen and nitrogen content was determined. Figure 6 gives the dependencies of the change of oxygen and nitrogen content in the welds on the concentration of these gases in the protective nozzle argon. Comparison of the obtained gas analysis results shows that with increase of air concentration in the protective nozzle argon, oxygen and nitrogen content in the weld metal stays practically within the same limits, as in welds, made in pure argon. These data lead to the conclusion that air addition to the protective nozzle argon within the studied limits does not increase the content of gases in welds. Therefore, it can be assumed that during welding the molten metal of the weld pool practically does not interact with oxygen and nitrogen of the air added to the protective nozzle argon.

To determine the influence of oxygen concentration in the protective nozzle argon on the strength and relative elongation of weld metal, flat samples were cut out for testing, locating them along the weld axis and removing 0.25 mm from the surface. Results of mechanical testing of the welds showed that despite an increased concentration of air in the protective nozzle argon in the studied range, the ultimate strength and relative elongation of weld metal (σ_t = = 456.9–451.4 MPa, β = 35.7–35.4 %) remain in the same ranges, as in welds, made in pure argon (σ_t = = 453.0 MPa, δ = 36.0 %).

Discussion of the results. Investigations showed that the colour of weld surface after welding depends on oxygen and nitrogen content in the protective nozzle argon. Results of investigations of the microstruc-

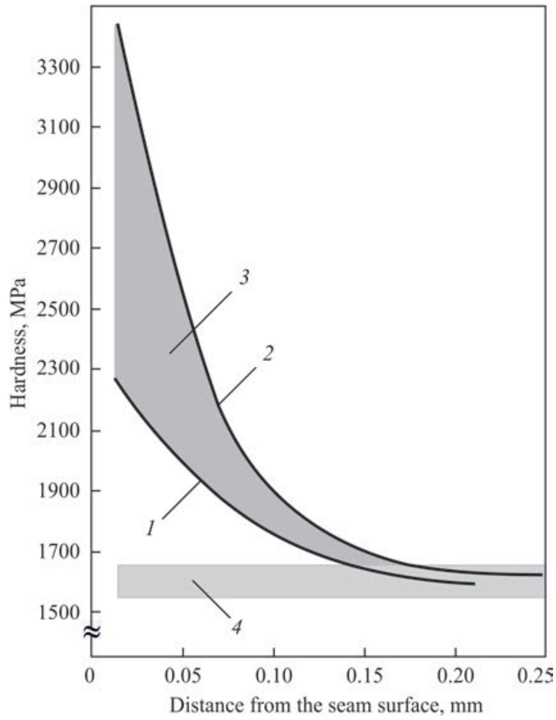


Figure 4. Microhardness of surface layers of the metal of welds made at the following oxygen content in the protective nozzle argon (vol.%): *1* — 0.024; *2* — 1.18; *3* — microhardness zone at oxygen content in the range of 0.038–0.440; *4* — zone of microhardness of the surface layer of a weld made without adding air to the protective nozzle argon

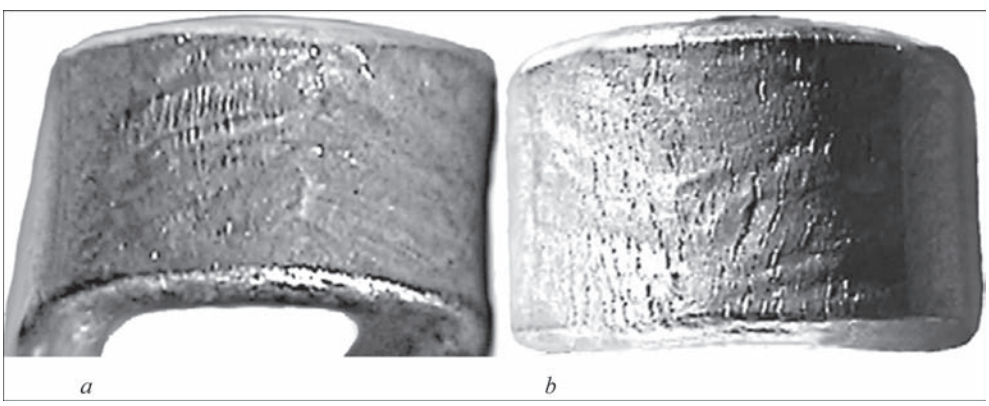


Figure 5. Microcracks on the surface of samples welded at the following oxygen content in the protective nozzle argon (vol.%): *a* — 0.024; *b* — 1.18

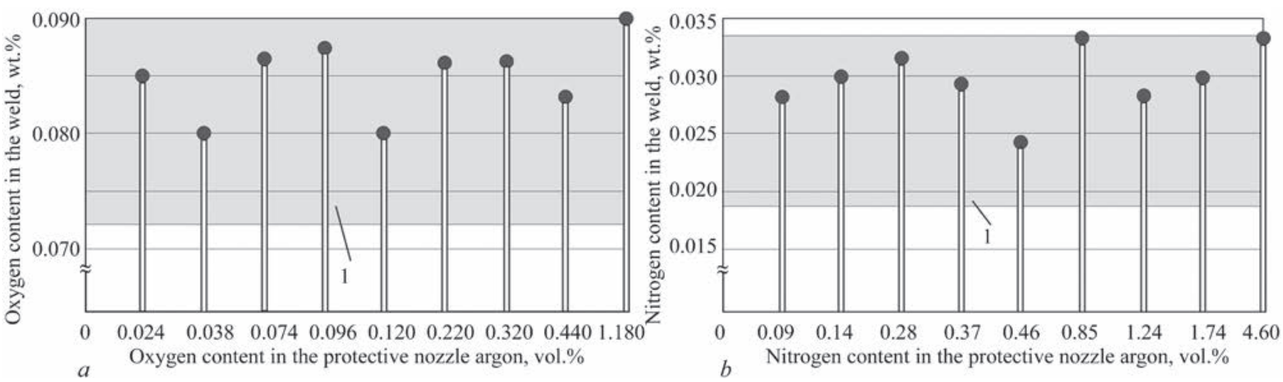
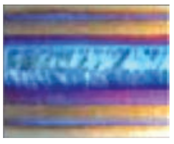
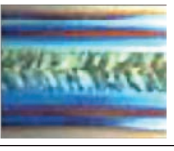
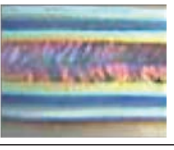
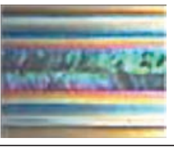
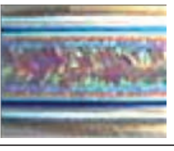
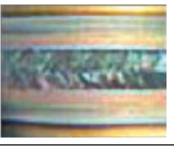


Figure 6. Content of oxygen (*a*) and nitrogen (*b*) in the welds, depending on the content of these gases in the protective nozzle argon: 1 — range of oxygen and nitrogen content in welds made without adding air to the protective nozzle argon

Table 2. Correlation dependence of weld surface colour–gas-saturated layer thickness–oxygen content in the protective nozzle

Weld index	Weld surface colour	Oxygen content in the protective nozzle argon, vol.%	Maximum thickness of a layer of higher hardness, mm
1		0.024	0.10
2		0.038	0.10
3		0.074	0.10
4		0.006	0.10
5		0.120	0.12
6		0.220	0.20
7		0.320	0.25
8		0.440	0.25
9		0.180	0.25

ture and layer-by-layer measurement of microhardness of the weld surface layer show a good matching of the data on the intensity of gas-saturated layer depth, depending on the weld surface colour. Thus, an experimental correlation was established between the change of weld surface colour and gas-saturated layer depth (Table 2).

Maximum depth of this layer is equal to not more than 0.25 mm. Investigations of bending test samples show that even at minimum content of oxygen in the protective nozzle argon (0.024 %) and golden colour of the weld surface (see Figure 2, *a*), microcracks form in it, which at the welded assembly operation under load can lead to its destruction, because of the surface layer brittleness.

Analysis of the results of gas analysis and mechanical testing of welds shows that oxygen and nitrogen of the air in the protective nozzle argon practically do not interact with the weld pool metal during welding. Therefore, in order to increase the operational reliability of welded structure assemblies with a coloured surface of a weld region, we can recommend removal of the gas-saturated layer to a depth, depending on weld colour, in keeping with the data in Table 2. If required, compensation of the removed metal by building-up is possible after removal of a layer, in keeping with the technological instructions.

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