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FEATURES OF STRUCTURE FORMATION WHEN SURFACING STEEL (IRON) ON TITANIUM WITH PLASMA SPRAYED COATINGS IN THE TECHNOLOGY OF OBTAINING BUTT JOINT OF BIMETALLIC PLATES "TITANIUM – STEEL"

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The object of this study is structural formation during the surfacing of steel (iron) on titanium with plasma-sprayed coatings to obtain a butt connection of titanium-steel bimetallic plates. The task to be solved was to devise a technology for applying a barrier layer between titanium and steel to obtain a defect-free butt joint of the edges of bimetallic sheets of carbon steel, clad with a layer of titanium, under conditions of arc or plasma surfacing of carbon steel on titanium. The application of the barrier layer was carried out by plasma spraying of steel wire or iron powder. In this case, a coating with a thickness of 150...750 μm was applied on Grade2 titanium, on which 1–2 mm thick layers of materials similar to the sprayed ones were deposited by arc and plasma deposition. It was established that during spraying with subsequent surfacing of steel wire or iron powder, the main technological factors for eliminating cracks in the resulting compound are the thickness of the sprayed coating and the amount of linear surfacing energy. The thickness of the sprayed coating was selected (at least 400...600 microns) followed by plasma surfacing of ER70S-6 steel wire with a diameter of 1.0 mm or CNPC-Fe200 iron powder with unit energy up to ~200...250 J/mm. A defect-free transition layer from titanium to steel was obtained. It is a continuous layer with a thickness of 50–60 microns, consisting of intermetalides FeTi and $FeTi_2$, as well as a β-phase titanium with an enhanced iron content, which retains certain ductility without cracks and other defects. With the help of the devised approach for connecting titanium-steel bimetallic edges, it is planned to manufacture seam bimetallic pipes for main pipelines to transport oil and gas raw materials extracted from wells

Keywords: titanium – steel bimetal, multi-pass welding, barrier layer, intermetallide phases, section boundary

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1. Introduction

Bimetallic materials are used in modern industry to lighten the weight of structures, induce local changes in mechanical characteristics, for corrosion protection, etc. One of the varieties of bimetallic materials is sheets of steel clad with titanium. The task of obtaining one-piece joints of such sheets using welding technologies is difficult due to the danger of the formation of intermetallic phases (IMP) [1]. There are a number of technological solutions to avoid this phenomenon. One of the most promising approaches is welding using transition or barrier layers [2]. However, this approach does not always ensure the complete absence of intermetallic compounds due to the possibility of remelting the barrier layer when surfacing subsequent layers of metal (for example, steel). The relevant task is to devise such technological procedures that would make it possible to weld titanium-steel bimetal sheets without the formation of IMP.

2. Literature review and problem statement

The compound of bimetallic plates of steel clad with titanium is of particular interest to the oil and gas, nuclear, aerospace industries, as well as other industrial sectors. An example would be the manufacture of seam bimetallic pipes for main pipelines to transport oil and gas raw materials extracted from wells. Given the metallurgical incompatibility between these metals, it is very difficult to obtain reliable compounds due to the formation of brittle intermetallic compounds FeTi and Fe_XTi_Y. One of the rather attractive methods for obtaining compounds of such bimetallic plates can be friction welding, which has low heat injection and high accuracy. In this case, to eliminate IMP, it is proposed to insert aluminum as an intermediate layer between titanium and stainless steel [3]. The disadvantage of this approach is the high mechanical loads on the welded edges, which requires their very strong fastening, which cannot be developed for all cases of connections. Another well-known method for producing bimetal compounds is diffusion welding. In this case, to eliminate the threat of IMP formation, alloys based on Cu, Ni, Ag can be used [4]. However, due to the need to use specialized heating and load systems, this welding method is very difficult to apply for long-dimensional products such as pipeline pipes.

To connect bimetallic sheets TA1/Q345, paper [5] proposed laser surfacing welding using a multicomponent filler powder FeCoCrNiMn as a squat metal. In this case, the root of the seam was on the side of the base plate of steel Q345. But the issue of welding from the side of the base plate made of Q345 steel with the outlet of the seam root into the titanium plate remained unresolved. Work [6] reviews methods for welding titanium and steel. In particular, it was found that titanium welding with steel using the TIG method and friction is possible using copper and tantalum or vanadium layers. Much to our regret, the issue of welding the type of bimetal "steel clad with titanium" is not considered there. In [7], when welding bimetallic sheets Ti/Fe, it is proposed to first obtain a welded layer of steel, and then to weld a thin layer of titanium using a layer of Cu-V between Ti and Fe. Arc welding of butt joints obtained by welding by explosion of bimetallic plates steel – titanium was carried out using powder wires Cu–Nb with different Nb content (5 at. %), 20 at. %, and 30 at. %) [8]. The joints welded with the Cu20Nb additive contained no cracks and had a strength of ~334 MPa. The main disadvantage of the proposed approach is the use of rather expensive metals to create a barrier layer.

It follows from the review of works [2–8] that the use of fusion welding to obtain permanent butt joints of steel plates clad with titanium is associated with the threat of the formation of IMP. The basis of such a threat is the course of the corresponding reactions between Ti and Fe at melting points and above. An option to overcome the problems of IMP formation, the use of complex technological procedures and equipment, the use of precious materials, is the creation of Ti connections with Fe using spraying technologies to obtain a barrier layer at a temperature close to normal. The material of this layer can be the same or similar to that which will be fused on top using a certain traditional surfacing technology. In the case of spraying a layer of a similar material (for example, Fe or steel), the task arises to reduce or eliminate metallurgical interaction with titanium of steel planting wire during its subsequent surfacing. The proposed approach could minimize the thickness of the IMP layer, will make it possible to modify its chemical composition to eliminate the threat of cracks and other defects.

3. The aim and objectives of the study

The aim of this study is to improve the structure formation and minimize the formation of IMP during the surfacing of steel (iron) on titanium while obtaining a butt one-piece connection of titanium-steel bimetallic plates. To this end, it is proposed to use plasma spraying technology to create barrier coatings. This could make it possible to manufacture seam bimetallic pipes of main pipelines for the transportation of oil and gas raw materials extracted from wells.

To achieve the set aim, the following tasks have been solved:

– to devise a technological approach to obtaining a one-piece connection of titanium-steel bimetallic plates;

– to perform plasma spraying of barrier layers on titanium;

– to perform arc surfacing of thin layers of carbon steel on sprayed barrier layers.

4. The study materials and methods

The object of our study is the structure formation during the surfacing of steel (iron) on titanium with plasma-sprayed coatings to obtain a butt compound of titanium-steel bimetallic plates.

The main hypothesis of the study assumes the following. To obtain a high-quality butt welded joint of sheet bimetal "titanium (thickness δ=2 mm) – steel of type Q235 (δ=10 mm)" (manufactured by PanGan Group Corporation, China), it is necessary to eliminate the danger of IMP formation in the zone of contact of titanium with steel. This can be achieved by applying a certain barrier insert. As such an insert, it is proposed to use a layer of steel sprayed on titanium, similar to a steel layer of bimetal, or iron. Subsequently, arc surfacing of steel will be carried out on top of the sprayed layer. To eliminate (minimize) the formation of IMP, it is necessary to select the thickness of the layers sprayed and welded on it and the appropriate modes of spraying and surfacing.

Previous studies of the base metal have shown that the structure of the titanium layer corresponds to the structure of technically pure titanium Grade2, and the steel layer corresponds to the perlite-ferritic structure of structural low carbon steel (Table 1, Fig. 1).

To achieve the goal of the research, we shall accept the following assumption: in order to obtain an inseparable connection of the edges of a bimetallic sheet, it is necessary to develop them in advance in a certain form [9]. A sheet of carbon steel with a thickness of 10 mm was connected with a plated sheet titanium 2 mm thick (Fig. 2, *a*). To do this, on the edges of the joint, a U-shaped design was performed so that the titanium layer was on the bottom and the steel layer was on top (Fig. 2, *b*). The execution of such a compound begins with the titanium layer by its single-pass plasma welding (Fig. 2, *c*). After that, a barrier layer is applied to the titanium layer with plasma spraying (for example, CNPC-Fe200 powder based on iron, Table 2) (Fig. 2, *d*), on top of which the development is filled in the steel layer of bimetal (Fig. 2, *e*). Filling the development should be carried out by surfacing the steel squat material by the arc method so that it is fused with the edges of the steel layer (Fig. 2, *f*). To eliminate the threat of IMP formation, it is important to prevent the remelting of the sprayed barrier coating and metallurgical interaction with titanium of the melt of the planting material based on steel or iron. It is necessary to minimize the formation of IMP type Ti_XFe_Y so as to eliminate the threat of cracking and destruction of the connection [2]. Therefore, to reduce the thermal load on the sprayed barrier layer, it is necessary to surface a thin (1–2 mm) layer of steel with minimal unit energy on it. The ER70S-6 welding wire with a diameter of 1.0 mm was used as a surfacing material (Table 2). Further, it is advisable to apply steel (wire ER70S-6, Ø1.0 mm) layers with a thickness of 3–5 mm on such a weld layer to finally fill the development of bimetal edges.

Table 1

The content of elements (wt%) in local areas of the base metal, determined by the method of X-ray spectral microanalysis (XSMA)

Spectrum	Ti	Mn	Fe	Total
Spectrum 1	–	0,81	99,19	100
Spectrum 2	100	–	–	100
Spectrum 3	100	–	–	100
Spectrum 4	100	–	–	100

Barrier coatings were applied by two plasma spraying techniques: supersonic plasma-powder spraying of CNPC-Fe200 iron powder (manufactured by Shanghai CNPC Powder Material Co. Ltd, China) and plasma-arc spraying of conductive wire-anode ER70S-6 with a diameter of 1.6 mm (Table 2). Schemes and visualization of these processes are shown in Fig. 3, 4. For the application of barrier coatings, we used installations for supersonic plasma-powder spraying PLAZER 80-PL [10] and high-speed spraying PLAZER 30PL-W by conductive wire-anode [11], respectively. To assess the adhesion strength of the sprayed coatings with the base, the value of the destructive stress in the composition "coating - base" was used at normal separation, determined by the method of "cone pin" [12]. For the surfacing of steel wire ER70S-6 on top of the sprayed barrier coatings, a technological bench was designed, shown in Fig. 5.

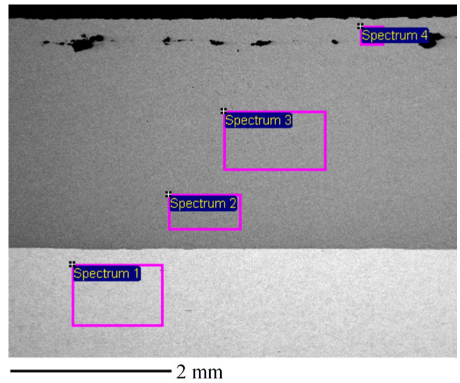


Fig. 1. Macrostructure and local content of elements (X-ray spectral quantitative chemical microanalysis) in the titanium-steel bimetallic plate

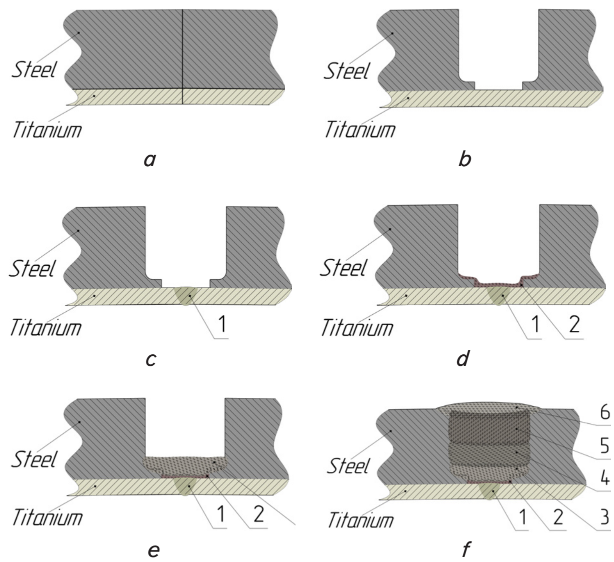
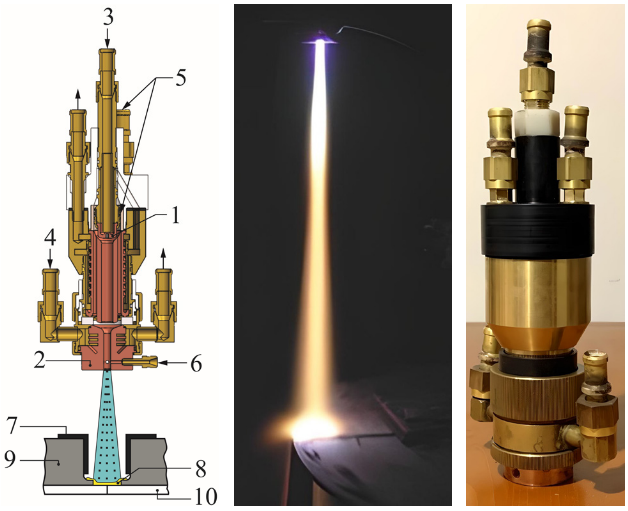


Fig. 2. Working out bimetallic edges and the sequence of obtaining a butt connection of titanium-steel bimetallic plates: *a* – the joint of two titanium-steel bimetallic plates (without working out the edges); *b* – the shape of working out the edges for obtaining a butt connection; *c* – titanium layer welding; *d* – plasma-arc spraying of the barrier coating made of steel (iron); *e* – surfacing of the first steel layer on the barrier coating; *f* – multi-pass surfacing of steel to fill the development in bimetal to obtain a butt compound of the bimetal; 1 – weld of the titanium layer; 2 – sprayed coating of steel (iron); 3 – weld layer of steel (iron) on a sprayed coating on titanium; 4, 5 – steel layers (rollers) obtained by arc surfacing to fill the development in bimetal; 6 – facing layer (seam) of the butt joint of bimetal, made by arc welding

Table 2

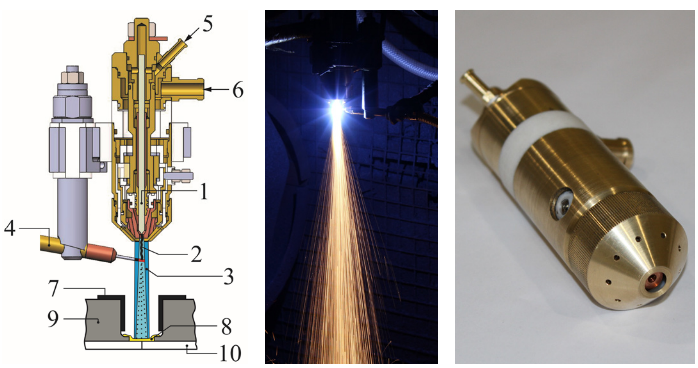
Chemical composition of the applied materials

Material	Content of elements, wt%										
	Fe	Ti	C	Si	Mn	Ni	Cr	Cu	Al	V	P	S
Titanium-steel bimetal with a total thickness of 12 mm												
Titanium layer Grade2 (thickness 2 mm)	<0.25	base	<0.07	<0.1	–	–	–	–	–	–	–	–
Steel layer Q235 (thickness 10 mm)	base	–	0.14–0.22	0.05–0.15	0.4–0.65	<0.3	<0.3	<0.3	–	–	<0.04	<0.05
Materials for applying barrier coatings to the titanium layer of bimetal and surfacing the next layer												
Wire ER70S-6 (Ø1.0 and 1.6 mm)	base	–	<0.08	0.7–0.95	1.8–2.1	<0.25	<0.2	<0.25	–	–	<0.03	<0.025
Iron powder CNPC-Fe200 (Ø60–100 microns)	base	–	0.02	<0.12	<0.04	–	–	–	–	–	<0.02	<0.02



a *b* *c*

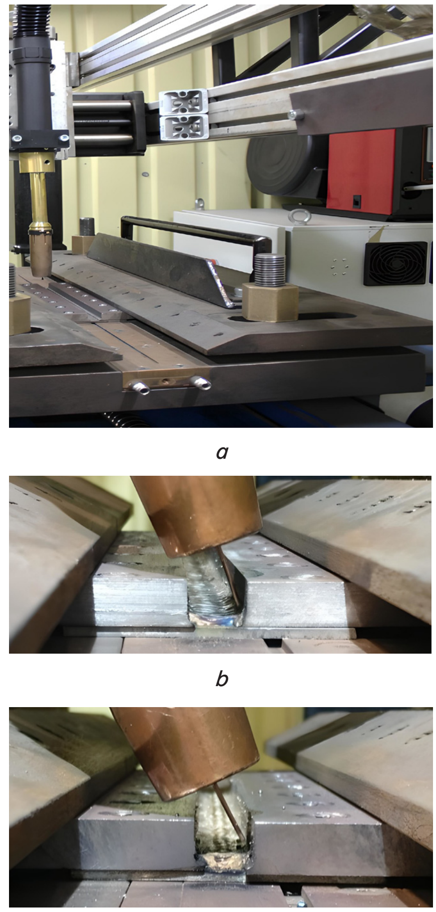
Fig. 3. Supersonic plasma-powder spraying of the barrier coating: *a* — process diagram; *b* — visualization of the process; *c* — the general view of the plasma torch; 1 — cathode; 2 — nozzle-anode; 3, 4 — cooling systems of the cathode and anode, respectively; 5 — plasma-forming gas supply; 6 — supply of powder with transporting gas; 7 — protective screen; 8 — coating; 9 — steel; 10 — titanium



a *b* *c*

Fig. 4. Plasma-arc spraying with conductive steel wire of the barrier coating: *a* — process diagram; *b* — visualization of the process; *c* — general view of the plasma torch; 1 — cathode; 2 — electric arc; 3 — crimping jet; 4 — wire anode; 5 — plasma-forming gas supply; 6 — supply of accompanying gas; 7 — protective screen; 8 — coating; 9 — steel; 10 — titanium

To carry out metallographic analysis, transverse templets were cut from sprayed and fused samples and micro-grindings were made. Polished micro-grindings were subjected to chemical etching with a 4 % alcohol solution of HNO_3. The obtained samples were examined by optical (Neophot-31 microscope) and electron (CamScan-4 microscope) microscopy. The distribution of components, the presence and composition of IMP in the sample metal were determined using X-ray spectral microanalysis (XSMA) and electron probe analysis. For this purpose, the CAMEBAX microanalyzer and the CamScan-4 electron microscope were used, respectively. Microdurometric analysis of the deposited samples was carried out on a LECO microhardometer with a measurement step of 10 microns at a load of 20 g.



a

b

c

Fig. 5. Bench for surfacing of steel (iron) after plasma-arc spraying of barrier coatings: *a* — general view; *b* — surfacing of the first steel layer on the sprayed steel coating; *c* — multi-pass arc surfacing of steel to fill the development

5. Results of the study of spraying barrier layers on titanium with subsequent steel surfacing

5. 1. Devising a technological approach to obtaining a one-piece connection of titanium-steel bimetallic plates

To be able to connect the bimetallic edges of carbon steel sheets clad with a layer of titanium, it is necessary to develop a technology for applying a barrier coating between these metals. Such a coating should be applied to the titanium layer of bimetal without the formation of IMP, have the ability to form a chemical bond with the steel filler in the part of the development that is made in the steel layer of the bimetal. In this case, the barrier coating must maintain its integrity during the subsequent surfacing of the steel layer on it. This will ensure the avoidance of metallurgical interaction of the steel melt with the titanium layer of titanium-steel bimetal and the formation of brittle intermetallic compounds, cracks, and other defects.

Technological research on filling the development of titanium-steel bimetal was carried out using the processes of arc and plasma surfacing. To reduce the thermal load on the sprayed coating, the following technologies were chosen (Fig. 6):

– arc pulse surfacing with a melting electrode (wire) ER70S-6 in the environment of active gases (P-MAG);

– plasma surfacing with additive neutral wire ER70S-6;

– plasma-powder surfacing with CNPC-Fe200 iron powder.

When conducting technological experiments according to the specified schemes, the spraying of the barrier layer was carried out on a plate-imitator made of titanium Grade2. After spraying and surfacing, the samples were examined both visually and by optical and electronic metallography methods. The criteria for obtaining sprayed coatings and welded metal rollers are the quality of their formation, the absence of cracks, and geometric parameters (height and width).

When conducting technological experiments on the plate of titanium Grade2 (δ=2 mm), spraying was performed, on top of which there was surfacing. To do this, the working surface of the plate was prepared by shot blasting processing. Supersonic plasma-powder spraying was performed according to the scheme and with the help of equipment shown in Fig. 3. The laboratory bench was designed on the basis of the PLAZER 80-PL equipment toolkit [10]. This equipment made it possible to spray the barrier layers with CNPC-Fe200 powder with a working current of up to 150 A at voltages up to 280 V. Spraying of samples by plasma-arc spraying of wire-anode ER70S-6 (Ø1.6 mm) was carried out according to the scheme in Fig. 4 using the PLAZER 30 PL-W equipment system [11]. Such equipment allowed spraying with a working current of up to 250 A at voltages up to 120 V.

After spraying the barrier layer, arc and plasma-arc surfacing was performed according to schemes in Fig. 6, using the bench shown in Fig. 5. To implement the P-MAG pulsed surfacing processes, the Fronius Magic Weve 2200 power source was used, with the help of which thin (1–2 mm) layers of ER70S-6 steel were surfaced at currents of 150...200 A at voltages up to 24 V. For the implementation of plasma surfacing processes of the same steel wire ER70S-6 using plasmtoron [13] at a current of 140...160 A and a voltage of 20 V, a Tetrix 421 power supply and a Fronius Plasma-Module 10 plasma module were used. For plasma surfacing with CNPC-Fe200 powder, we mounted on the bench in Fig. 5 a plasma torch, the scheme of which is shown in Fig. 6, *f*. Surfacing was performed using equipment [14] at a current of 100...120 A and voltage on an arc of about 30 V.

As a result, high-quality samples of Grade2 alloy plates with sprayed layers ER70S-6 and CNPC-Fe200 with a thickness of 150...750 microns were obtained. There are also similar plates with the indicated sprayed layers, on top of which we deposited the layers ER70S-6 and CNPC-Fe200 with a thickness of 1–2 mm (Table 3). Samples were cut from these plates for further metallographic research.

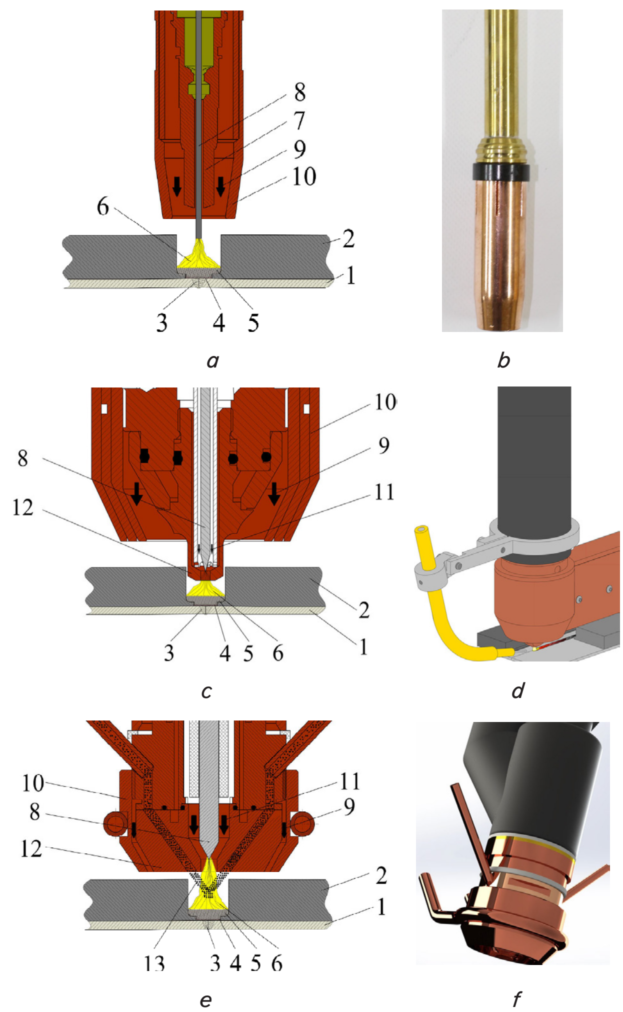


Fig. 6. The scheme and general view of heads for the implementation of the investigated surfacing processes on top of the barrier coatings to fill the development when obtaining a butt welded bond of titanium-steel bimetal: *a, b* – arc pulsed surfacing with a melting electrode; *c, d* – plasma surfacing with squat wire; *e, f* – plasma powder surfacing; 1 – titanium layer; 2 – steel layer; 3 – weld of the titanium layer; 4 – sprayed coating of steel (iron); 5 – weld layer of steel (iron) on a sprayed coating on titanium; 6 – welding arc; 7 – current supply; 8 – electrode (in cases *a, b* – wire, in cases *c–f* – non-melting electrode); 9 – flow of protective gas; 10 – protective nozzle; 11 – plasma-forming gas flow; 12 – plasma-forming nozzle; 13 – filler powder carried by transporting gas

Table 3

Basic information on the spraying of barrier coatings on titanium plates and the subsequent surfacing of steel (iron) layers on them

Sample number	Spraying/surfacing method	Applied material	Unit energy, J/mm	Outcome
1	2	3	4	5
1. 1	Plasma-arc spraying with conductive anode wire (Fig. 4)	Steel wire ER70S-6	–	Layers with a thickness of 150...250 to 600...750 microns are applied
1. 2	Surfacing of P-MAG with fusible wire (Fig. 5, *a*, *b*)	Steel wire ER70S-6	450	A layer with a thickness of 1–2 mm is surfaced
2. 1	Plasma-arc spraying with conductive anode wire (Fig. 4)	Steel wire ER70S-6	–	A layer with a thickness of 150...250 to 600...750 microns is applied
2. 2	Plasma surfacing with squat wire (Fig. 5, *c*, *d*)	Steel wire ER70S-6	330	A layer with a thickness of 1–2 mm is surfaced

Continuation of Table 3

1	2	3	4	5
3. 1	Supersonic plasma-powder spraying (Fig. 3)	Iron powder CNPC-Fe200	–	A layer with a thickness of 150...250 to 600...750 microns is applied
3. 2	Plasma surfacing with squat wire (Fig. 5, *c*, *d*)	Steel wire ER70S-6	330	A layer with a thickness of 1–2 mm is surfaced
4. 1	Supersonic plasma-powder spraying (Fig. 3)	Iron powder CNPC-Fe200	–	A layer with a thickness of 150...250 to 600...750 microns is applied
4. 2	Plasma-powder surfacing (Fig. 5, *d*, *e*)	Iron powder CNPC-Fe200	250	A layer with a thickness of 1–2 mm is surfaced

In determining the amount of linear surfacing energy, the following procedure was used. The running power of a thermal source was defined as the ratio of its power (the product of welding current and arc voltage) to the speed of movement. After that, linear energy was determined as the product of running power and efficiency of the process. The latter was chosen according to the recommendations from the literature [15–18] as 85 % for the P-MAG process, 60 % for plasma-arc processes.

5. 2. Plasma spraying of barrier layers on titanium

A typical view of the steel coating obtained by plasma-arc spraying of conductive wire-anode ER70S-6 (Ø1.6 mm) on titanium, in the development of bimetallic edges made for welding, is shown in Fig. 7, *a*. In the collision of steel particles with the titanium substrate, no melting and mixing of metal sections was observed (Fig. 7, *b*). X-ray spectral microanalysis (XSMA) showed the absence of IMP at the boundary of the sprayed layer and titanium (Fig. 8, Table 4). In the course of subsequent experiments, surfacing with steel wire or iron powder was performed on top of the sprayed steel layer.

The microstructure of the coating on titanium obtained by supersonic plasma spraying of CNPC-Fe200 powder is similar to that obtained by spraying conductive steel wire. In this case, there were also no particles of metallurgical interaction between the separation boundary between the sprayed coating and the titanium base. X-ray spectral microanalysis (XSMA) showed the absence of IMP at the border of sprayed layers and titanium.

Table 4

The content of elements (wt%) in local areas of plasma-arc spraying of steel wire-anode ER70S-6 on Grade2 titanium (Fig. 8), determined by X-ray spectral microanalysis (XSMA)

Spectrum	O	Al	Si	Ti	Mn	Fe	Ni	Total
Spectrum 1	–	0.42	–	99.58	–	–	–	100
Spectrum 2	–	–	–	1.88	0.64	97.47	–	100
Spectrum 3	–	–	–	1.48	0.87	97.65	–	100
Spectrum 4	–	–	0.59	0.65	1.37	97.39	–	100
Spectrum 5	21.81	–	0.41	0.84	0.83	76.1	–	100
Spectrum 6	–	–	–	13.92	–	80.19	5.89	100
Spectrum 7	27.68	–	–	0.77	–	71.55	–	100

The thickness of the sprayed coatings obtained by the two described technologies (Fig. 3, 4) was 150...250, 200...450, and 600...750 microns. In all cases, the values of the adhesion strength of these sprayed coatings with the titanium substrate when breaking at normal were at least 35–40 MPa), which ensured the stability of these coatings when molten metal was welded on them. In the case of increasing the thickness of sprayed coatings above 750–1000 microns, the value of their adhesion strength to the base is reduced to 20–25 MPa.

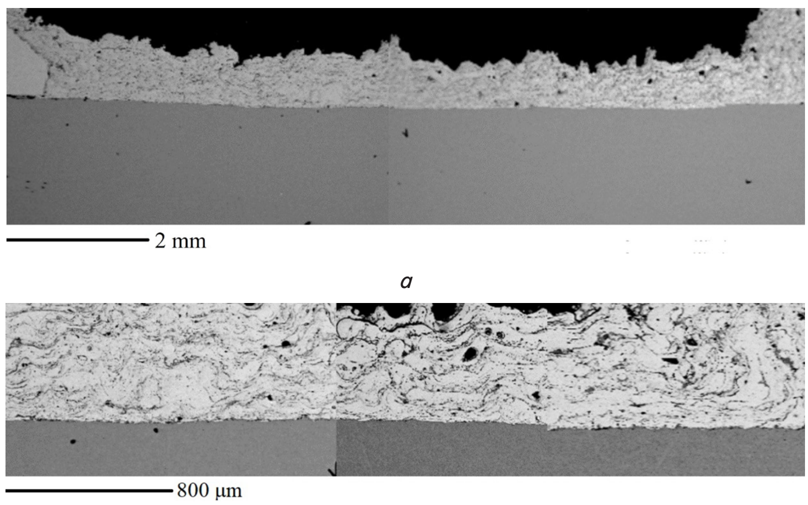


Fig. 7. Cross-section of the sample obtained by plasma-arc spraying of ER70S-6 wire on titanium: *a* — general view; *b* — fragment

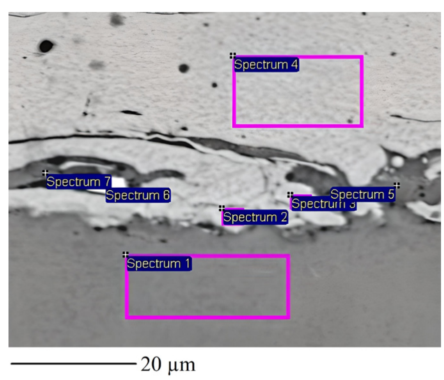


Fig. 8. Local areas for determining the content of elements in the Ti-Fe transition zone by the XSMA method after plasma-arc spraying of steel wire-anode ER70S-6 on Grade2 titanium

5. 3. Arc surfacing of thin layers of carbon steel on sprayed barrier layers

On top of the steel and iron layers sprayed on titanium, we were surfacing with steel wire and iron powder. In this case, methods such as pulsed arc surfacing of a melting electrode (P-MAG), plasma-arc surfacing with additive neutral steel wire, and plasma-powder surfacing were used (Table 3).

Below are the features of the interfacial interaction between titanium and iron, characteristic of the methods used.

The macrostructure of the sample obtained by P-MAG by surfacing steel wire on a steel coating obtained by plasma-arc spraying of conductive wire is presented in Fig. 9, *a*. Metallographic studies of such surfacing revealed the presence of a continuous intermetallide layer on the border of the sprayed metal with the base (titanium). In the process of surfacing steel wire on a sprayed steel coating, melting of coating fragments takes place. This leads to the mixing of steel in different ratios with the titanium base, followed by the formation of IMP at the boundary of titanium and steel. The thickness of the intermetallide layer around the perimeter of surfacing is not constant and varies from 170 to 220 microns. Structural defects such as pores and microcracks are noticeable (Fig. 9, *b*).

According to local X-ray spectral microanalysis, the composition of the intermetallide layer varies (wt%): from 67.5...69.06 Ti – 30.15...31.73 Fe – 0.13...0.63 Mn; to 47.86...48.81 Ti – 50.32...51.49 Fe – 0.32...0.42 Mn (Fig. 10, Table 5).

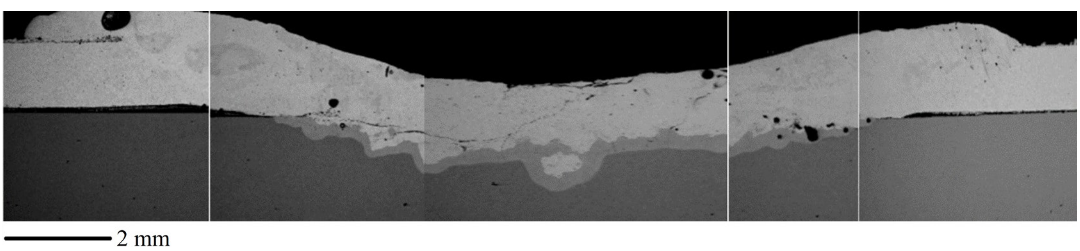
To minimize the formation of IMP at the titanium-steel boundary, a way to reduce the linear surfacing energy was chosen. In addition to P-MAG, the processes of plasma surfacing on a coating sprayed onto a titanium base, namely, plasma surfacing of ER70S-6 squat wire and plasma-powder surfacing of CNPC-Fe200 powder (Table 3) were investigated.

When plasma surfacing of ER70S-6 wire on a coating sprayed on a titanium base with a thickness of 150...250 microns, CNPC-Fe200 powder forms a transition layer of IMP with a thickness of 100...250 microns (Fig. 11). The composition of the compounds of titanium and iron formed in this case approximately corresponds to the intermetallic compound $FeTi_2$ (Table 6). It is necessary to note the absence of defects (cracks, pores), both in this intermetallic compound layer and in the zones adjacent to it. Similar results were obtained for plasma-arc surfacing of CNPC-Fe200 powder on a sprayed coating from powder of identical composition CNPC-Fe200, namely the formation of a continuous defect-free layer of IMP of similar thickness. Transition zone of up to 250 microns thick titanium – steel compound obtained in this way is characterized by the presence of intermetallic compounds such as FeTi and $FeTi_2$ and titanium β alloy with a high iron content of 28.23...28.26 wt% (Fig. 11, 12, Table 7).

Table 5

Content of elements (PCMA method) in the local areas of P-MAG surfacing of steel wire ER70S-6 on steel coating applied to titanium by plasma-arc spraying of conductive wire ER70S-6

Sample in the area of Fig. 10, *a*							Sample in the area of Fig. 10, *b*						
Sp.	Chemical composition, wt%						Sp.	Chemical composition, wt%					
	Al	Si	Ti	Mn	Fe	Total		Al	Si	Ti	Mn	Fe	Total
1	0.23	0.52	27.15	0.84	71.26	100	1	0.43	0.36	61.14	0.21	37.86	100
2	0.29	0.22	68.19	0.63	30.68	100	2	0.13	0.21	47.86	0.32	51.49	100
3	0.22	0.14	67.5	0.41	31.73	100	3	0.22	0.23	48.81	0.42	50.32	100
4	–	0.61	30.28	0.91	68.2	100	4	0.31	0.15	55.27	0.36	43.91	100
5	0.59	–	99.41	–	–	100	5	0.39	0.27	69.06	0.13	30.15	100
–	–	–	–	–	–	–	6	0.16	0.43	33.51	0.67	65.23	100
–	–	–	–	–	–	–	7	0.08	0.42	44.36	0.71	54.42	–



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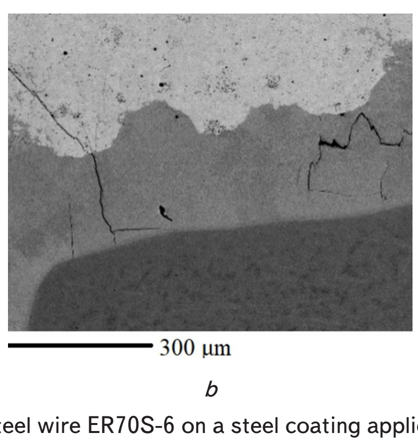

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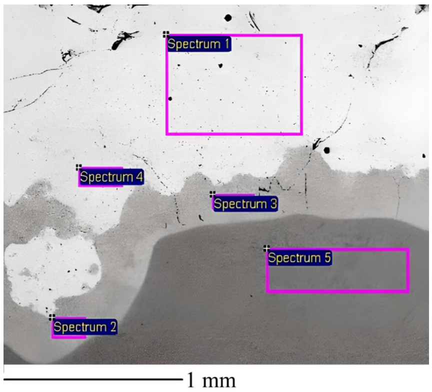
Fig. 9. Sample of P-MAG surfacing of steel wire ER70S-6 on a steel coating applied to titanium by plasma-arc spraying of similar wire: *a* – general view; *b* – fragment of the cross section of the sample



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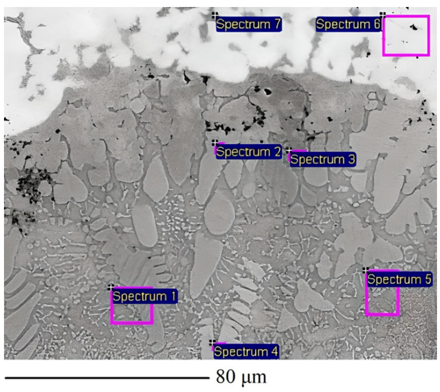

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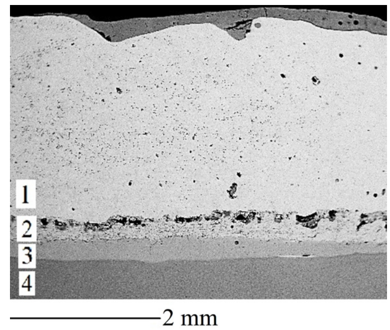
Fig. 10. Transition zone of Ti-Fe after P-MAG surfacing of steel wire ER70S-6 on a coating applied to titanium by plasma-arc spraying of similar wire, indicating the zones for determining the content of elements by the XSMA method: *a* — general view of the local section of the transition zone; *b* — enlarged fragment

Similar phenomena occur for other studied technological options for plasma surfacing of ER70S-6 fitting steel wire on coatings sprayed on titanium. This refers to the coatings obtained by supersonic plasma spraying of CNPC-Fe200 iron powder and coatings obtained by plasma-arc spraying of conductive steel wire ER70S-6. In general, it can be concluded that during plasma surfacing of steel wire or iron powder on a sprayed steel or iron coating in the transition zone between the coating and titanium, IMP is formed. There were two types of inclusions of eutectic intermetallic compounds having a composition (wt%): 50.2...53.27 Ti – 46.36...49.35 Fe – 0.28...0.71 Mn and 74.24 Ti – 25.25 Fe – 0.23 Mn. This roughly corresponds to the composition of titanium compounds with iron – FeTi and $FeTi_2$ and titanium β alloy with a high iron content.

By optimizing plasma surfacing modes, the minimization of energy injection and linear energy values of 200...250 J/m was achieved. Due to this, there is a decrease in the thickness of the intermetallic compound layer of the transition zone between the sprayed coating and titanium (at the border of the titanium-steel section) after surfacing on the coating of steel wire or iron powder – up to 50–60 microns. X-ray spectral microanalysis showed (Table 8) that this layer has the following content of elements (wt %): 70.55 Ti – 28.49 Fe – 0.34 Mn.

This content approximately corresponds to the composition of the compound of titanium with iron $FeTi_2$. In this case, the formation of this layer does not lead to cracks and other defects (Fig. 13), which makes it possible to recommend this technological solution for the production of butt welded joints of titanium-steel bimetallic plates.



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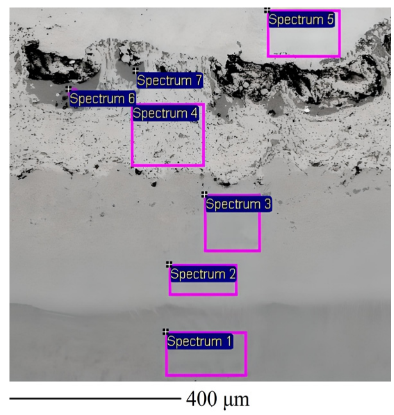

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Fig. 11. The compound obtained by plasma surfacing of CNPC-Fe200 iron powder on a layer of plasma-arc spraying of steel wire ER70S-6 on titanium: *a* — macrostructure; 1 — surfaced layer; 2 — sprayed coating; 3 — transition zone formed during the surfacing process; 4 — titanium base; *b* — microstructure

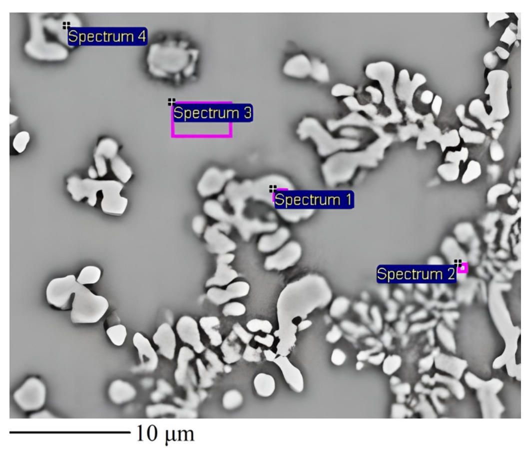
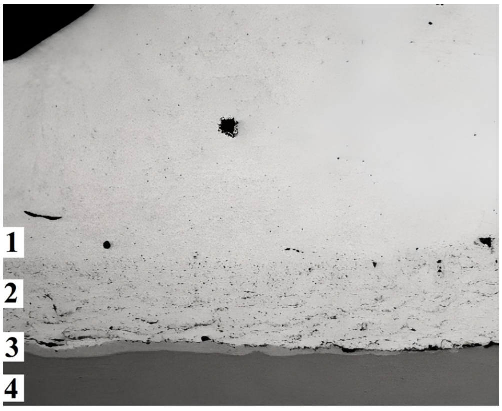


Fig. 12. Microstructure of the transition zone between steel plasma coating and titanium after plasma-powder surfacing on this coating

The structures of individual sections of the titanium-steel compound shown in Fig. 13 demonstrate a general tendency to form a defect-free compound. During its formation, there is no peeling of the coating applied by plasma-arc spraying, and the deposited steel layer does not mix with titanium.



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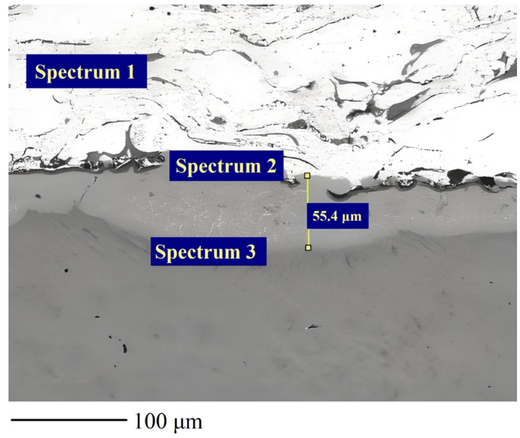

b

Fig. 13. The connection obtained by plasma surfacing of steel wire ER70S-6 on the coating applied to titanium by plasma-arc spraying of conductive wire ER70S-6: *a* — macrostructure; 1 — surfaced layer; 2 — sprayed coating; 3 — transition zone formed during the surfacing process; 4 — titanium base; *b* — microstructure

Table 6

Chemical composition of the titanium-coating compound obtained by spraying ER70S-6 wire onto the CNPC-Fe200 powder surfacing layer (Fig. 11, *b*)

Spectrum	O	Al	Si	Ti	Mn	Fe	Total
Spectrum 1	–	0.43	–	99.57	–	–	100
Spectrum 2	–	0.33	–	71.01	–	28.66	100
Spectrum 3	–	0.44	0.22	70.87	0.24	28.23	100
Spectrum 4	–	–	0.55	0.55	1.11	97.8	100
Spectrum 5	–	–	0.1		0.04	99.86	100
Spectrum 6	26.49	–	–	3.37	2.79	67.35	100
Spectrum 7	26.6	–	–	4.56	1.99	66.86	100

Table 7

Chemical composition of the local sections of the transition zone shown in Fig. 12

Spectrum	Si	Ti	Mn	Fe	Total
Spectrum 1	0.12	50.2	0.32	49.35	100
Spectrum 2	0.15	52.93	0.25	46.67	100
Spectrum 3	0.28	74.24	0.23	25.25	100
Spectrum 4	0.08	53.27	0.28	46.36	100

Table 8

Chemical composition of the compound obtained by plasma surfacing of ER70S-6 wire on a steel coating applied to titanium by plasma-arc spraying of conductive wire ER70S-6 (Fig. 13, *b*)

Spectrum	Al	Si	Ti	Mn	Fe	Total
Spectrum 1	–	0.66	–	1.12	98.22	100
Spectrum 2	0.32	0.3	70.55	0.34	28.49	100
Spectrum 3	0.35	0.07	99.48	0.1	–	100

6. Discussion of results of research on the influence of technological techniques on the features of structure formation

Experiments were carried out on spraying a steel (ER70S-6) or iron (CNPC-Fe200) layer on Grade2 titanium plates, followed by surfacing of layers of similar materials. Surfacing of steel wire ER70S-6 was carried out by P-MAG and plasma-arc methods, surfacing of iron powder CNPC-Fe200 – plasma-arc (Fig. 5). In this case, by reducing the surfacing thickness in one pass to 1–2 mm, the running energy of the processes was minimized to ~250...330 J/mm (Table 3). The fundamental difference between this approach and the approaches reported in [5, 7] is the formation of the root zone of the steel layer connection in the transition zone from the side of the titanium layer. In this case, plasma-arc spraying was used to obtain a barrier layer, in contrast to [2–8].

On the titanium base, spraying of steel wire or iron powder was performed, followed by arc or plasma surfacing of similar materials (steel wire or iron powder) on them. It was established that in the case of a thickness of plasma coatings of 150–250 microns, their complete melting is observed with the formation of a continuous layer of IMP up to 250 microns thick. For example, plasma surfacing with ER70S-6 wire (running energy ~330 J/mm) on a sprayed coating of the same wire with a thickness of 150–250 microns creates a transitional layer of IMP with a thickness of 50...250 microns. And during R-MAG surfacing with ER70S-6 wire (linear energy ~450 J/mm) on plasma coatings with a thickness of 150–250 microns, sprayed using steel wire or iron powder, transitional intermetallic compound layers with a thickness of 170...220 microns. In this case, plasma coatings are also completely melted down and do not perform the function of a barrier layer, which prevents metallurgical interaction between the surfaced steel layer and titanium. The results obtained are close to those described in [2] and, according to the conclusions made in this paper, are unsatisfactory.

However, already with the thickness of the sprayed steel or iron coating on titanium of at least 400...600 microns, their integrity is preserved during plasma surfacing of steel or iron layer with a thickness of 1–2 mm on them. With a running energy value of 200...250 J/mm of plasma surfacing on sprayed coatings at the interface of the titanium-steel section, an IMP layer with a thickness of 50–60 microns is formed. Despite the improvement in the result, according to the data of work [1], such a layer of IMP should contain compounds like FeTi+α-Ti, which are fragile and can lead to the destruction of the compound.

When applied in practice, including in further research, the developed methodology should take into account the following limitations. When plasma coatings with a thickness of 750 microns and above are applied to titanium, their adhesion strength with a titanium base is reduced to values of 20 MPa. This in some cases can lead to their detachment in the process of surfacing. It should be noted that in certain cases, plasma-arc spraying processes can provide greater values of adhesion strength of coatings (for example, titanium coatings with steel in work [19]). But this is due to the use of another method of preparing the sprayed surface, difficult to access in the case of spraying on the welded titanium layer. When choosing the height of the barrier coating, it is necessary to take into account the fact that it must reliably cover the depth of the milling grooves, which is carried out in the preparation of the sprayed surface. That is, the height of this coating should be at least 0.25...0.30 mm. Taking into account the fact that the height of the coating should be guaranteed to exceed the size of the transition zone (that is, the IMP layer), it must be at least 0.4 mm.

The main disadvantage of the devised procedure is a rather narrow interval of linear energies of arc surfacing (Table 3). In this interval, fusing with a sprayed barrier layer does not lead to its separation from the titanium layer of bimetal, as well as to the threat of remelting of the latter. Another disadvantage is the need for additional mechanical operation in the form of preparing a titanium layer for spraying.

The surfacing method when filling the development of steel edges of titanium-steel bimetal should minimize the thermal effect on the sprayed coating and the width of the transition zone between the surfacing metal and the coating. The linear energy of the surfacing process should not exceed 200...250 J/mm. In this way, plasma surfacing of steel wire or plasma-powder surfacing can be optimized. In this case, the optimal values of the thickness of the sprayed steel or iron barrier coating on titanium, applied by plasma-arc spraying of steel wire or supersonic plasma spraying of iron powder are within 0.4...0.6 mm.

Further development of this study is to increase the stability intervals of the formation of a defect-free transition zone from titanium layer to steel in welded joints of bimetallic sheets. To this end, it is necessary to more clearly define the boundaries of the zones of increase and decrease in the thickness of the sprayed layer and the linear energy of surfacing. It is also necessary to improve the hardware solutions of the technological equipment used for highly accurate and stable reproduction of the spraying and surfacing modes defined in this work. Another area of further research is to determine the most effective approach to the preparation of the titanium layer for spraying, which will maximize the adhesion strength of the sprayed barrier layer with titanium.

7. Conclusions

1. The possibility of applying steel or iron layers by plasma-arc spraying of steel wire or iron powder has been investigated. Such layers minimize the formation of fragile intermetallic compound zones and associated defects that occur during butt welding of titanium-steel bimetallic plates by melting methods. The technological approach for obtaining a welded bimetal joint by applying a special U-shaped development of the edges of bimetallic plates has been investigated. This approach allows you to spray steel/iron coating with a thickness of 150...750 microns onto a titanium layer and subsequent multi-pass surfacing/welding to fill the specified development.

2. It is shown that the thickness of the sprayed steel (iron) coating and the amount of linear surfacing energy are the most important technological factors for obtaining the butt compound of titanium-steel bimetal. These factors affect the avoidance of cracking in the resulting welded joint. When using arc R-MAG surfacing with ER70S-6 wire, transition intermetallic compound layers with a thickness of 170...220 microns are formed. These layers are characterized by the presence of pores and microcracks, which can be explained by the increased values of linear energy characteristic of this method (~450 J/mm). To eliminate the IMP layer, the minimum thickness of the sprayed coating should be at least 400 microns, and the amount of linear surfacing energy should be up to 200...250 J/mm. Such indicators of linear energy are achieved with plasma-arc surfacing with iron powder and additive steel wire. The thickness of the weld layer does not exceed 1–2 mm.

3. It was established that in the welded joint, made using the described technological approach, a transition zone is formed on the border with titanium, which consists of a β-phase titanium with a high content of iron and intermetallic compounds FeTi and $FeTi_2$. When minimizing the running energy of surfacing steel wire or iron powder on sprayed coatings to 250 J/mm, the thickness of this zone is up to 50...60 microns. This layer retains a certain plasticity, which makes it possible to obtain welded bimetallic joints without cracks and other defects.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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