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ARGON-ARC WELDING OF HIGH-STRENGTH SPARSELY-DOPED PSEUDO-β-TITANIUM ALLOY Ti–2.8Al–5.1Mo–4.9Fe

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Structural sparsely-doped titanium alloys are developed with the purpose of lowering the finished product cost. Possibility of application of tungsten electrode argon-arc welding (AAW) for sparsely-doped pseudo-β-titanium alloy Ti–2.8Al–5.1Mo–4.9Fe was evaluated. Influence of different kinds of argon-arc welding on weld formation and mechanical properties of Ti–2.8Al–5.1Mo–4.9Fe alloy joints were assessed. The effect of through penetration AAW, semi-submerged AAW, AAW with feeding unalloyed titanium welding filler wire VT1-00sv was studied. It was found that the structure of metal of the weld and HAZ in welded joints of sparsely-doped titanium alloy Ti–2.8Al–5.1Mo–4.9Fe made by AAW consists mainly of β-phase with precipitates of metastable α-phase. Lowering of AAW heat input for Ti–2.8Al–5.1Mo–4.9Fe alloy has a positive impact on the joint strength. So, among the welded joints made without changing the weld metal composition, the joints produced by semi-submerged arc welding have the highest strength of 972 MPa and the highest impact toughness on the level of 5.7 J/cm^2. 15 Ref., 3 Tables, 3 Figures.

Keywords: titanium, titanium alloys, argon-arc welding, heat input, flux, wire, mechanical properties

Tungsten-electrode argon-arc welding (AAW) became the most widely accepted for welding titanium alloys owing to the fact that this welding process is the least expensive and the most versatile [1, 2]. It allows making joints in different positions in space, under the conditions of limited space, and does not requires complex readjustment of the equipment at the change of welded product thickness or joint type. Welding can be performed both with application of filler metal, and without it. Used as filler metal are welding wires or rods from titanium alloys [3]. There is a number of variants of this method: welding with through penetration, and semi-submerged arc welding, which expand its technological capabilities [4]. In order to lower the cost of the production process and the cost of titanium alloy products, the concept of «sparse doping» of titanium alloys became widely accepted. It is based on selection of such alloying elements for the alloys which would have relatively low cost. Iron is the most widely spread alloying element for such alloys [5, 6]. Iron, owing to its stabilizing impact on β-phase, is also used for alloying several low-cost alloys, based on β-phase [7–9]. Welding such alloys based on β-phase is a little studied process. A large quantity of iron can cause considerable deterioration of welded joint properties due to brittle phase formation [10]. The currently available fluxes can have a refining effect in welding of sparsely-doped alloys [11]. Therefore, the possibility of applying fluxes for welding these alloys should be considered separately. In addition, in view of the absence of welding wires from sparsely-doped titanium alloys, it is rational to consider the impact of low-alloyed titanium wire on the properties of joints of such an alloy [12, 13].

The objective of the work was studying the impact of argon-arc welding modes on weld formation and mechanical properties of the produced joints of sparsely-doped pseudo-β-titanium alloy Ti–2.8Al–5.1Mo–4.9Fe.

Unalloyed titanium welding wire VT1-00sv of 2 mm diameter was used as the filler metal. It allows changing the degree of weld metal alloying within narrow limits. The relative quantity of filler metal in the weld metal was determined by calculation of the area of joint metal penetration on transverse weld sections.

Samples of titanium pseudo-β-alloy Ti–2.8Al–5.1Mo–4.9Fe of 200×100×6 mm were welded. Welding was performed from one side. Modes of through penetration tungsten electrode argon-arc welding from one side of sparsely-doped titanium pseudo-β-alloy Ti–2.8Al–5.1Mo–4.9Fe are given in Table 1.

Welding modes were selected under the condition of providing through penetration of joints of 6 mm Ti–2.8Al–5.1Mo–4.9Fe alloy. Tungsten electrode argon-arc welding can be performed in wide ranges of welding speed and welding current values. The most

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Table 1. Modes of through penetration AAW from one side of sparsely-doped titanium pseudo- β-alloy Ti–2.8Al–5.1Mo–4.9Fe

Mode number	Welding current, I_w, A	Arc voltage U_a, V	Welding speed v_w, m/h	Wire feed rate $v_{f.w}$	Preset arc length L_a, mm	Preheating temperature, T_{preh}, °C
1	330	12	10	–	2	–
2	350	12	10	30	2	–
3	350	12	10	60	2	–
4	310	12	10	–	2	400
5 (over a layer of flux)	240	12	16	–	2	–

widely used range of speeds of automatic AAW for titanium alloys is 10–20 m/h range. Full penetration of 6 mm samples occurs at through penetration AAW without filler at welding current of 330 A and welding speed of 10 m/h. Addition of filler wire leads to increase of welding current. Welding with preheating allows somewhat lowering the welding current to 310 A. Semi-submerged AAW due to argon arc constriction enables an essential lowering of welding current to 240 A, increasing the welding speed and providing full penetration of Ti–2.8Al–5.1Mo–4.9Fe alloy metal 6 mm thick. Thus, semi-submerged AAW allows welding titanium pseudo-β-alloy Ti–2.8Al–5.1Mo–4.9Fe in modes with minimum heat input and cross-sectional area of the metal of weld and HAZ (Table 2).

Transverse macrosections of the produced welds are given in Figure 1. An example of through penetration tungsten electrode welding (Figure 2) confirms formation of a through hole under the tungsten electrode at through penetration welding. When welding current is switched off, a hole forms under the tungsten electrode, if the crater welding up mode is not used.

Calculation of filler metal quantity in the weld metal was performed by the results of studying the prepared transverse macrosections. It was found that at 60 m/h feed rate of 2 mm VT1-00sv filler wire and 8 m/h welding speed the quantity of VT1-00 filler metal in the weld metal is 21–25 %. Accordingly, at 30 m/h feed rate of the filler wire, the quantity of VT1-00 filler metal in the weld metal is 10–13 %.

The base metal of welded joint of sparsely-doped titanium pseudo β-alloy Ti–2.8Al–5.1Mo–4.9Fe consists of recrystallized grains (Figure 3, *a*), equiaxed polyhedral β-grains, both in the near-surface layers, and inside the metal. The size of β-grains is equal to 200–600 μm. Located inside β-grains are dispersed particles of α-phase. Dispersed particles of different shape and dimensions precipitate in base metal microstructure, both in the surface areas, and those remote from the surface. Precipitate dimensions vary within a broad range (from less than 1 μm up to 15 μm), and are nonuniformly distributed in the grain body.

Figure 3, *b*–*f* shows the weld metal microstructure. The weld structure is dendritic (modes No.1 and No.2, see Table 1). Particles of another precipitating phase are smaller than those in the base metal, and their dimensions are from less than 1 to 3–4 μm (Figure 3, *b*, *c*). In the weld of a joint made by AAW with filler wire feeding at the rate of 60 m/h that ensures 21–25 %, unlike the above-considered cases, the weld microstructure also changed, as a result of considerable change of the weld metal chemical composition and its dilution. In the weld metal of this joint, the instability of β-solid solution leads to a significant

Table 2. Parameters of welds in AAW joints of sparsely-doped titanium alloy Ti–2.8Al–5.1Mo–4.9Fe made by AAW*

Mode number	Sample type, I_w, v_w, $v_{f.w}$	Weld width, mm	HAZ width, mm	Weld area, mm^2	Heat input, J/cm	Quantity of β-phase, %
BM	Base metal	–	–	–	–	76
1	Welded joint without filler, I_w = 330 A, v_w = 10 m/h	13	21	53	14256	77
2	Welded joint with filler, I_w = 350 A, v_w = 10 m/g, $v_{f.w}$ = 30 m/h	15.1	24.1	59.8	15120	75
3	Welded joint with filler, I_w = 350 A, v_w = 10 m/g, $v_{f.w}$ = 60 m/h	16.5	25.5	73.1	1511.9	56
4	Welded joint with preheating to 400 °C, I_w = 310 A, v_w = 10 m/h	17	25	65.0	13392	75
5	Welded joint produced by semi-submerged-arc welding I_w = 240 A, v_w = 16 m/h	7.2	17.2	33.9	6480	63
*Joint thickness is 6 mm.						

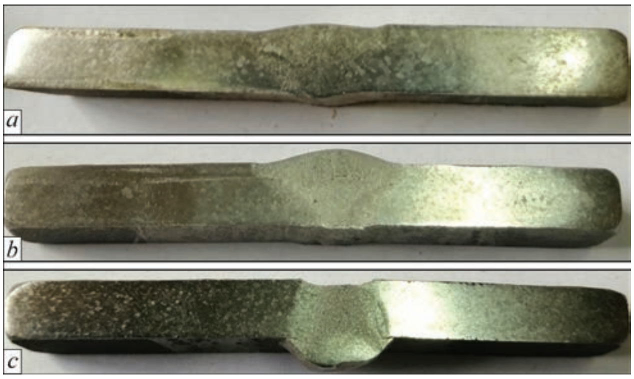

Figure 1. Transverse macrosection of the joint of sparsely-doped titanium pseudo-β-alloy Ti–2.8Al–5.1Mo–4.9Fe made by AAW: *a* — through penetration without filler wire application; *b* — with filler metal addition to the weld in the quantity of 10 %; *c* — made by semi-submerged AAW without filler wire

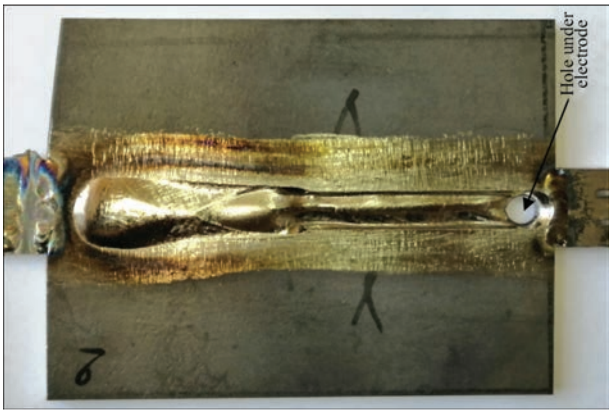

Figure 2. Example of welded joint of a sparsely-doped pseudo-β-alloy Ti–2.8Al–5.1Mo–4.9Fe, made by through penetration AAW without filler wire, mode No.1

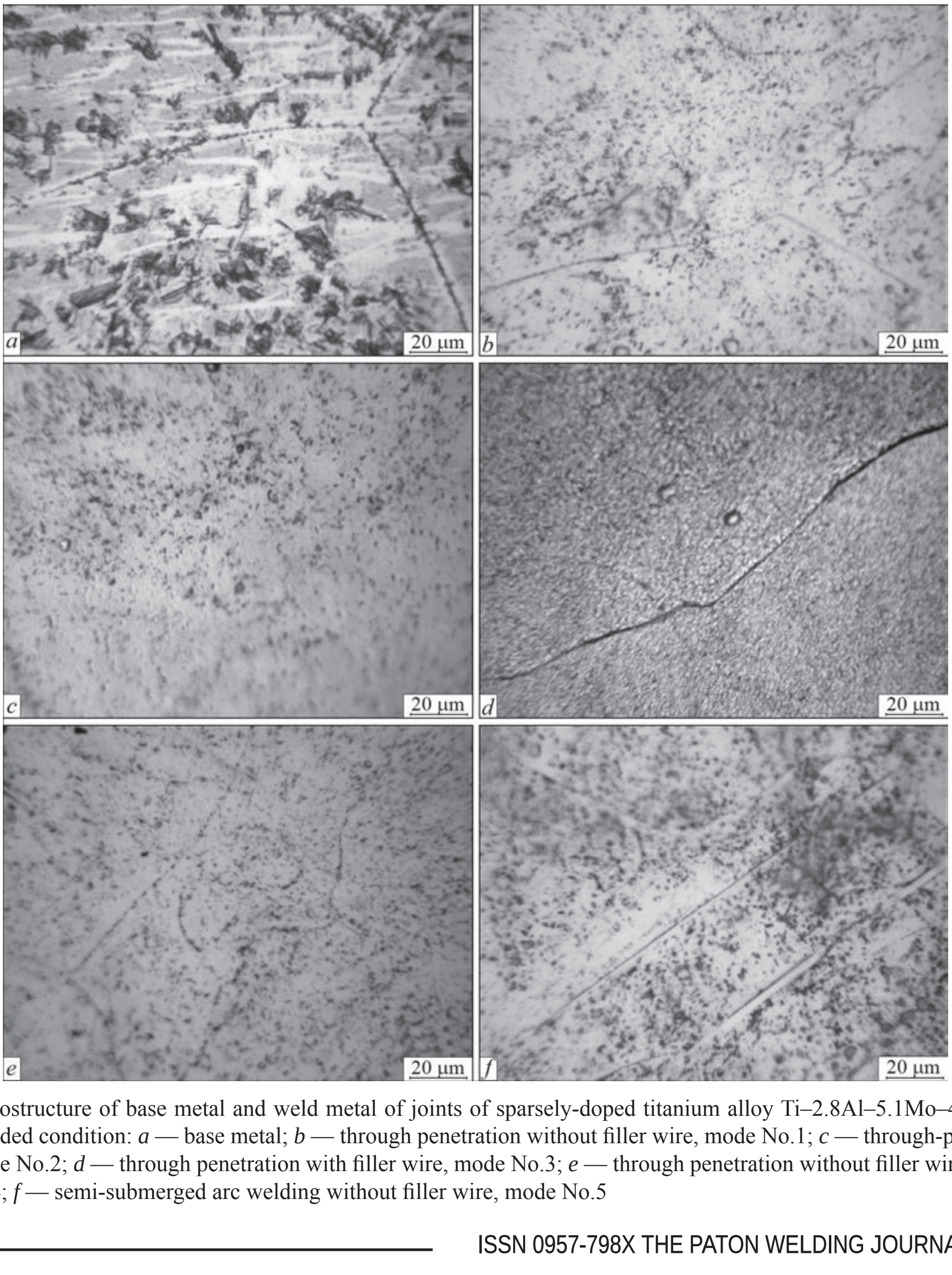

Figure 3. Microstructure of base metal and weld metal of joints of sparsely-doped titanium alloy Ti–2.8Al–5.1Mo–4.9Fe, made by AAW in as-welded condition: *a* — base metal; *b* — through penetration without filler wire, mode No.1; *c* — through-penetration with filler wire, mode No.2; *d* — through penetration with filler wire, mode No.3; *e* — through penetration without filler wire with preheating, mode No.4; *f* — semi-submerged arc welding without filler wire, mode No.5

Table 3. Mechanical properties of base metal and joints of sparsely-doped titanium alloy Ti–2.8Al–5.1Mo–4.9Fe, made by AAW in as-welded condition

Mode number	Sample type	Tensile strength σ_t, MPa	Yield limit σ_y, MPa	Relative elongation δ, %	Reduction in area ψ, %	Impact toughness, *KCV*, J/cm^2
BM	Base metal	1071	971	2.0	–	5.3
1	Joint	921	–	–	–	4.9
2	Same	1002(968)	936	10	27	5.5
3	–	960	–	–	–	3.5
4	–	799	–	–	–	4.3
5	–	972	925	8.0	23	5.7

decomposition at weld metal cooling after welding with precipitation of a considerable quantity of α-phase (Figure 3, *d*). The welds of the joints made by through-penetration AAW method without feeding the filler wire (mode No.4, see Table 1) with joint preheating to 400 °C temperature and over a layer of flux (mode No.5, see Table 1) are based on β-phase, similar to welding in modes No.1 and No.2 (Figure 3, *e, f*).

Thus, in the structure of the metal of welds the most finely-dispersed precipitates of metastable α-phase of up to 1–2 μm size, are found in joints made by semi-submerged arc welding. Joints made by AAW with preheating, alongside large dimensions of welds and HAZ in as-welded state demonstrate nonuniform precipitation of fine particles of metastable α-phase: finer in the weld upper part than in the lower one. It may point to a too high temperature of the applied preheating which in this case was 400 °C [14]. On the whole, application of preheating for AAW of joints of sparsely-doped titanium alloy Ti–2.8Al–5.1Mo–4.9Fe is undesirable.

The smallest quantity of β-phase was registered in welds, made by AAW with feeding VT1-00 filler wire at the rate of 60 m/h that ensures 21–25 % content of filler wire in the weld, and is equal to 56 % (Table 2) which is attributable to lowering of the degree of weld metal alloying. In welds, made by semi-submerged AAW the quantity of β-phase also decreased to 63 %. Note that at semi-submerged AAW the joints made with the lowest heat input values (see Table 2), have the smallest width of the weld and HAZ, and the weld area. In other welds made without any change of weld alloying, the quantity of β-phase in as-welded condition is equal to 75–77 %.

Establishing the mechanical properties of welded joints of sparsely-doped titanium alloy Ti–2.8Al–5.1Mo–4.9Fe made by AAW, led to the conclusion that the lowest values of strength in as-welded condition are determined for joints made with preheating to 400 °C, and they are equal to 799 MPa that is 75 % of base metal strength (Table 3). The strength of joints made with application of VT1-00sv filler wire in the modes that ensure the content of VT1-00 metal in the weld on the level of 10–13 %, is the highest. In this case, the strength values reach 1002 MPa, or 93 % of base metal strength. Impact toughness of weld metal samples with a sharp-angled notch (*KCV*) made with application of VT1-00sv filler wire at feed rate of 30 m/h at VT1-00 metal content in the weld on the level of 10–13 % reaches maximum values (5.5 J/cm^2). Impact toughness values of samples with a sharp-angled notch from AAW joints are almost on the same level of 4.9–5.7 J/cm^2. The highest values are found in samples, made with flux application.

As the strength of VT1-00sv filler wire material (295–470 MPa) is much lower than that of base metal of Ti–2.8Al–5.1Mo–4.9Fe titanium alloy (1071 MPa), and it cannot be used as the strengthening alloying material, the cause for increased strength of the joints is the change of the structure and phase composition in welding with addition of VT1-00sv filler wire and loss of weld metal alloying. Quantity of β-phase decreases, so welded joints with loss of alloying will have higher strength values compared to joints without any change in weld alloying.

If we separately consider the properties of welded joints of Ti–2.8Al–5.1Mo–4.9Fe alloy, made without changing the weld metal composition, then the highest strength of the joints on the level of 972 MPa and the highest impact toughness of weld metal on the level of 5.7 J/cm^2 are found in joints made in the modes with lower heat input. So, semi-submerged arc welding has minimum heat input of the process on the level of 6480 J/cm, which is almost two times higher than that of through penetration AAW (14256 J/cm) and AAW with preheating (13392 J/cm). Note that the cross-sectional area of weld metal is the largest at AAW with preheating (see Table 2). Increase in the strength of joints made in the modes with lower heat input is attributable to a smaller quantity of β-phase in the weld metal. Reduction of the quantity of β-phase in the weld metal occurs under the conditions of lowering of the cooling rates in the temperature range of β→α+β polymorphous transformations at joint cooling.

Obtained data lead to the conclusion that the highest strength is found in joints where the weld metal composition is different from that of the base metal. If we compare joints, in which the chemical composition of the metal did not change, then the highest strength (972 MPa or 90 % of base metal strength) is demonstrated by joints made with flux application.

It leads to the conclusion about the rationality of application of tungsten electrode semi-submerged AAW for producing joints of sparsely-doped titanium alloy Ti–2.8Al–5.1Mo–4.9Fe. Semi-submerged AAW ensures the lowest values of the heat input and minimal dimensions of the weld and HAZ.

Contrarily, the joints made with preheating up to 400 °C have the lowest strength values, which is indicative of the unsuitability of this welding process for producing joints of sparsely-doped titanium alloy Ti–2.8Al–5.1Mo–4.9Fe.

Note that as a result of the impact of AAW on joints of VT19 pseudo-β-alloy, also β-phase is predominantly reported in the welds [15]. Here, the level of strength of the joints at AAW with application of VT1-00sv filler wire in the quantity of 22 % is on the level of σ_t = 965 MPa. In joints of VT19 alloy made by TIG-welding without filler wire application, the values of tensile strength are on the level of σ_t = = 860 MPa, that is much lower than the strength of Ti–2.8Al–5.1Mo–4.9Fe alloy.

Thus, the properties of welded joints of sparsely-doped titanium alloy Ti–2.8Al–5.1Mo–4.9Fe made by tungsten electrode AAW were studied, and it was established that joints made with application of VT1-00sv filler wire in the quantity of 10–13 %, demonstrate the highest strength on the level of 1002 MPa, or 93 % of that of the base metal. Here, the quantity of β-phase in the weld metal is 75 %. In order to ensure a homogeneous structure, and decomposition of metastable phases, and to produce full strength joints, they have to be subjected to further heat treatment.

Conclusions

1. The modes of argon-arc welding with lower heat input for sparsely-doped pseudo-β-alloy Ti–2.8Al–5.1Mo–4.9Fe have a positive impact on joint strength. So, among the welded joints, made without any change of weld metal composition, the joints produced by semi-submerged welding with minimum heat input and cross-sectional area of the weld metal, demonstrate the highest strength of 972 MPa and the highest impact toughness at the level of 5.7 J/cm^2.

2. The structure of the metal of weld and HAZ of the joints of sparsely-doped titanium alloy Ti–2.8Al–5.1Mo–4.9Fe made by AAW, consists mainly of β-phase, with precipitates of metastable α-phase; the size of α-phase particles precipitates is smaller, than in the base metal, and it is equal from less than 1 μm to 3–4 μm. The finest precipitates of metastable α-phase are found in joints made by semi-submerged AAW, precipitate size being up to 1–2 μm.

3. The strength of joints of Ti–2.8Al–5.1Mo–4.9Fe titanium alloy made by AAW with application of VT1-00sv filler wire in the quantity of 10–13 % in as-welded condition is equal to 1002 MPa or 93 % of that of the base metal. Here, the quantity of β-phase in the weld metal is equal to 75 %. To ensure a homogeneous structure of the weld, HAZ and base metal and decomposition of metastable phases, and to produce full strength joints, all the joints have to be subjected to further heat treatment.

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