

This paper considers a possibility to obtain high-quality butt junctions of bimetallic sheets from steel clad with a layer of titanium, with the use of barrier layers. The task that was tackled related to preventing the formation of Ti-Fe intermetallic phases (IMPs) between the steel and titanium layer. The barrier layers (height ~0.5 mm) of vanadium and copper alloys were surfaced by arc techniques while minimizing the level of thermal influence on the base metal. To this end, plasma surfacing with a current-driving wire and pulsed MAG surfacing were used. The obtained samples were examined by methods of metallography, X-ray spectral microanalysis, durometric analysis. It has been established that when a layer of vanadium is plated on the surface of titanium, a defect-free structure of variable composition (53.87–65.67 wt % Ti with (33.93–45.54) wt % V is formed without IMPs. The subsequent surfacing of steel on a layer of vanadium leads to the formation of eutectics (hardness up to 5,523 MPa) in the fusion zone, as well as to the evolution of cracks. To prevent the formation of IMPs, a layer of bronze CuBe₂ was deposited on the surface of vanadium. The formed layer contributed to the formation of a grid of hot cracks. In the titanium-vanadium-copper transition zones (0.1–0.2 mm wide), a fragile phase was observed. To eliminate this drawback, the bronze CuBe₂ was replaced with bronze CuSi₃Mn₁; a defect-free junction was obtained. When using a barrier layer with CuSi₃Mn₁, a defect-free junction was obtained (10–30 % Ti; 18–50 % Fe; 5–25 % Cu). The study reported here makes it possible to recommend CuSi₃Mn₁ as a barrier layer for welding bimetallic sheets “steel-titanium”. One of the applications of the research results could be welding of longitudinally welded pipes of main oil and gas pipelines formed from bimetallic sheets of steel clad with titanium

Keywords: steel-titanium bimetal, barrier layer, structure, intermetallic phases, interface boundary

ANALYZING METALLURGICAL INTERACTION DURING ARC SURFACING OF BARRIER LAYERS ON TITANIUM TO PREVENT THE FORMATION OF INTERMETALLICS IN TITANIUM-STEEL COMPOUNDS

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Received date 19.08.2021

Accepted date 22.10.2021

Published date 29.10.2021

How to Cite: Korzhyk, V., Khaskin, V., Grynyuk, A., Ganushchak, O., Shcheretskiy, V., Peleshenko, S., Konoreva, O., Demianov, O., Fialko, N., Kvasnytskyi, V. (2021). Analyzing metallurgical interaction during arc surfacing of barrier layers on titanium to prevent the formation of intermetallics in titanium-steel compounds. *Eastern-European Journal of Enterprise Technologies*, 5 (12 (113)), 69–82. doi: <https://doi.org/10.15587/1729-4061.2021.240154>

1. Introduction

Clad bimetallics are used in the manufacture of various articles in the modern industry [1]. A steel layer is often

used in such metals in order to achieve structural strength, and a titanium layer is applied for corrosion resistance. Typically, bimetallic sheets of the steel-titanium class are obtained by hot rolling or cladding by explosion [2]. There

is a task of manufacturing welded pipes from these sheets for main oil and gas pipelines [3]. The presence of titanium and steel layers in combination with the requirements for the strength and corrosion resistance of welded junctions predetermines a series of issues. First of all, the emergence of hard and fragile Fe-Ti intermetallics contributing to the cracking and destruction of junctions [4]. It is a relevant task to devise manufacturing techniques for welding sheets of titanium-clad steel, which, at relatively low costs, would make it possible to obtain structures of the required quality.

2. Literature review and problem statement

Paper [4] investigated the issues related to welding butt junctions of sheets of steel clad with a layer of titanium. The study results showed that the main problem of reducing the strength with the simultaneous melting of steel and titanium is the danger of the formation of intermetallic phases such as Fe_2Ti and FeTi . Such phases have high hardness and fragility. They lead to a decrease in the strength of the welded junction and the formation of cracks in the fusion zone, which causes its destruction. To eliminate this problem, work [5] recommended using barrier layers. It is shown that the creation of such layers between steel and titanium protects against the mixing of these two metals during welding.

This approach was reported in [6]. In it, when welding the titanium Ti6Al4V alloy and the stainless steel SS316, in order to eliminate the formation of brittle Ti-Fe intermetallics, it was proposed to use a barrier layer of several (three) metals. To make a compound, V, Cr, and Fe were deposited layer-by-layer on the alloy Ti6Al4V using laser powder cladding (LMD). The resulting transient composition $\text{Ti6Al4V} \rightarrow \text{V} \rightarrow \text{Cr} \rightarrow \text{Fe} \rightarrow \text{SS316}$ avoided the appearance of intermetallic phases between Ti6Al4V and SS316. Note that the use of laser radiation for welding bimetallic junctions is not always economically justified. It is possible to improve the economic indicator by partially replacing laser energy with cheaper arc energy through the use of hybrid laser-arc processes [7].

However, an increase in the number of applied layers increases the time of manufacture of the compound, and, at the same time, increases its cost. In work [8], to connect the titanium alloy PT-3V with the stainless steel 08H18N10T, it is proposed using an intermediate layer of ultrafine nickel powder. That makes it much easier to obtain a compound. However, the diffusion welding used in this case has low productivity. A significant increase in productivity can be achieved by explosion welding [9]. However, this welding technique can be used only for a very limited number of tasks – mainly for the manufacture of transition elements. Thus, it is desirable to use a single- or double-layer barrier layer applied by a simple, high-performance, and widely affordable method.

To improve the efficiency of the process of obtaining non-detachable junctions of bimetallic sheets “steel-titanium”, it is advisable to take the following steps:

- choose an affordable and inexpensive way of applying the barrier layer;
- choose an affordable and economically acceptable material (or materials) of the created layer;
- to work out manufacturing techniques that make it possible to apply a barrier layer with maximum productivity.

The most affordable and inexpensive techniques of applying barrier layers are methods of arc surfacing [10]. Their use for surfacing barrier layers requires minimizing the level of thermal influence on the base metal. Therefore, it is desirable to exclude or reduce the presence of a cathode or anode spot and the time of its existence [11]. One of the ways to achieve this result is the use of plasma cladding with current-carrying wire [12]. To reduce the thermal effect on the base metal, it is advisable, in this case, to use a plasma-forming nozzle that has a larger diameter compared to the diameter of the nozzle of standard PAW surfacing [13]. Another way to reduce heat input when applying barrier layers can be the use of pulsed MAG surfacing [14]. Both techniques were used in the described experimental studies.

Titanium is satisfactorily welded with a limited number of metals, namely zirconium, hafnium, niobium, tantalum, and vanadium [5]. Of these metals, only vanadium during welding with steel (iron) forms a continuous series of solid solutions, and, therefore, can be used as a barrier layer material (Fig. 1). It provides suppression of the formation of fragile intermetallics of titanium with iron in the molten state. Studies [15] show that Ti and Fe form solid solutions with V; in the transition zone of contact, there is a solid solution of variable concentration, which is characterized by increased hardness compared to the hardness of the welded metals.

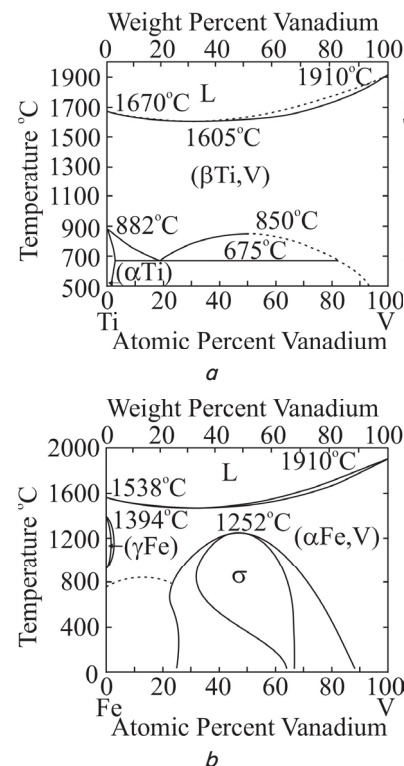


Fig. 1. State diagrams: *a* – Ti with V; *b* – Fe with V [15]

For a more detailed study of the issue of metallurgical interaction of vanadium with titanium and steel in welding processes using plasma cladding with current-carrying wire and pulsed P-MAG surfacing, it is necessary to conduct a series of relevant experiments. Taking into consideration the melting points of vanadium (1,910 °C) and carbon steel (about 1,450–1,520 °C), it is advisable to use methods different in the concentration of the thermal source for surfacing the barrier layer on titanium and layers of steel on the barrier layer [16]. For the application of vanadium, plasma cladding with cur-

rent-carrying wire is more suitable, and for steel layers – pulsed surfacing with an arc of a melting electrode (P-MAG).

3. The aim and objectives of the study

The purpose of this study is to identify the features of the metallurgical interaction of various metals with titanium and steel, as the basis for effective arc surfacing of barrier layers formed when obtaining high-quality butt junctions of bimetallic sheets of steel clad with a layer of titanium.

To accomplish the aim, the following tasks have been set:

- surfacing of vanadium layer on titanium and study of the obtained samples;
- surfacing of vanadium layer on steel and study of the obtained samples;
- welding of steel on a layer of vanadium, previously deposited on titanium, and the study of the samples obtained;
- sequential cladding of vanadium and bronze interlayers on titanium, followed by the cladding of steel (compound “titanium – vanadium – bronze – steel”), a study of the samples obtained;
- cladding of a bronze layer on titanium followed by the cladding of steel, study of the obtained samples.

tative formation of the weld bead. Surfacing was performed by pulsed MAG (P-MAG) and plasma techniques.

4. 2. Sample surfacing procedure

Multi-pass surfacing was performed on a plate of the titanium VT1-0 with a thickness of 2 mm or carbon steel of type Q235 with a thickness of 10 mm (Table 1). To reduce heat input, the height of the weld bead was minimized when applying the barrier layer and the subsequent steel layer. Plasma cladding with current-carrying wire and/or P-MAG surfacing were used [12–14]. To improve the quality of the formation of weld beads, transverse vibrations of the welding torch were used.

The material of the layer in the form of a wire with a diameter of 1.0 mm of vanadium (V-2, Table 1) and bronze CuSi3Mn1 and CuBe2 (Table 1) was applied by plasma cladding with current-carrying wire on the titanium (material, VT1-0, $\delta=2.0$ mm) and steel (steel Q235, $\delta=10$ mm) plates. On top of the layer welded on a titanium plate, ER70S-6 wire ($\varnothing 1.0$ mm, Table 1) was welded using the P-MAG technique. The criteria for obtaining beads of surfaced metals were the quality of their formation, the absence of cracks, and geometric parameters (height and width).

Table 1

Chemical composition of the materials used

Material	Elemental content, wt %											
	Fe	Ti	C	Si	Mn	Ni	Cr	Cu	Al	V	P	S
Sample's base metal												
Steel Q235	base	–	0.14–0.22	0.05–0.15	0.4–0.65	<0.3	<0.3	<0.3	–	–	<0.04	<0.05
Titanium VT1-0	<0.25	Base	<0.07	<0.1	–	–	–	–	–	–	–	–
Surfacing (filler) wires												
ER70S-6 ($\varnothing 1.0$ mm)	base	–	<0.08	0.7–0.95	1.8–2.1	<0.25	<0.2	<0.25	–	–	<0.03	<0.025
V-2 ($\varnothing 1.0$ mm)	<0.2	–	0.02	0.004	–	–	<0.2	–	<0.1	Base	Remaining: O ₂ 0.035; N ₂ 0.01	
CuSi3Mn1 ($\varnothing 1.0$ mm)	<0.3	–	–	2.7–3.5	1.01.5	<0.2	–	base	–	–	Remaining: Zn<0.5; Sn<0.25	
CuBe2 ($\varnothing 1.0$ mm)	0.15	–	–	0.15	–	0.2–0.5	–	base	0.15	–	Remaining: Be 1.8–2.1; Pb<0.005	

4. The study materials and methods

4. 1. The study's object and hypothesis

The object of research was the metallurgical interaction during arc surfacing between the metal of the barrier coating (vanadium, bronze CuBe2, and Cu-Si3Mn1), as well as the titanium VT1-0 and steel of type Q235 (components of the bimetallic sheet titanium – steel). In this case, the barrier coating should be deposited on titanium (sheet thickness, 2 mm) with a subsequent cladding of steel (thickness, up to 10 mm).

The main hypothesis of our study was the assumption that the use of a barrier coating of one or two of these metals during arc surfacing would avoid the formation of fragile Fe-Ti intermetallic phases. At the same time, a defect-free transition zone would be formed between titanium and steel, having a width ranging from 0.1 to 1.0 mm. In such a zone, blurring and fuzzy expressions of the boundaries of metal fusion are permissible. However, it is mandatory to have a metallurgical contact (fusion) of barrier layers with layers of titanium and steel.

To simplify the experiments, the barrier layers were welded onto titanium plates (2 mm thick) and steel (10 mm thick). In the case of satisfactory results, after surfacing the barrier coating on titanium, a layer of steel (about 1–2 mm thick) was welded into one run. Satisfactory results of surfacing the barrier coating were the absence of cracks in it and the quali-

4. 3. Metallographic study procedure

To conduct metallographic analysis, transverse templates were cut from the deposited samples and micro sections were made. At the same time, chemical etching with a 4 % alcohol solution of HNO₃ and electrolytic etching with chromic acid or a 20 % solution of ammonium sulfate were used. The obtained samples were examined by methods of optical (microscope Neophot-31) and electron (microscope CamScan-4) microscopy. The distribution of components in the fusion zone and in the deposited metal, as well as the presence and composition of intermetallic phases, were determined using X-ray spectral microanalysis (XSMA), performed at the CAMEBAX microanalyzer, and electron probe analysis, performed at the CamScan-4 electron microscope. Microdurometric analysis of the deposited samples was carried out at a LECO microhardness tester with a measurement step of 10 μ m at a load of 20 g.

5. The results of studying the metallurgical interaction of metal barrier layers with titanium and steel

5.1. Surfacing of vanadium layer on titanium and studying the samples obtained

The surfacing of vanadium wire on a titanium plate was carried out by a plasma technique by a direct-action arc (the anode is a welded sample). This technology uses a more concentrated source and provides a more controlled heat input compared to the argon-arc surfacing. This is important to minimize the heating of bimetal sites in the zone of thermal influence of the weld bead and prevent the formation of intermetallics at the titanium-steel boundary. For surfacing, we used the filler vanadium wire V-2 (Ø1.0 mm, Table 1) and a plasma-forming nozzle with a diameter of 2 mm. To increase the width of the weld bead, we used transverse vibrations of the plasmatron with a wire positioner fixed on it. Cladding modes are given in Table 2. In the first case, the surfacing was performed without protection of the tail part of the seam (Fig. 2), and in the second – with protection (Fig. 3).

The vanadium layer on sample No. 1 (Table 2) is fairly uniform (Fig. 2, a). Metallographic and micro X-ray spectral studies of the resulting vanadium-titanium junction show that a structure of the variable chemical composition is formed in the

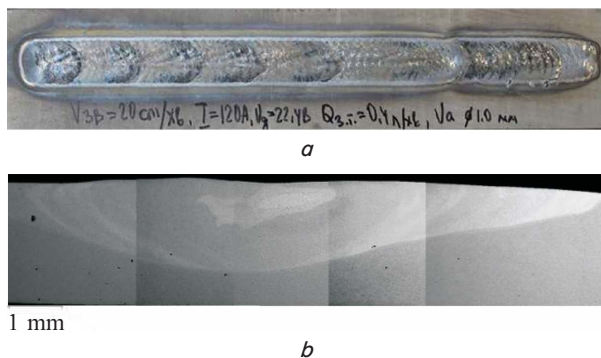


Fig. 2. Ti-V junction (sample No. 1, Table 2): a – general view; b – macrostructure

fusion zone (Fig. 4, 5, Table 3). As a result of the mutual diffusion of elements at the interface in the study area, the transition zone is a continuous series of solid solutions of Ti with V of variable composition: (70.54–77.83) % Ti and (28.3–21.89) % V. X-ray spectral microanalysis (XSMA) detected diffusion zones of significant size without the formation of intermetallic phases. On the titanium side, it has a structure characteristic of the α -Ti phase, and on the vanadium side, a layer doped with titanium. Fragile phases at the junction boundary and in the transition zone are not formed. The interface between vanadium surfacing and titanium is defect-free.

Our study of surfacing on sample No. 1 (Table 2) showed that due to the high chemical activity of titanium when interacting with atmospheric air, it is advisable to strengthen the gas protection of the hot part of the seam. Therefore, when

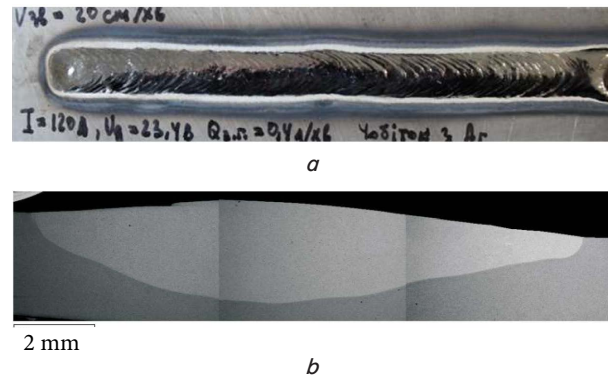


Fig. 3. Ti-V junction (sample No. 2, Table 2): a – general view; b – macrostructure

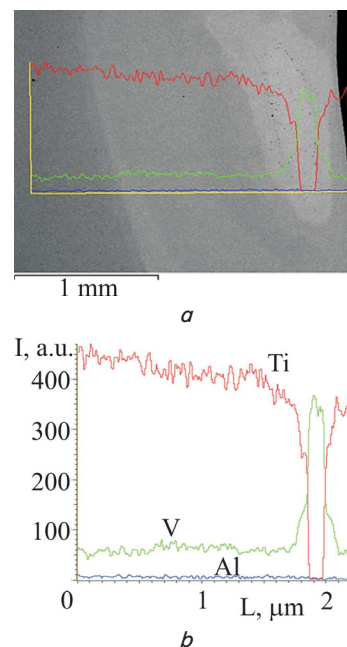


Fig. 4. Transition zone of a Ti-V junction: a – microstructure; b – distribution of components (electron probe analysis CamScan-4)

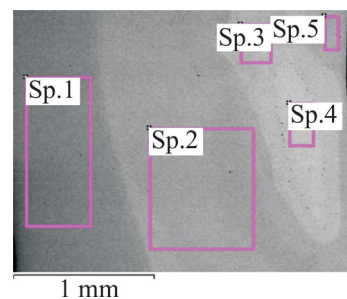


Fig. 5. Local sites for determining the content of elements in the transition zone Ti-V (sample No. 1, Table 2) by X-ray spectral microanalysis (XSMA)

Table 2

Modes of cladding the vanadium wire V-2 on a titanium plate

Sample No.	Welding current, A	Arc voltage, V	Gas	Plasma-forming gas flow rate, l/min	Protective gas flow rate, l/min	Shield gas consumption, l/min	Blowing gas consumption, l/min	Welding speed, mm/min	Wire feed speed, m/min	Oscillation amplitude, mm	Oscillation speed, mm/s
1	120	22.4	Ar	0.4	25	–	30	200	0.5	4	40
2	120	23.4	Ar	0.4	25	30	30	200	0.5	4	40

surfacing sample No. 2 (Table 2), such protection was applied. It was determined (Fig. 6, 7, Table 4) that a narrow crystallization interval contributes to the hardening of the metal with a slight change in composition: Ti (78.73; 78.14; 78.49) wt % and V (20.96; 21.54; 21.24) wt %. That created favorable conditions for obtaining a homogeneous surfacing of the metal throughout the cross-section in the junction. The level of microhardness in the surfacing area increases on average from 2,500 MPa to 3,750 MPa (Fig. 8). This effect is likely due to the hardening of vanadium due to the dissolution of titanium.

Thus, the cladding of vanadium on titanium with the use of additional gas protection performed according to the described technology can be considered successful.

Table 3

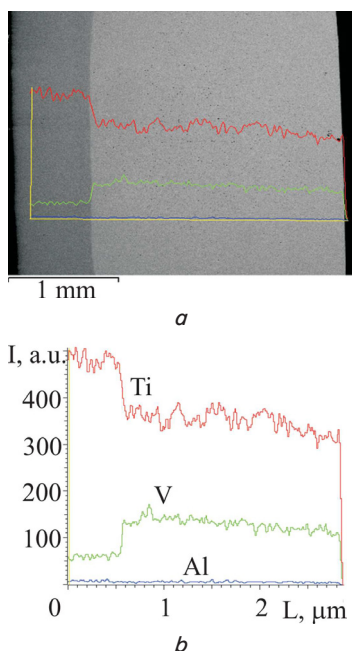


Fig. 6. Transition zone of a Ti-V junction: *a* – microstructure; *b* – distribution of components (electron probe analysis CamScan-4)

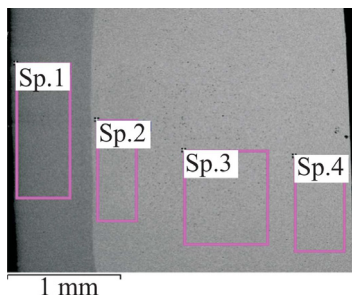


Fig. 7. Local areas for determining the content of elements in the transition zone Ti-V (sample No. 2, Table 2) by X-ray spectral microanalysis (XSMA)

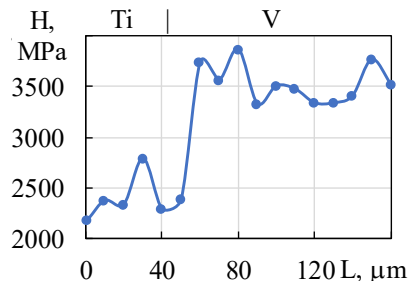


Fig. 8. Microhardness distribution in the Ti-V junction zone

The content (wt. %) of elements in local areas of the transition zone Ti-V (Fig. 5), determined by X-ray spectral microanalysis (XSMA)

Spectrum	Chemical composition, wt %				Total
	Al	Ti	V	Fe	
Spectrum 1	0.42	99.58	–	–	100
Spectrum 2	0.45	95.44	2.9	1.21	100
Spectrum 3	0.34	89.08	9.33	1.25	100
Spectrum 4	–	–	100	–	100
Spectrum 5	0.35	93.92	4.16	1.58	100

Table 4

The content (wt. %) of elements in local areas of the Ti-V transition zone (Fig. 7), determined by X-ray spectral microanalysis (XSMA)

Spectrum	Chemical composition, wt %			
	Al	Ti	V	Total
Spectrum 1	0.43	99.57	–	100
Spectrum 2	0.31	78.73	20.96	100
Spectrum 3	0.32	78.14	21.54	100
Spectrum 4	0.27	78.49	21.24	100

5. 2. The surfacing of a vanadium layer on steel and study of the samples obtained

The application of vanadium on a steel plate of the Q235 grade (Table 1) with a thickness of 8 mm was performed by plasma cladding, similar to Table 2. For cladding, we used the filler vanadium wire V-2 (Ø1.0 mm, Table 1) and a plasma-forming nozzle with a diameter of 2 mm. The wire positioner was fixed on the plasmatron and, together with it, executed transverse oscillations in the process of cladding. The cladding mode is given in Table 5; the general view of the resulting track is shown in Fig. 9.

The microstructure of the surfacing metal with different vanadium content in the surfacing metal is shown in Fig. 10, 11. Metallographic studies have shown that at the border of fusion of steel with vanadium there is a formation of cracks. There is also fine micro-porosity. At the vanadium-steel boundary, there is a zone of mutual diffusion of the following composition: 47.7 % Fe and 52.3 % V (Fig. 11, Table 6).

Table 5

Cladding mode of the vanadium wire V-2 on the Q235 steel plates

Welding current, A	Arc voltage, V	Gas	Plasma-forming gas flow rate, l/min	Protective gas flow rate, l/min	Boat gas consumption, l/min	Blowing gas consumption, l/min	Welding speed, mm/min	Wire feed speed, m/min	Oscillation amplitude, mm	Oscillation speed, mm/s
150	–	Ar	0.4	25	30	30	200	0.5	4	40

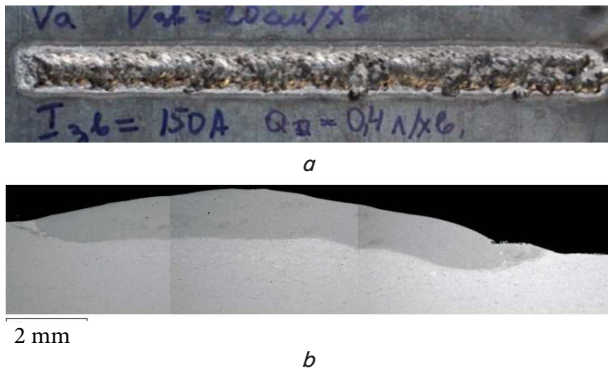


Fig. 9. Surfacing the vanadium wire V-2 on a plate of steel, the type of Q235: *a* – general view; *b* – macrostructure

Metallographic analysis showed that in the structure of the transition zone of fusion along the entire perimeter of the steel side, a section of metal enriched with vanadium is formed, which is a solid solution of vanadium in steel. As it follows from the Fe-V state diagram [14], there is a possibility of the formation of fragile intermetallics. Limiting the content of vanadium in the metal (up to 8–10 %) prevents their formation in the fusion zone along the boundary of the compound. According to the state diagram, the content of vanadium above the critical value of 15 wt % in the composition of the metal is theoretically dangerous. With an increase in the content of vanadium in the seam, a fragile phase is released. A significant increase in the content of vanadium in the surfacing metal (in our case, from 42.57 to 75.77 wt %, Fig. 11, Table 6) leads to cracks at the steel-vanadium interface. To create a defect-free compound of vanadium with steel, it is necessary to use a layer that prevents the formation of a fragile phase in the fusion zone.

The analysis of the microhardness distribution was performed according to the height of the deposited samples in increments of 5 μm (Fig. 12).

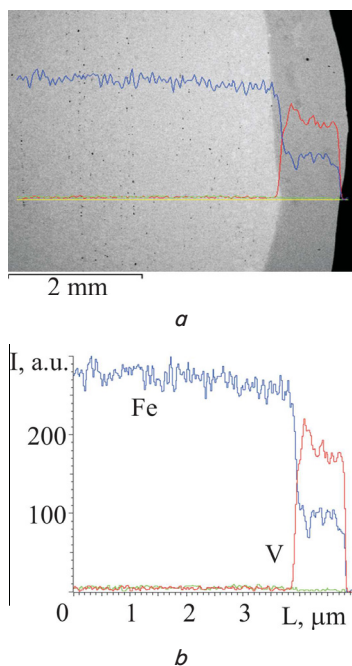


Fig. 10. Transition zone of the V-Fe junction: *a* – microstructure; *b* – distribution of components (electron probe analysis CamScan-4)

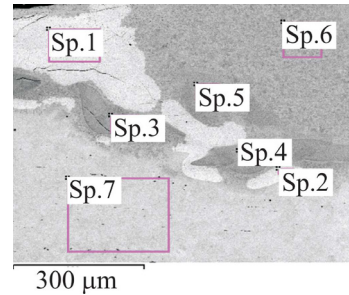


Fig. 11. Local sites for determining the content of elements in the transition zone V-Fe (sample No. 1, Table 5) by X-ray spectral microanalysis (XSMA)

Table 6

Content (wt %) of elements in local areas of the transition zone V-Fe (Fig. 11), determined by X-ray spectral microanalysis (XSMA)

Spectrum	Chemical composition, wt %			
	V	Mn	Fe	Total
Spectrum 1	42.57	–	57.43	100
Spectrum 2	42.83	–	57.17	100
Spectrum 3	75.77	–	24.23	100
Spectrum 4	74.9	0.2	24.9	100
Spectrum 5	65.14	–	34.86	100
Spectrum 6	52.3	–	47.7	100
Spectrum 7	–	–	100	100

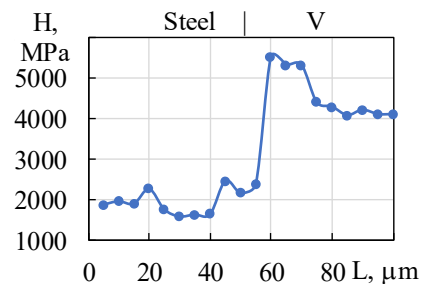


Fig. 12. Microhardness distribution in the steel-vanadium junction zone

It was found that the solid solution along the fusion line in the transition zone of variable concentration is characterized by increased hardness compared to the hardness of the welded metals (vanadium and steel) and is up to 5,523 MPa.

5. 3. Surfacing of steel on a layer of vanadium, previously deposited on titanium, and the study of the samples obtained

On a pre-scraped titanium plate with a thickness of 2 mm, layer No. 1 of vanadium with transverse vibrations of the welding head was surfaced. Next, the layer No. 2 of steel was surfaced on top of layer No. 1 (Table 7):

- layer No. 1: indirect arc plasma surfacing of the current-carrying vanadium wire-anode V-2 (Ø1.0 mm, Table 1); plasma-forming nozzle diameter, 4 mm; dimensions of the resulting bead: width, 8.5 mm, height 0.75 mm;

- layer No. 2: pulsed MAG surfacing with the steel wire ER70S-6 (Ø1.0 mm, Table 1); dimensions of the resulting bead: width 8.5 mm, height 2.7 mm.

The method of plasma surfacing of layer No. 1 by an indirect arc with the current-carrying vanadium wire-anode V-2 on a plate of titanium VT1-0 was chosen from the standpoint

of minimizing heat input in order to prevent the formation of intermetallic phases. For the same purpose, a plasma-forming nozzle of Ø4 mm was chosen. The choice of pulsed MAG surfacing of layer No. 2 with the steel wire ER70S-6 on top of the deposited layer V-2 was associated with the need to increase productivity while maintaining a relatively low heat input.

Several samples were involved under different energy modes (Table 7). In all samples, cracks were observed in the root part of the steel layer (near the vanadium-steel interface). As a typical example, Fig. 13 shows the general view and cross-section of sample No. 2.

Iron additions to the Ti-V compound showed a negative effect on the strength of the junction. Fe and V, soluble in the liquid state, which do not have mutual solubility in the solid state, form eutectics. The microstructure is a solid solution with the formation of eutectics (Fig. 14, 15). When the iron content in the surfacing metal is exceeded by 27.42 % to 43.25 % (Table 8), due to excessively intensive mixing of the melt of steel and vanadium in almost all surfacing modes, cracking is observed.

Especially pronounced is the formation of cracks at the periphery of the junction. This may be due to the deterioration of the heat sink conditions in the metal of the weld bead.

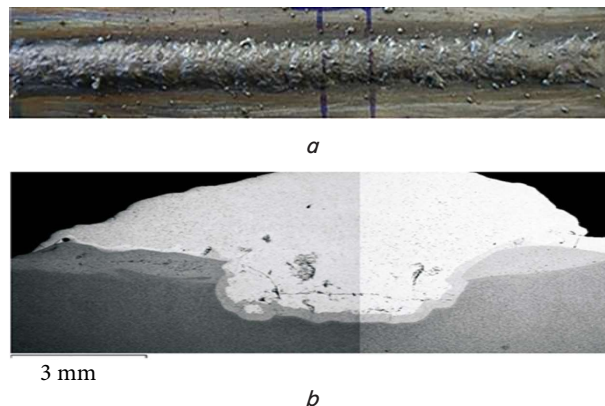


Fig. 13. Surfacing the vanadium wire V-2 and steel on titanium (sample No. 2, Table 7): *a* – general view; *b* – macrostructure



Fig. 14. Transition zone of the Ti-V-Fe junction: *a* – microstructure; *b* – distribution of components (electron probe analysis CamScan-4)

Table 7

Modes of surfacing layer No. 1 of the vanadium wire V-2 on titanium and layer No. 2 of the wire ER70S-6 on layer No. 1

Sample No.	Surfacing Layla No.	Welding current, A	Arc voltage, V	Gas	Plasma-forming gas consumption, l/min	Shielding gas consumption, l/min	Boat gas consumption, l/min	Blowing gas consumption, l/min	Welding speed, cm/min	Wire feed speed, m/min	Amplitude of vibrations, mm	Oscillation speed, mm/s
1	1	80	20	Ar	0.6	25	30	30	200	0.7	6	40
	2	45	14.5	82 % Ar+ +18 % CO ₂	–	25	–	–	200	2.1	4	40
2	1	85	20	Ar	0.6	25	30	30	20	0.7	7	40
	2	45	14.5	82 % Ar+ +18 % CO ₂	–	25	–	–	20	2.1	3	40
3	1	120	22.4	Ar	0.4	25	–	30	200	0.5	4	40
	2	120	16	Ar	0.4	25	–	30	200	0.5	4	40

Table 8

The content (wt %) of elements in local areas of the transition zones Ti-V-Fe (Fig. 15), determined by X-ray spectral microanalysis (XSMA)

Sample No. 3 in a zone in Fig. 15, <i>a</i>						Sample No. 3 in a zone in Fig. 15, <i>b</i>							
Spectrum	Chemical composition, wt %					Spectrum	Chemical composition, wt %						
	Si	Ti	V	Fe	Total		Al	Si	Ti	V	Mn	Fe	Total
Spectrum 1	–	100	–	–	100	Spectrum 1	0.33	0.12	53.82	17.92	0.39	27.42	100
Spectrum 2	0.39	67.75	31.85	–	100	Spectrum 2	0.22	0.45	37.71	21.57	0.62	39.44	100
Spectrum 3	0.5	67.56	31.94	–	100	Spectrum 3	0.15	0.2	48.26	8.01	0.14	43.25	100
Spectrum 4	0.51	51.25	16.45	31.78	100	Spectrum 4	0.2	0.42	55.73	10.08	0.2	33.37	100
–	–	–	–	–	–	Spectrum 5	0.16	0.52	40.41	21.02	0.52	37.37	100
–	–	–	–	–	–	Spectrum 6	0.29	0.28	49.12	17.62	0.43	32.26	100

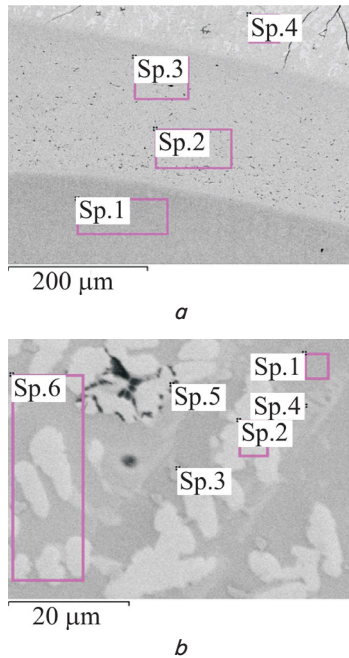


Fig. 15. Determining the content of elements in the transition zones Ti-V-Fe (sample No. 3, Table 7) by X-ray spectral microanalysis (XSMA): *a, b* – local areas

5. 4. Studying the titanium-vanadium-bronze-steel junction

To join V with steel (Fe), there must also be a barrier layer between them, which prevents the diffusion of carbon from steel to vanadium and eliminates the formation of brittle phases in the zone of contact V with steel (Fe). Copper meets these requirements because carbon does not diffuse through copper, and intermetallic junctions and fusible eutectics are not formed in the V-Cu and Cu-Fe systems. The surfacing of copper in its pure form can lead to significant overheating of the sample due to its high thermal conductivity. Therefore, from the standpoint of improving weldability, it is advisable to replace copper with bronze. In the experiments, 2 types of bronze filler wire were used: CuBe2 and CuSi3Mn1 (Table 1). First, let us consider the results of the use of CuBe2 wire.

To test the possibility of using a double barrier layer V-Cu, several samples were layered (Table 9). Sample No. 1 was welded with a fixed plasmatron in 2 layers applied to a pre-pierced titanium plate, 2 mm thick (Fig. 16, *a*):

- layer No. 1 – plasma surfacing with the filler wire V-2 (Table 1) of vanadium layer on a titanium plate, a plasma-forming nozzle diameter is 2 mm, an anode is a sample, weld bead, width 10 mm, height 0.3 mm;

- layer No. 2 – plasma surfacing with filler wire of the bronze layer on the vanadium layer, the diameter of the plasma-forming nozzle is 2 mm, the deposited bead (in total with layer No. 1) – 10 mm wide, 1 mm high.

The techniques of plasma surfacing of layers No. 1 and No. 2 are selected similarly to Table 2.

The surfacing of sample No. 2 was performed on a pre-scraped titanium plate 2 mm thick with transverse oscillations of the plasmatron in 2 layers (Table 9, Fig. 16, *b*):

- layer No. 1 – plasma surfacing with the filler wire V-2 (Table 1) of vanadium layer on a titanium plate, plasma-forming nozzle diameter is 2 mm, anode – a wire feed mouthpiece, weld bead, 7 mm wide, 1 mm high;

- layer No. 2 – plasma surfacing with filler wire of the bronze layer on the vanadium layer, the diameter of the plasma-forming nozzle is 2 mm, the anode is the mouthpiece of the wire feed, surfacing with separate drops, mainly on the right side of the layer No. 1.

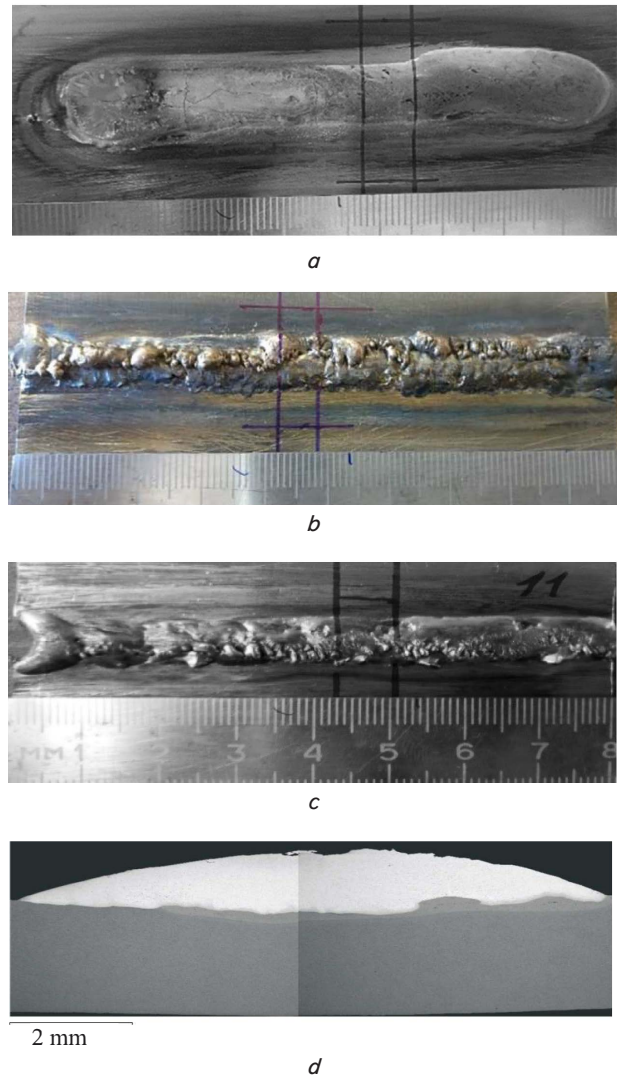


Fig. 16. General view of samples of titanium plates deposited with layers of vanadium and bronze for further surfacing with steel, the type of Q235: *a* – sample No. 1; *b* – sample No. 2; *c* – sample No. 3; *d* – macrostructure of cross-section of sample No. 3

The techniques of plasma surfacing of layers No. 1 and No. 2 of sample No. 2 were chosen similar to the techniques of surfacing the corresponding layers of sample No. 1 for the above reasons.

The surfacing of sample No. 3 was performed on a pre-scraped titanium plate with a thickness of 2 mm with transverse oscillations of the plasmatron in 2 layers (Table 9, Fig. 16, *c, d*):

- layer No. 1 – plasma surfacing with the filler wire V-2 (Table 1) of vanadium layer on a titanium plate, a plasma-forming nozzle diameter is 4 mm, anode – a wire feed mouthpiece, weld bead, 8 mm wide, 0.8 mm high;

- layer No. 2 – plasma surfacing with filler wire of the bronze layer, the diameter of the plasma-forming nozzle is 4 mm, the anode is the mouthpiece of the wire feed.

Table 9

Modes of surfacing samples with a double barrier layer (layer No. 1 of vanadium V-2 and No. 2 of bronze CuBe2) on a titanium plate

Sample No.	Surfacing Layla No.	Welding current, A	Arc voltage, V	Gas	Plasma-forming gas consumption, l/min	Shielding gas consumption, l/min	Boot gas consumption, l/min	Blowing gas consumption, l/min	Welding speed, cm/min	Wire feed speed, m/min	Amplitude of vibrations, mm	Oscillation speed, mm/s
1	1	130	23.7	Ar	0.4	25	30	30	20	0.8	7	40
	2	130	24	Ar	0.4	25	30	30	20	0.8	5.6	40
2	1	60	17.6	Ar	3.5	25	30	30	20	1	7	40
	2	60	17.6	Ar	3.5	25	30	30	20	1	5	40
3	1	90	18	Ar	0.6	25	30	30	20	0.76	6.6	40
	2	70	18	Ar	0.6	25	30	30	20	0.76	3	40

With plasma surfacing of sample No. 3, a technique was chosen that is close to that used in the surfacing of samples No. 1 and No. 2. The difference was the use of a plasma-forming nozzle of twice the diameter (4 mm). In this case, the task of reducing the concentration of the plasma heat source was performed to reduce the depth of penetration, both the titanium substrate and the applied vanadium layer.

In the case of the surfacing of sample No. 1, there was a good formation of the bead, but its intensive cracking was observed with the formation of a grid of hot cracks (Fig. 16, a). When surfacing sample No. 2, the bronze spread over vanadium fairly evenly, in the left part of the deposited bead there were drops of non-spread bronze (Fig. 16, b). This is likely due to deviations of the filler wire from the axis of the arc, which led to a lack of energy for its complete melting. When surfacing sample No. 3 (Fig. 16, c, d) from the copper side, a layer is found that has a dendritic structure, a plate structure. There is a mutual diffusion of elements at the interface of titanium-vanadium-copper without the formation of fragile phases (Fig. 17, Table 10).

However, when used as a second barrier layer of bronze CuBe2 in the beads deposited on the surface of vanadium, the formation of a grid of hot cracks is observed. To eliminate this drawback, the bronze CuBe2 was replaced by bronze CuSi3Mn1. Such surfacing was carried out by a plasma technique known as "soft plasma" [17]. The vanadium layer was deposited under a mode similar to that used for sample No. 3 (Table 9). The mode of surfacing with a "soft plasma" of the bronze layer CuSi3Mn1 is given in Table 11. Surfacing was carried out both with transverse oscillations of the burner (together with filler wire) and without. In the case of fluctuations, their amplitude was 3 mm per side, the delay in the extreme positions was 0.2 seconds. In the process of surfacing, the part was an anode, the tungsten electrode of the plasmatron was a cathode (direct polarity). As a result, there was a satisfactory spread of the deposited bead, its surface was smooth, cracking was not observed (Fig. 18). On the copper side, a dendritic layer of the lamellar structure was found (Fig. 19). Mutual diffusion of elements at the titanium-vanadium-copper interface is very insignificant and does not lead to the formation of fragile phases (Fig. 20, Table 12).

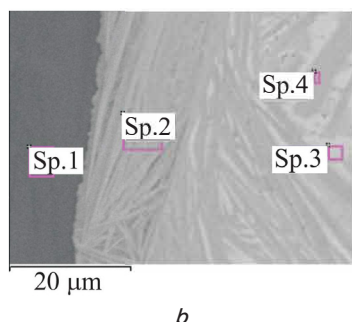
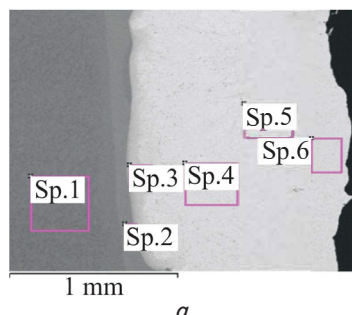


Fig. 17. Determining the content of elements in the transition zones Ti-V-Cu (sample No. 3, Table 9) by X-ray spectral microanalysis (XSMA): a, b – local areas

Table 10

The content (wt %) of elements in local areas of the transition zones Ti-V-Cu (Fig. 17), determined by X-ray spectral microanalysis (XSMA)

Sample No. 3 in a zone in Fig. 17, a						Sample No. 3 in a zone in Fig. 17, b					
Spectrum	Chemical composition, wt %					Spectrum	Chemical composition, wt %				
	Al	Ti	V	Cu	Total		Al	Ti	V	Cu	Total
Spectrum 1	0.34	99.66	–	–	100	Spectrum 1	0.33	87.29	11.79	0.58	100
Spectrum 2	0.35	78.47	15.61	5.57	100	Spectrum 2	0.12	39.99	6.82	53.08	100
Spectrum 3	0.17	29.61	5.11	65.1	100	Spectrum 3	–	23	1.09	75.91	100
Spectrum 4	–	12.92	1.06	86.02	100	Spectrum 4	–	39.94	2.31	57.75	100
Spectrum 5	–	16.59	1.88	81.53	100	–	–	–	–	–	–
Spectrum 6	–	20.57	2.01	77.42	100	–	–	–	–	–	–

Table 11

Mode of surfacing the solder CuSi3Mn1 by "soft plasma" on titanium (δ=2 mm)

Burner vibrations	Welding current, A	Arc voltage, V	Gas	Focusing gas consumption, l/min	Shielding gas consumption, l/min	Blowing gas consumption, l/min	Welding speed, cm/min	Wire feed speed, m/min	Amplitude of vibrations, mm	Oscillation speed, mm/s
Yes	100	16–18	Ar	0.6	25–30	15–20	25	1.8	6	35
No	120–160	16–18	Ar	0.6	25–30	15–20	30	1.5	6	35

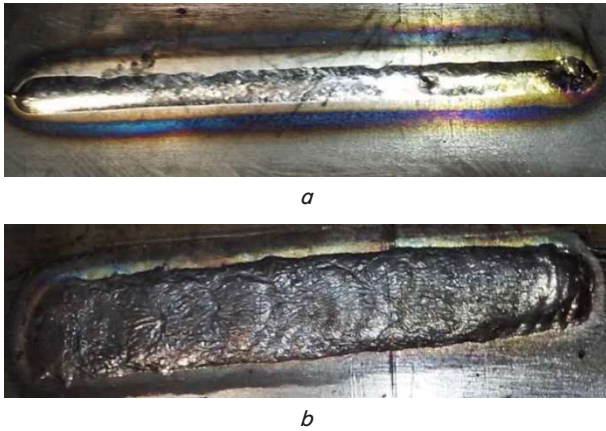


Fig. 18. General view of layers made by “soft plasma” surfacing: *a* – vanadium wire V-2 on titanium; *b* – CuSi3Mn1 alloy wire on the layer deposited with V-2 wire

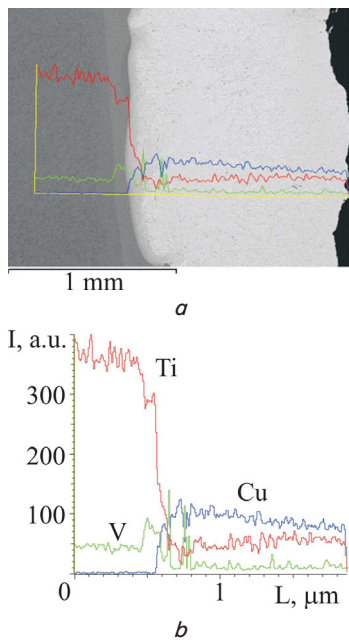


Fig. 19. Ti-V-Cu junction zones (sample No. 3, Table 9): *a* – microstructure; *b* – distribution of components (electron probe analysis CamScan-4)

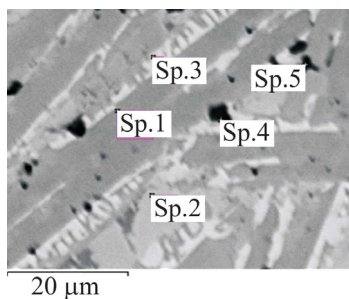


Fig. 20. Local sites for determining the content of elements in the transition zones Ti-V-Cu (bronze CuSi3Mn1) by X-ray spectral microanalysis (XSMA)

Dendrites in the layer observed from the bronze Cu-Si3Mn1 side are oriented at an angle to the plane of the interface V–CuSi3Mn1. This is most likely caused by a combination of heating conditions during vibrations of the

welding torch and subsequent cooling. The absence of fragile phases in the transition zones is confirmed by the absence of cracks and microhardness bursts.

Table 12

Content (wt %) of elements in the local areas of transition zones Ti-V-Cu (Fig. 20), determined by X-ray spectral microanalysis (XSMA)

Spectrum	Chemical composition, wt %					
	Si	Ti	V	Fe	Cu	Total
Spectrum 1	–	21.18	0.5	–	78.33	100
Spectrum 2	–	16.57	0.35	–	83.08	100
Spectrum 3	–	6.98	0.57	–	92.46	100
Spectrum 4	0.76	7.22	78.06	0.61	13.34	100
Spectrum 5	0.86	8.15	75	0.51	15.48	100

5. 5. Surfacing of a layer of bronze on titanium with the subsequent surfacing of steel, a study of the samples obtained

The obtained positive results in confirming the prospects of using CuSi3Mn1 bronze as a surfacing material contributed to the next step in conducting our research – its direct surfacing on a titanium plate using the “soft plasma” technology. With the help of this technology, a multilayer material “titanium – copper alloy CuSiMn1 – steel ER70S-6” was obtained. To this end, we used the modes of surfacing given in Table 11. This technology is characterized by a weaker compression of the arc due to the plasma-forming nozzle of increased diameter and occupies an intermediate position between the technology of plasma surfacing and surfacing with a free arc with a non-consumable electrode (argon-arc surfacing). Its use reduces the input of heat in the fused sample and the depth of penetration of the substrate (compared to conventional plasma surfacing), which helps minimize cracking. The results of the experiments showed a good formation of the surfacing layer without significant defects (Fig. 21). The advantage of this approach is the elimination of the need for surfacing a layer of vanadium and surfacing on titanium barrier coating of bronze CuSi3Mn1 in one layer.

The study has shown that the deposited layer of metal throughout the cross-section is heterogeneous; in the fusion zone, a structure of the variable chemical composition is formed (Fig. 22). Due to the heterogeneity in the chemical composition of the deposited layer, different etching degrees of the transition zone and solid solution with different concentrations of elements in the deposited metal are detected on the micro section. In the junction at the interface of the “titanium-steel”, there is a transition zone with a thickness of about 100 μm. Near the contact surface of the transition zone on the interface, there is a diffusion zone. On the titanium side, the interface boundary has a structure characteristic of the α-Ti phase, followed by a transition zone with supersaturation of iron concentration up to 18.13 %. The solubility of Si in the copper-titanium solid solution of the transition zone is small and is 0.79 %. X-ray microanalysis of the deposited metal by surfacing height showed that the average chemical composition contains approximately 52–53 % Fe, from 19.93 to 22.1 % Cu, 22.73–21.33 % Ti, and 2.94–3.45 % Si (Fig. 23, Table 13).

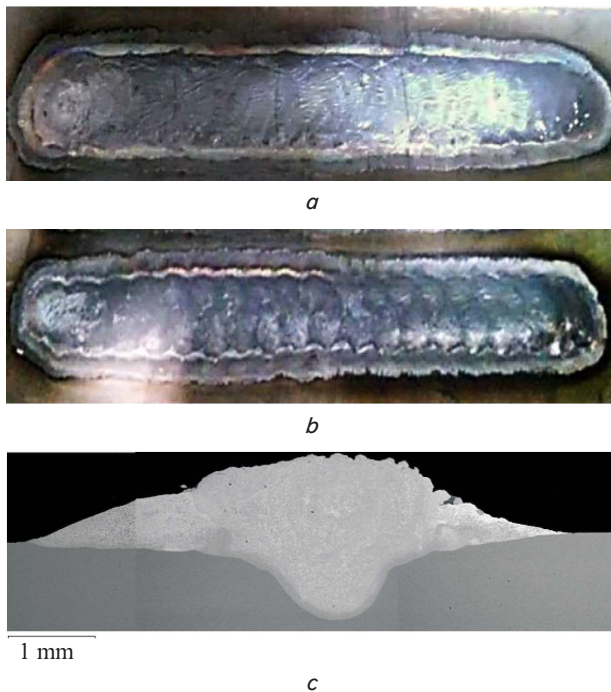


Fig. 21. Three-layer surfacing "titanium – alloy CuSi3Mn1 – steel ER70S-6": *a* – the general view of the layer of copper alloy CuSi3Mn1 deposited with "soft plasma" on titanium; *b* – a layer of the subsequent surfacing of steel wire, grade ER70S-6; *c* – macrostructure of cross-section

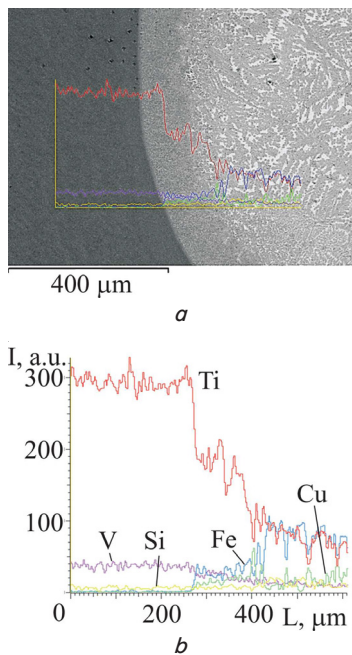


Fig. 22. Zones of junction "titanium – alloy CuSi – steel": *a* – microstructure; *b* – distribution of elements (electron-probe analysis CamScan-4)

As a result of the non-equilibrium crystallization of the metal, the chemical composition of the deposited layer is variable, and the composition of the individual zones in depth differs somewhat. This occurs as a result of the formation of separate phases that are visible in the photographs of the structures as dark and light (Fig. 24, Table 14).

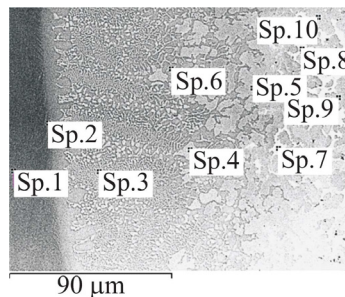


Fig. 23. Local sites for determining the content of elements in the transition zones of Ti-CuSi-Fe by X-ray spectral microanalysis (XSMA)

Table 13

The content (wt %) of elements in the local areas of transition zones "titanium – copper alloy CuSiMn1 – steel ER70S-6" (Fig. 23), determined by X-ray spectral microanalysis (XSMA)

Spectrum	Chemical composition, wt %						Total
	Al	Si	Ti	Mn	Fe	Cu	
Spectrum 1	–	–	77.85	–	15.68	6.46	100
Spectrum 2	0.6	0.62	90.4	–	5.52	2.86	100
Spectrum 3	–	0.92	71.29	–	16.83	10.49	100
Spectrum 4	–	5.82	56.17	–	30.26	7.49	100
Spectrum 5	–	1.46	54.34	–	23.6	20.22	100
Spectrum 6	–	1.24	68.95	–	16.67	13.14	100
Spectrum 7	–	3.59	44.03	–	41.89	10.48	100
Spectrum 8	–	3.41	34.95	1.23	29.44	30.96	100
Spectrum 9	–	1.71	22.32	0.79	71.54	3.64	100
Spectrum 10	–	5.46	39.04	–	48.48	7.02	100

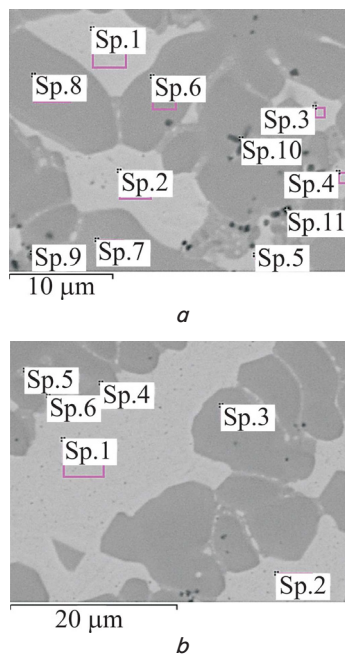


Fig. 24. Determining the content of elements in the transition zones Ti-CuSi-Fe by X-ray spectral microanalysis (XSMA): *a, b* – local areas

In the case of the dark phase, a solid solution with a high titanium content (from 10.42 to 27.98 wt %) is represented in the form of dendrites formed at higher crystallization

temperatures. The boundary layer of dendrites is enriched with Fe (72.2÷72.14 wt %) and Ti (13÷22.5 wt %). The light phase, formed in the interdendritic space at lower cooling temperatures, is enriched with a copper content of 86.72 and 92.16 wt %.

the possibility of the formation of fragile intermetallics with a vanadium content of more than 8–10 %. The solid solution along the alloy line in the transition zone has a variable concentration and is characterized by increased hardness up to 5,523 MPa (Fig. 12).

Table 14

The content (wt %) of elements in the local areas of the transition zones “titanium – copper alloy CuSiMn1 – steel ER70S-6” (Fig. 24), determined by X-ray spectral microanalysis (XSMA)

Sample in a zone in Fig. 24, a							Sample in a zone in Fig. 24, b						
Spectrum	Chemical composition, wt %						Spectrum	Chemical composition, wt %					
	Si	Ti	Mn	Fe	Cu	Total		Si	Ti	Mn	Fe	Cu	Total
Spectrum 1	–	0.68	2.02	5.15	92.16	100	Spectrum 1	–	0.43	1.74	4	93.67	100
Spectrum 2	–	0.71	2.29	4.84	92.16	100	Spectrum 2	–	0.73	1.99	5.06	92.23	100
Spectrum 3	1.69	11.71	1.3	33.11	52.17	100	Spectrum 3	2.88	26.29	0.41	66.5	3.92	100
Spectrum 4	1.63	17.81	1.07	50.27	29.04	100	Spectrum 4	1.14	26.07	0.55	69.21	3.02	100
Spectrum 5	–	1.92	1.76	9.6	86.72	100	Spectrum 5	1.23	22.5	0.49	72.2	3.57	100
Spectrum 6	4.03	27.98	0.61	64.13	3.13	100	Spectrum 6	0.4	13	0.92	72.14	13.54	100
Spectrum 7	3.67	26.32	0.59	65.22	4.2	100	–	–	–	–	–	–	
Spectrum 8	4	27.42	0.61	64.59	3.05	100	–	–	–	–	–	–	
Spectrum 9	0.27	27.15	0.83	64.23	7.38	100	–	–	–	–	–	–	
Spectrum 10	0.95	45.1	0.42	48.49	4.89	100	–	–	–	–	–	–	
Spectrum 11	0.33	16.6	0.88	73.79	8.35	100	–	–	–	–	–	–	

6. Discussion of results of comparing the surfacing of different types of materials of the barrier layer

When steel is deposited on a titanium substrate using melting welding methods, cracks appear in the transition zone, leading to the destruction of the junction. Consequently, obtaining a high-quality bimetallic compound “titanium-steel” is possible with the use of a reliable mechanism of protection against the metallurgical interaction of titanium and steel. In this paper, the implementation of such a mechanism was carried out by applying various protective (barrier) layers between titanium and steel.

In the case of surfacing by the vanadium wire V-2 (Ø1.0 mm, Table 1) by the plasma technique involving direct arc (anode – fused sample) of the layer of thickness of 0.3–0.5 mm on a titanium plate, the thickness of 2 mm (Table 2), the transition zone has a width of 0.1 to 1.0 mm. Changes in width depend on the nature of mixing Ti with V. This zone is a continuous series of solid solutions Ti with V of variable composition, in which the content of Ti is 70...80 %, and the content of V – about 20...30 % (Tables 3, 4). In the lower part of the vanadium surfacing, the level of microhardness increases on average from 2,500 MPa to 3,750 MPa (Fig. 8). This effect is probably due to the hardening of vanadium due to the ingress of titanium into it with subsequent dissolution. Fragile phases at the junction boundary and in the transition zone are not formed. The interface between vanadium surfacing and titanium is defect-free.

In the case of plasma surfacing by a direct-action arc (anode – a deposited sample) of a layer of vanadium (the wire V-2, Ø1.0 mm, Table 1) with a thickness of 0.3–0.5 mm on a steel plate 8 mm thick (Table 5), the width of the transition zone is from 0.1 to 1.1 mm. Here, there is a mutual diffusion with the formation of a solid solution, the composition of which varies within 25...60 % Fe and 75...40 % V, respectively (Table 6). In this zone, the formation of cracks and fine porosity are observed. The presence of cracks is explained by

width of 30 µm or more. Fe and V, which do not have mutual solubility in the solid state, dissolve in the liquid state with the subsequent formation of fragile eutectics. At the V-Fe boundary, with an increase in the iron content in the surfacing metal from 25 % to 45 % (Table 8), crack formation is observed due to excessively intensive mixing of the melt of steel and vanadium.

Thus, it was found that to obtain a strong bimetallic compound Ti-Fe, the use of vanadium alone as a barrier layer is undesirable. To eliminate cracking between vanadium and steel, it is necessary to introduce another barrier layer. One of the options for such a layer can be copper or such an alloy based on it as bronze.

In the case of the surfacing of the compound “titanium – vanadium V2 – alloy CuBe2 – steel ER70S”, in all cases, we used a compressed arc of direct action with the appropriate filler wires (V-2, CuBe2, ER70S-6). We successively welded layers of vanadium with a thickness of 0.3–0.5 mm and bronze CuBe2 with a thickness of 0.5–1.0 mm on a titanium plate 2 mm thick, followed by steel surfacing (Table 9). At the same time, significant mixing of the deposited layers of bronze and steel was observed. There was a mutual diffusion of elements at the titanium-vanadium-copper interface without the formation of fragile phases. On the side of copper, a layer was found that has a dendritic structure with a plate structure. When layer V was deposited on Ti, cracks were observed in the first one. During the subsequent surfacing of the bronze CuBe2, cracks were absent. However, after surfacing the third steel layer, a grid of cracks was observed in it. Therefore, it was decided to replace CuBe2 with bronze CuSi3Mn1.

In the case of the sequential surfacing of the three-layer material “titanium – copper alloy CuSi3Mn1 – steel ER70S-6”, in all cases, we used “soft plasma” with a weaker compression of the arc due to the plasma-forming nozzle of increased diameter, compared with plasma surfacing (Table 11). We successively welded layers of vanadium with a thickness of 0.3–0.5 mm (the wire V-2, Ø1.0 mm) and bronze CuSi3Mn1, a thickness of 0.5–1.0 mm (the wire CuSi3Mn1, Ø1.0 mm) on a plate of titanium VT1-0, a thickness of 2 mm,

In the case of the surfacing of the compound “titanium – vanadium V2 – steel ER70S-6” at the Ti-V stage, the technique of plasma surfacing with an indirect arc with the current-carrying wire-anode V-2 was used, and, at the V-Fe stage, the pulsed MAG surfacing (Table 7). At the same time, a layer of steel up to 3 mm thick was welded with wire (Ø1.0 mm, Table 1) on a layer of vanadium (the wire V-2, Table 1) with a thickness of 0.3–0.5 mm, previously welded on a titanium plate 2 mm thick. 2 fusion zones were obtained: Ti-V with a width of ~60 µm and V-Fe with a

with the subsequent surfacing of steel (the wire ER70S-6, $\varnothing 1.0$ mm). The mixing of the deposited layers was reduced. Thus, the transition zone between Ti and V was 0.2–0.3 mm, and between V and CuSi3Mn1 – about 0.2 mm (Fig. 19). As in the previous case, a dendritic layer of the lamellar structure is found on the side of copper (Fig. 20). The mutual diffusion of elements at the titanium-vanadium-copper interface is very insignificant and does not lead to the formation of fragile phases. Cracking is not observed.

The next step in analyzing the criticality of the metallurgical interaction of the barrier layer material with Ti and Fe was to test the possibility of its application without the use of vanadium. In the case of the surfacing of a layer of bronze CuSi3Mn1 with a thickness of 0.5–1.0 mm on a titanium plate with a thickness of 2 mm, followed by the surfacing of steel in the fusion zone, a structure of variable chemical composition was formed. The reason for this was the almost complete mixing of CuSi3Mn1 bronze with the ER70S-6 steel deposited on top. The transition zone beginning at the pronounced surface of titanium with a width of about 100 μm (Fig. 22, 23) has a relatively low (up to 18 %) iron content. Further, in the direction of surfacing the ER70S-6, the iron content increases to 50 % or more, and the copper content drops from 25 % or less (Tables 13, 14). In the transition zone, a solid solution with an increased (from 10 to 30 %) titanium content, having a dendritic structure, is observed (Fig. 24). The interdendritic space is a eutectic enriched with copper (85... 95 %) (Table 14). Along the boundary of fusion of Ti-CuSi3Mn1, pores are observed. There are no cracks.

Our study makes it possible to conclude that with the correct selection of the technique and mode of surfacing, the type and chemical composition of the surfacing material, a barrier layer of silicon bronze can be used for butt welding of bimetallic steel-titanium sheets. At the same time, bronze should be deposited on the welded layer of titanium, and steel should be layered on top of it. The process of surfacing the first layer of steel on a bronze barrier layer should be implemented with increased thermal locality and minimal thermal impact so as to reduce the mixing of steel with bronze. Subsequent steel layers can be fused with a slightly reduced thermal locality.

Our research is aimed at studying the features of metallurgical interaction with titanium and steel of such metals as vanadium, bronze CuBe2, and bronze CuSi3Mn1. Such features are typical for arc techniques of surfacing – first of all, plasma and pulsed MAG. In the case of plasma surfacing, a direct-acting arc (anode – a deposited sample) and an indirect arc (anode – filler wire) were considered. In addition, with plasma surfacing, compressed and soft (weakly compressed) plasma was considered. The studied features of the formation of barrier layers demonstrate the possibility of creating a copper layer CuSi3Mn1 by the plasma-arc surfacing techniques. Such a layer has satisfactory metallurgical properties and acceptable technical and economic indicators. That makes it possible for its further industrial application in the manufacture of welded pipes for main oil and gas pipelines from sheets of titanium-steel bimetal. Our research can form the basis of the development of technologies for obtaining both the welded pipes and their junctions.

7. Conclusions

1. When using plasma surfacing with a direct-acting arc (anode – a deposited sample) of the filler wire V-2 on

a titanium plate, it has been confirmed that due to the unlimited mutual solubility, the titanium fuses well with vanadium without the formation of brittle phases. The structure of the deposited metal along the entire section of the junction is homogeneous. In the fusion zone, there is a solid solution of variable concentration, which is characterized by a high content of V. It is formed as a result of mutual diffusion of elements at the interface in the transition zone and is a continuous series of solid solutions of Ti with V of variable composition: (53.87–65.67) wt % Ti with (33.93–45.54) wt % V, respectively. Fragile phases at the junction boundary and in the transition zone are not formed. There is no cracking.

2. When plasma surfacing with a direct-acting arc (anode – a deposited sample) of the vanadium wire V-2 on the steel of type Q235, their mutual diffusion occurs with the formation of a solid solution of variable concentration, the composition of which varies within 40 ... 75 % V and 60... 25 % Fe, respectively. The increased hardness (up to 5,523 MPa) of the solid solution along the fusion line in the transition zone can be explained by the presence of intermetallic phases. The formation of cracks is observed, which is explained by the possibility of the formation of fragile intermetallics with a vanadium content of more than 8–10 %.

3. When the Ti-V-Fe compound is deposited in 2 stages (Ti-V by plasma surfacing by an indirect arc with the current-carrying wire-anode V-2 and V-Fe – pulsed MAG surfacing) in the transition zone between vanadium and steel, eutectics containing Fe-V phases are formed. Under different modes of surfacing, there is a mixing of melt of steel and vanadium in different ratios. As a result, in the transition zone, the iron content can be from 27.42 wt % up to 43.25 wt %, which usually leads to the formation of cracks.

4. It has been shown that to eliminate the formation of a fragile phase of Fe-V, it is advisable to fuse an alloy based on copper on top of the vanadium layer. The use of two filler wires CuBe2 and CuSi3Mn1 for surfacing with direct-acting plasma with a weak compression of a plasma-forming nozzle of increased diameter was compared. In the case of the use of CuBe2 wire, in the transition zone, cracks were observed due to the occurrence of fragile phases at the bronze-steel interface. In the case of using silicon bronze wire CuSi3Mn1, we observed the formation of a dendritic layer of the plate structure. The mutual diffusion of elements at the interfaces of Ti-V-Cu was relatively small and did not lead to the formation of fragile phases.

5. Experiments were carried out on surfacing with the weakly crimped plasma of direct action of the bronze wire CuSi3Mn1 on a titanium plate. As a result, there was a good formation of the surfacing layer with the absence or a minimum number of defects in the form of individual pores in the fusion zone with steel. Mutual diffusion of elements at the interface of Ti-CuSi3Mn1-Fe does not lead to the formation of fragile phases and cracking. The use of such a barrier layer opens up the possibility of eliminating the need for the use of vanadium and creating effective protection against the formation of Ti-Fe intermetallic phases.

Acknowledgments

This work was funded within the framework of the fundamental departmental topics of the National Academy of Science of Ukraine “Study of the regularities of the course

of physical and metallurgical processes in the formation of intermetallic phases during plasma-arc welding of the steel-titanium bimetal with applied protective layers" (state registration number 0118U100524).

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