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MECHANICAL CHARACTERISTICS OF WELDED JOINTS OF HIGH-STRENGTH TITANIUM ALLOYS PRODUCED BY VARIOUS WELDING METHODS

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ABSTRACT

Properties of welded joints of VT19 and Ti–2.8Al–5.1Mo–4.9Fe titanium pseudo-β-alloys and complex T120 titanium (α+β)-alloy, produced by electron beam and argon-arc welding and after several kinds of heat treatment (annealing, controlled annealing, quenching in water, delayed cooling) were studied. In addition to reliable protection of welded joints, another advantage of the technology of electron beam welding of titanium and alloys on its base is the possibility of performing local preheating and further heat treatment in the vacuum chamber. A quality criterion was proposed in order to compare the properties of welded joints in as-welded condition and after additional heat treatment. It was determined that performance of electron beam welding using local heat treatment and preheating, as well as making the joints by argon-arc welding using filler material, which allows lowering by 10–20 % the amount of alloying elements in the weld metal, compared to base metal, ensures a high quality of welded joints of high-strength titanium pseudo-β-alloys in as-welded condition.

KEYWORDS: titanium, titanium alloys, two-phase, (α+β)-, sparsely-doped, pseudo-β-, welded joints, heat treatment, annealing, quenching, aging, microstructure, mechanical properties

INTRODUCTION

A considerable increase of the scope of investigations aimed at producing titanium alloys with a new set of properties has been observed over the recent decades [1–3]. In the leading world materials science centers of the USA, China and EC intensive work is being conducted on development of new titanium alloys with enhanced performance.

Structural pseudo-β-titanium alloys are some of the most promising titanium-based metal materials. One of the advantages of the modern pseudo-β-alloys of titanium is their high manufacturability, which allows them to be deformed at lower forces and temperatures than the traditional high-temperature and high-strength alloys with pseudo-α- and (α+β) structures [3, 4]. In addition, heat treatment of structures from these alloys can be performed without their transferring into the quenching medium, which reduces the deformational and residual stresses and prevents metal oxidation [5]. The possibility of comparing the properties of pseudo-β-alloy welded joints with those of high-strength (α+β)-alloys attracts special attention.

A wider application of titanium alloys in different industries requires both improving their mechanical characteristics [6], and lowering the production cost, which can be achieved by developing new alloys with improved service properties and application of new high-efficient manufacturing technologies, including welding.

As regards pseudo-β-alloys of titanium there is a tendency in the world practice of application of alloying elements, which have a relatively low cost. It allows reducing the cost of the production process and lowering the cost of the semi-finished products, respectively [7]. Such alloys are usually called sparsely-doped. The sparsely-doped titanium alloys include low alloys which do not contain expensive or deficit elements (Mo, Ta, Zr, Nb, W, etc.) and have relatively inexpensive components of commercial purity at the base of their alloying systems (Al, Fe, Cu, etc.). Sparsely-doped alloys can also contain oxygen as an alloying element [8].

Alloys, which harden to β-phase at rapid cooling from β-region temperatures, are considered to be titanium β-alloys. Coefficient of β-stabilization of such alloys is $K_\beta > 1$ [9]. Among these alloys, β-alloys and alloys with a relatively small amount of α-phase — pseudo-β-alloys with $K_\beta = 1.4 - 2.4$ are singled out, the polymorphous transformation running by β→(β+α) scheme here. In a stable condition they have (β+α) structure [10].

A special feature of pseudo-β-alloys is their high ductility, which allows them to be subjected to intense cold deformation. At treatment for β-solid solution, pseudo-β and β-titanium alloys compared to α- or α+β-alloys, have the same yield limit, much higher ductility and fracture toughness, as well as higher deformability at different kinds of loading. At the same time, their strength properties can be significantly higher due to aging, which leads to decomposition of β-solid solution and precipitation of strengthening phases [11, 12].

Investigations of the properties of welded joints of alloys having a large amount of β-stabilizers, revealed their significant shortcomings: high susceptibility to alloying element liquation, strong dependence of aging duration on the content of alloying elements and impurities, as well as low thermal stability, which is due to precipitation of intermetallics, for instance $TiCr_2$ in these alloy structure [13]. In welding sparsely-doped pseudo-β-alloys the welded joints have the following shortcomings: insufficient level of strength, ductility, instability of properties, as a result of which they are recommended for application in "ground objects" (medical implants, automotive parts and different decorative products).

Therefore, it is rational to assess the properties of welded joints of structural and sparsely-doped titanium pseudo-β-alloys made by electron beam (EBW) and argon-arc welding (AAW), and to compare them with the properties of welded joints of a high-strength complex titanium (α+β) alloy T120 of Ti–5.5Al–2.8.Mo–2.3V–4Nb–1.3Cr–1Fe–2.7Zr system, and well as to determine the level of welded joint hardening due to heat treatment.

The objective of this work is determination of the influence of electron beam and argon-arc welding and of several kinds of heat treatment, such as annealing, quenching in water, controlled annealing, delayed cooling, on the properties of base metal and welded joints of titanium pseudo-β-alloys VT19, Ti–2.8Al–5.1Mo–4.9Fe (LCB-5.1) and (α+β)-alloy T120, made by fusion welding.

EXPERIMENTAL PROCEDURE

To achieve the defined objective, we studied the structure and properties of base metal and joints of titanium pseudo-β-alloys VT19, Ti–2.8Al–5.1Mo–4.9Fe (LCB-5.1) and (α+β)-alloy T120 [14, 15], produced by tungsten-electrode argon-arc welding with through penetration and by electron beam welding, which were subjected to postweld heat treatment.

EBW of 10 mm thick samples from structural pseudo-β-alloy VT19, from sparsely-doped pseudo-β-alloys, such as Timet LCB and Ti–2.8Al–5.1Mo–4.9Fe (LCB-5.1) alloys, and (α+β)-alloy T120. EBW modes are given in Table 1. One of the advantages of the technology of EBW of titanium and alloys on its base, in addition to ensuring reliable protection of the welded joints, is the possibility of performing local preheating and further heat treatment in the vacuum chamber [16, 17]. Modes of EBW with local heat treatment (LHT) of 10 mm thick joints with welding speeds of 7 mm/s are given in Table 1.

AAW of 6 mm thick samples of VT19, Ti–2.8Al–5.1Mo–4.9Fe (LCB-5.1) alloys and (α+β)-alloy T120 was also performed. Modes of through penetration AAW without filler metal application are presented in Table 2. For promising high-strength titanium alloys, such as VT19, sparsely-doped LCB-5.1 alloy and (α+β)-alloy T120, welding wires of the respective chemical composition are not available. Therefore, if required, it is rational to use unalloyed titanium wire of VT1-00sv brand as filler metal, which allows, without changing the weld alloying system, reducing the content of alloying elements in the weld metal, depending on welding conditions. Modes 9-12 (Table 2) are for AAW with filler wire.

Titanium alloy welded joints can be produced in modes with different energy input values. To assess the efficiency of the selected welding mode, as well as after heat treatment of welded joints of high-strength titanium alloys, a criterion of welding mode quality in conditional units was proposed, which consists of the contribution of the modes of welding and heat treatment into comprehensive increase in overall indices of strength, ductility and impact toughness of titanium alloy welded joints relative to base metal of the respective alloy. On the whole

Table 1. Modes of EBW of experimental pseudo-β-titanium alloys VT19, LCB-5.1 and (α+β)-alloy T120

Mode	Alloy grade	Beam current, I_b, mA	V_w, mm/s	T_{pr}, °C	LHT temperature, °C	LHT duration, min
1	VT19	120	7	–	–	–
2	–»–	–»–	11	–	–	–
3	Timet LCB	–»–	7	–	–	–
4	LCB-5.1	–»–	–»–	–	–	–
5	VT19	90	–»–	400	–	–
6	–»–	–»–	–»–	–»–	750	10
7	LCB-5.1	–»–	–»–	–»–	–	–
8	–»–	–»–	–»–	–»–	750	10
9	T120, T110	–»–	–»–	–	–	–
10	T120	–»–	–»–	–	900	10

Table 2. Modes of AAW of high-strength pseudo-β-titanium alloys VT19, LCB-5.1 and (α+β)-alloy T120

Mode	Alloy	I_w, A	U_a, V	V_w, m/h	T_{pr}, °C	$V_{w\,f}$, m/h	Filler metal content in the weld, %
1	VT19	310	12	10	–	–	–
3 (over flux)	–»–	220	11	–»–	–	–	–
5 (over flux)	–»–	320	–»–	16		–	–
6	LCB-5.1	330	12	10	–	–	–
7	–»–	310	–»–	–»–	400	–	–
8 (over flux)	–»–	240	11	16	–	–	–
9	VT19	380	12	8	–	30	10
10	–»–	420	–»–	–»–	–	60	20
11	LCB-5.1	350	–»–	10	–	30	10
12	–»–	–»–	–»–	–»–	–	60	20
13	T120	380	–»–	–»–		–	–
14	–»–	360	11	16	–	–	–
15	–»–	320	–»–	10	–	–	–
16	–»–	350	12	–»–	–	30	10
17	–»–	–»–	–»–	–»–	–	60	20

for titanium alloys increase of some mechanical properties, for instance, strength, cases a respective lowering of ductility and impact toughness values. In some cases, however, it goes out of proportion. Analysis of the obtained results of welded joint mechanical characteristics led to the conclusion that in titanium alloy welded joints having high ductility values, the impact toughness values are at a high level. In the case, if we consider just the strength and impact toughness values, and determine their significance as equal, a coefficient of welding mode quality was proposed, which is defined as follows:

$$K_{w\,m} = 0.5(\sigma_w/\sigma_{BM}) + 0.5(KCV_w/KCV_{BM}).$$

The strength coefficient was also calculated by the following formula:

$$K_{w\,m} = \sigma_w/\sigma_{BM}.$$

RESULTS AND THEIR DISCUSSION

JOINT PROPERTIES AFTER WELDING

Welded joints of sparsely-doped Timet LCB titanium alloy have the highest strength. For this alloy the values of as-welded joint strength are equal to 1068 MPa or 89 % of base metal strength (Table 3). Impact toughness of samples with a sharp notch (*KCV*) of weld metal of Timet LCB alloy welded joints made by EBW, is equal to 3.2 J/cm^2. Strength of LCB-5.1 alloy welded joint is on the level of 95 % of that of base metal in as-rolled condition. On the whole, the strength of welded joints of the considered sparsely-doped alloys in as-welded condition after EBW is on the level of 90 % of that of as-rolled alloy.

Conducted studies led to the conclusion that the strength of VT19 alloy welded joints is the highest in the condition after preheating and LHT, but their quality factor is lower than that of welded joints after EBW without preheating or LHT. This is attributable to high values of impact toughness of VT19 alloy welded joints without preheating or LHT. Lowering of this welded joint strength at calculation of the quality characteristic is compensated by high values of relative elongation and impact toughness. High values of relative elongation and impact toughness are associated with a large amount of metastable β-phase in the weld metal after EBW.

Sparsely-doped pseudo-β-alloys have lower values of quality characteristic in the condition after EBW, compared to structural pseudo-β-alloy VT19. Quality characteristic of EB welded joints of high-strength (α+β)-alloy T120 is lower than the values of this characteristic for pseudo-β-alloys. EB welded joints after LHT have the highest values of quality characteristic of (α+β)-alloy T120 (Table 3).

In terms of mechanical properties, EB welded joints of sparsely-doped LCB-5.1 titanium alloy have lower values of strength in as-welded condition and of quality factor, compared to structural alloy VT19. Welded joints of (α+β)-alloy T120 have the lowest values of strength in as-welded condition and of the quality factor.

The highest values of strength in as-welded condition and of the quality factor are demonstrated by LCB-5.1 alloy joints made by EBW with application of preheating and LHT.

Investigation of mechanical properties of welded joints of titanium pseudo-β-alloys made by tungsten electrode AAW (including use of flux) showed that the strength values in as-welded condition are on the same level, while VT19 alloy joints made without flux application have larger values of the quality factor (Table 4). For LCB-5.1 alloy flux application ensured the highest values of quality characteristic for welds

Table 3. Properties of 10 mm thick EB welded joints of pseudo-β-titanium alloys VT19, LCB-5.1 and (α+β)-alloy T120

Sample	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	*KCV*, J/cm^2	$K_{w\,m}$	K_s
VT19, BM	958	887	12	29	–	–
VT19, welded joint:						
mode 1;	876	842	11.3	28	0.93	0.91
mode 2;	891	847	10.0	27	–»–	0.93
mode 5 (preheat 400 °C);	893	879	12.0	20	0.8	–»–
mode 6 (preheat 400 °C, LHT 750 °C)	937	868	5.3	21	0.85	0.98
Timet LCB, BM	1187	1145	12.7	13	–	–
Timet LCB, welded joint, mode 3	1068	1033	5.1	3.2	0.57	0.89
LCB-5.1, BM	1015	939	1.9	6.4	–	–
LCB-5.1, welded joint:						
mode 4;	960	921	3.8	3.6	0.75	0.94
mode 7 (preheat 400 °C);	992	959	5.1	3.6	0.76	0.98
mode 4 (preheat 400 °C, LHT 750 °C)	997	964	6.5	5.3	0.9	0.98
T120, BM	1133	1040	10.7	33	–	–
T120, welded joint:						
mode 9;	1082	1006	6.7	15.2	0.72	0.95
mode 10 (LHT 750 °C)	1061	1012	8.0	24	0.85	0.93
T110, BM	1130	999	6	38	–	–
T11, welded joint, mode 9	1080	–	–	11	0.62	0.96

made without changing the weld metal chemical composition. Application of filler wire and the associated change in the weld metal chemical composition and welded joint properties allowed increasing both the values of strength properties, and those of quality characteristics of the welded joints. Values of quality characteristics of welded joints of (α+β)-alloy T120 are inferior to respective values for pseudo-β-alloys.

The highest values of quality characteristics in as-welded condition were determined for welded joints of VT19 alloy made by AAW with addition of VT1-00sv filler wire in the amount of 20 %, and of sparsely-doped LCB-5.1 alloy, made with addition of VT1-00sv filler wire in the amount of 10 %. Values of quality characteristics of these welded joints are higher than those of EB welded joints.

Table 4. Mechanical properties of welded joints of pseudo-β-alloys VT19, LCB-5.1 and (α+β)-alloy T120 made by AAW, in as-welded condition

Sample	Alloy, sample	σ_t, MPa	$\sigma_{0.2}$, MPa	δ. %	*KCV*, J/cm^2	$K_{w\,m}$	K_s
1	VT19, welded joint	860	839	13.3	19	0.77	0.89
3	VT19, welded joint over a layer of flux	857	815	13.3	14	0.68	–»–
5	–»–	849	813	10.7	13	0.66	0.88
6	LCB-5.1, joint	921	–	–	4.9	0.89	0.85
7	LCB-5.1, joint with 400 °C preheating	799	–	–	4.3	0.77	0.74
8	LCB-5.1, joint over a layer of flux	972	936	10.0	5.7	0.99	0.90
9	VT19, VT1-00sv joint, 10 %	895	868	7.3	28	0.93	0.93
10	VT19, VT1-00sv joint, 20 %	963	942	6	32	1.01	0.89
11	LCB-5.1, VT1-00sv joint, 10 %	1002	–	–	5.5	0.98	0.93
12	LCB-5.1, VT1-00sv joint, 20 %	960	–	–	3.5	0.75	0.89
13	T120, V_w = 10 m/h	1157	1076.9	–	17.6	0.79	1.02
14	T120, over flux, V_w = 16 m/h	1162	1069	–	4.6	0.58	0.12
15	T120 over flux, V_w = 10 m/h	1075	985	15.3	4.9	0.55	0.95
16	T120, VT1-00sv filler, 10 %	1110	1047	–	24.2	0.88	0.98
17	T120, VT1-00sv filler, 25 %	1006	937.8	4.0	14.1	0.67	0.89

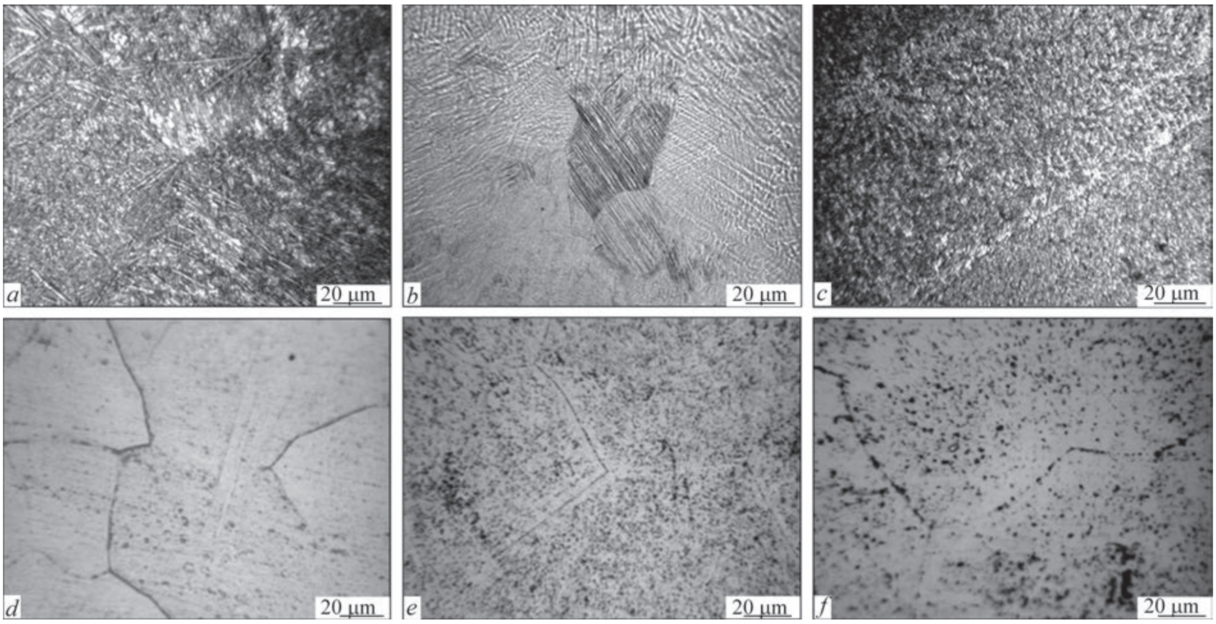

Figure 1. Microstructure of weld metal of EB welded joints: *a* — T120 base metal; *b* — T120 weld metal; *c* — T120 weld metal after LHT at 850 °C; *d* — VT19 weld metal; *e* — Timet LCB weld metal; *f* — LCB-5.1 weld metal

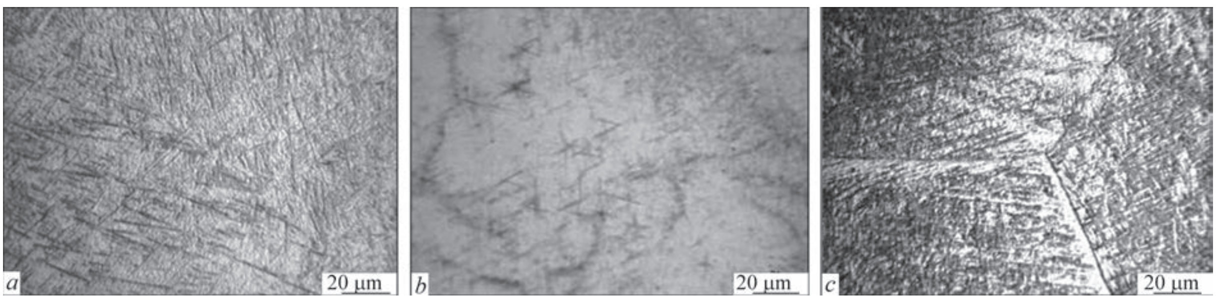

Figure 2. Microstructure of weld metal of AAW welded joints of T120 alloy: *a* — weld metal (mode 13); *b* — weld metal, over flux (mode 14); *c* — metal of the weld made with VT1-00sv filler wire (mode 16)

Lowering of strength in welded joints of all the alloys is attributable to increase of the amount of β-phase in the weld metal after EBW impact (Figure 1, *b*), compared to base metal (Figure 1, *a*). LHT application for T120 alloy allowed reducing the amount of β-phase almost to base metal level (Figure 1, *c*). The largest amount of β-phase in as-welded condition is determined in the weld metal of the welded joint of pseudo-β-alloy VT19, which consists of practically pure β-phase (Figure 1, *d*). In the weld metal of Timet LCB and LCB-5.1 alloys the amount of β-phase is also increased, but it is smaller compared to VT19 alloy.

A larger amount of β-phase is also found in as-welded condition in the structure of the metal of T120 alloy welds made by AAW (Figure 2). Here, flux application leads to increase of the amount of β-phase (Figure 2, *b*), while addition of unalloyed VT1-00sv filler metal and reduction of alloying element content leads to reduction of the amount of β-phase in the weld metal (Figure 2, *c*).

Thus, properties of welded joints of pseudo-β-alloys VT19, LCB-5.1 and (α+β)-alloy T120 made by EBW and AAW were studied, and it was determined that in as-welded condition the highest quality characteristics are typical for joints produced with addition of VT1-00sv filler wire in modes ensuring VT1-00 metal content in the weld on the level of 10 % for LCB-5.1 alloy, and on the level of 20 % for VT19 alloy.

INFLUENCE OF HEAT TREATMENT ON WELDED JOINT PROPERTIES

Heat treatment (HT) of welded joints of pseudo-β-titanium alloys is performed to eliminate internal stresses, achieve optimal physico-mechanical properties and stable structure not prone to a change of phase composition or properties at long-term heating at working temperatures. With this purpose, the influence of furnace annealing, quenching with subsequent aging and delayed cooling with the furnace at the rate of 1 °C/min on the properties of welded joints of pseudo-β-titanium alloys VT19 and LCB-5.1, made by EBW and AAW, in particular with application of filler wire VT-00sv [18, 19] was studied. Heat treatment modes are given in Table 5.

Table 5. Modes of furnace heat treatment of welded joints of pseudo-β-alloys VT19, LCB-5.1 and (α+β)-alloy T120

HT mode	Hardening HT type
1	VT19, LCB-5.1 annealing: heating up to 750 °C temperature, 1 h soaking, cooling with furnace
2	VT19, LCB-5.1 hardening and aging: heating up to 750 °C temperature, 1 h soaking, quenching in water, aging at 450 °C, 4 h soaking, cooling in air
3	VT19, LCB-5.1 delayed cooling: heating up to 750 °C temperature, 1 h soaking, cooling at a controlled rate of 1 °C/min
4	VT19, LCB-5.1 controlled annealing: heating and soaking at the temperature of 750 °C for 1 h; cooling to 680 °C, 1 h soaking; cooling to 380 °C; 8 h soaking, cooling in air; aging at 450 °C, 4 h soaking, cooling in air
5	T120 annealing: heating up to 900 °C temperature, 1 h soaking, cooling with the furnace
6	T120 controlled annealing: heating to 870 °C; 1 h soaking, cooling with furnace to 800 °C; 1 h soaking, cooling in air; aging at 380 °C for 8 h, cooling in air; 550 °C 2 h, cooling in air
7	T120 quenching and aging: heating up to 850 °C temperature, 1 h soaking, quenching in water, aging at 550 °C, 4 h soaking, cooling in air

Studying mechanical properties of welded joints of titanium pseudo-β-alloys VT19 and LCB-5.1 alloy led to the conclusion that in as-annealed condition AAW joints have the highest quality characteristics, for VT19 alloy without the filler wire and for LCB-5.1 alloy with filler wire in the amount of 10 % in the weld metal (Table 6).

On the whole, the strength of many welded joints in as-annealed condition is on the level not lower than that of base metal.

For (α+β) alloy T120, welded joints made by AAW with filler wire in the amount of 10 % in the weld metal have the highest values of the quality characteristic, due to high impact toughness values.

Analysis of mechanical properties of welded joints of sparsely-doped titanium pseudo-β-alloy LCB-5.1 and structural pseudo-β-alloy VT19, subjected to such kinds of thermal hardening as quenching in water with aging and delayed cooling with the controlled rate of 1 °C/min, led to the conclusion that the joints made without a change of chemical composition of the weld metal, namely by EBW and AAW without filler, have the highest values of quality characteristic (Table 7). EBW joints have the highest strength values.

Table 6. Mechanical properties of welded joints of pseudo-β-alloys VT19. LCB-5.1 and (α+β)-alloy T120б made by AAW and EBW. in as-annealed condition

Sample	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	*KCV*, J/cm^2	$K_{w\,m}$	K_s
VT19, EBW joint, V_w = 7 mm/s, preheating at 400 °C	1027	986	12.0	26	0.98	1.07
VT19, EBW joint, V_w = 11 mm/s	1024	984.9	8.7	24	0.94	1.06
VT19, AAW joint without filler	981	946	9.7	29.4	1.01	1.02
VT19, AAW joint with filler, 20 % VT1-00sv in the weld	1011	989	9.1	25.9	0.97	1.05
LCB-5.1 BM	1071	971	–	7.2	–	–
LCB-5.1, EBW joint	1169	1141	1.3	4.8	0.87	1.09
LCB-5.1, AAW joint without filler	1082	1033	–	5.3	0.87	1.01
LCB-5.1, AAW joint over flux	1197	1146	–	6.0	0.97	1.11
LCB-5.1, AAW joint with filler, 10 % VT1-00sv in the weld	1463	–	–	7.3	1.18	1.36
T120, EBW joint	1051.3	942.6	14.7	51.9	1.3	0.92
T120, AAW joint without filler	1013	936.3	4.0	42.9	1.13	0.89
T120, AAW joint over flux, V_w = 16 m/h	1151	1074	–	34.6	1.06	1.02
T120, AAW joint with 10 % VT1-00sv	1168	1083.6	4.0	48	1.29	1.03
T120, AAW joint with 25 % VT1-00sv	921	841	5.1	49	1.19	0.81

Table 7. Mechanical properties of welded joints of VT19, LCB-5.1 and T120 alloys made by AAW and EBW, in the condition after hardening HT

Sample	HT mode	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	*KCV*, J/cm^2	$K_{w\,m}$	K_s
LCB-5.1, AAW over flux	2, quenching in water and aging	1156	1127	4.2	6.9	1.10	1.13
LCB-5.1, AAW with VT1-00sv filler, 10 %	–»–	1055	1055	2.8	5.3	0.93	1.04
LCB-5.1, AAW with VT1-00sv filler, 10 %	3, delayed cooling	958	958	1.3	6.5	0.98	0.94
LCB-5.1, EBW	2, quenching in water and aging	1204	1199	8.6	4.2	0.92	1.19
LCB-5.1, EBW	3, delayed cooling	964	905	4.7	7.1	1.02	0.95
VT19, EBW	Quenching in water and aging	1285	1234	4.7	23.0	1.06	1.34
VT19, AAW	–»–	1273	–	–	11.0	0.85	1.33
VT19, EBW	EBW, delayed cooling	1068	1012	11.3	23.0	0.95	1.11
VT19, AAW	AAW, delayed cooling	1033	1005	6.0	24.0	0.95	1.07
T120, EBW	7, quenching in water and aging	1348	1275.3	1.3	8.3	0.73	1.19
T120, EBW	6, controlled annealing	1204.6	1109.3	4.5	13.2	0.74	1.06
T120, AAW without filler	7, quenching in water and aging	1350.6	1255	–	9.7	0.75	1.19
T120, AAW without filler	6, controlled annealing	1253.1	1165.2	2	16.3	0.81	1.1
T120, AAW with 10 % VT1-00sv filler	7, quenching in water and aging	1318	1305.7	2.7	10.8	0.75	1.16
T120, AAW with 10 % VT1-00sv filler	2, controlled annealing	1105.6	1040.4	–»–	18.1	0.77	0.98

Comparing the influence of HT without transferring to the quenching medium, namely annealing and delayed cooling, the annealed joints have the highest strength values. Annealing allows ensuring equal strength of the welded joints of titanium alloy VT19 and sparsely-doped LCB-5.1.

All the conducted HT operations lead to formation of a homogeneous structure in the welded joint and reduction of the amount of β-phase in the weld metal (Figure 3). After quenching the intragranular structure of T120 alloy welded joints consists of platelike α-phase, which here forms the basket weave pattern, while the platelike α-phase thickness is the smallest and equal to 0.7–1.0 μm (Figure 3, *b*). After controlled annealing the weld metal forms α-phase plates of different dimensions. They are characterized by a great diversity of structural element parameters with high impact toughness values (Figure 3, *c*).

After HT, the weld metal microstructure in pseudo-β-alloys also consists of equiaxed primary β-grains elongated in the direction of heat removal, where β-phase decomposition occurred at annealing, with formation of a uniform homogeneous (α+β)-structure with platelike α-phase of different length (1–5 μm) and thickness (0.5–1.0 μm) (Figure 4).

After quenching and aging the microstructure of weld metal is the most finely dispersed, the size of decomposition products most often does not exceed 1 μm (Figure 4, *b*). After delayed cooling at a controlled rate of 1 °C/min and controlled annealing, particles of α-phase 1.0–1.5 μm thick are observed in the weld metal structure (Figure 4, *c*, *d*).

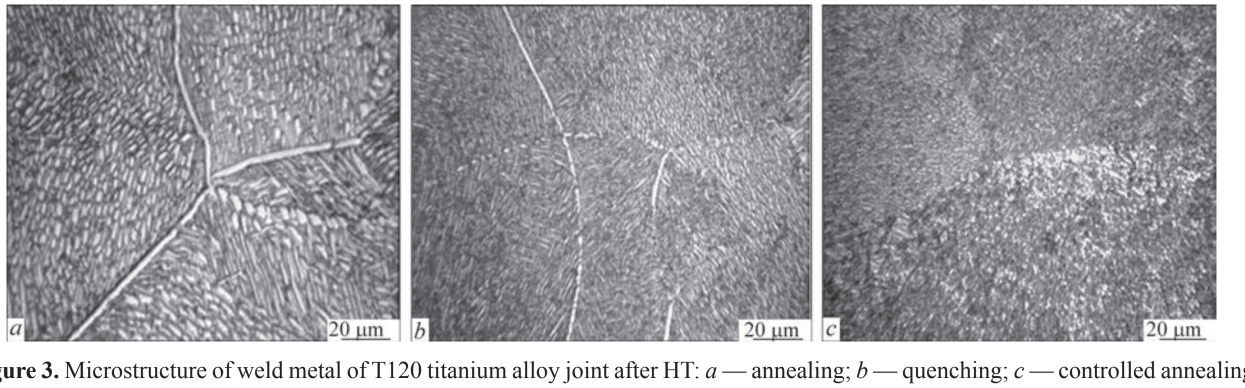

Figure 3. Microstructure of weld metal of T120 titanium alloy joint after HT: *a* — annealing; *b* — quenching; *c* — controlled annealing

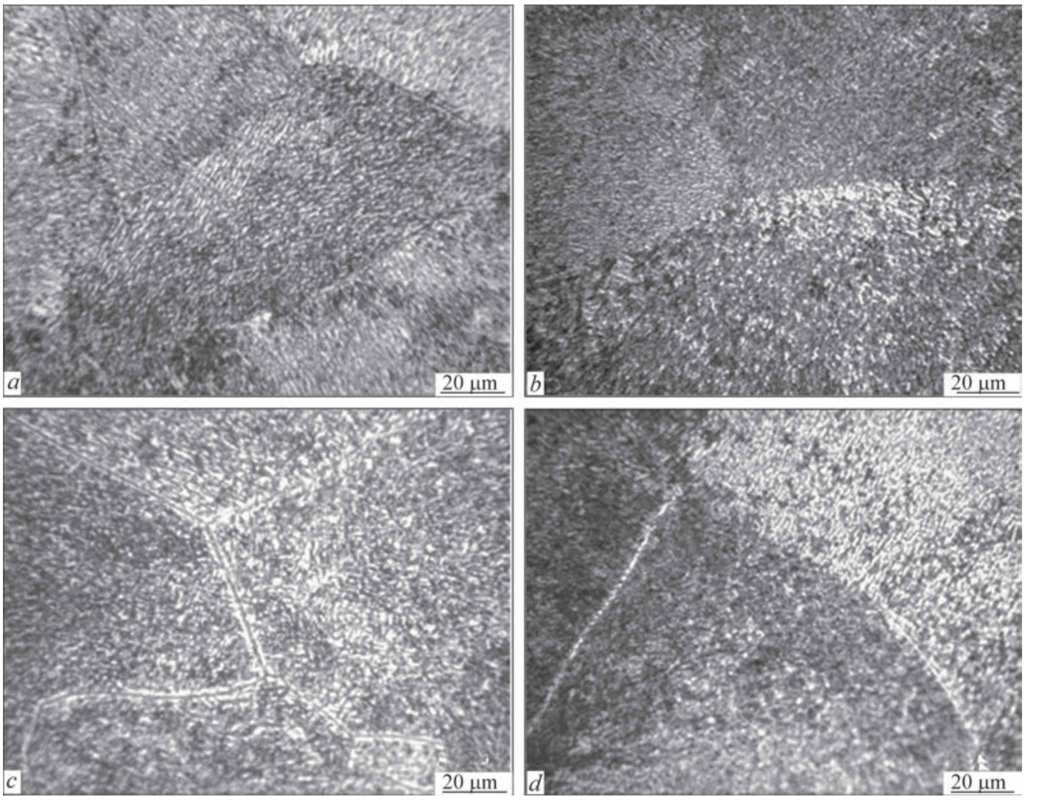

Figure 4. Microstructure of weld metal of EB welded joint of pseudo-β-alloy VT19 after HT: *a* — annealing; *b* — quenching and aging; *c* — delayed cooling; *d* — controlled annealing

Thus, comparison of quality factors of welding modes for pseudo-β-titanium alloy VT19 and LCB-5.1 alloy leads to the conclusion that AAW with feeding of the lower alloyed filler material is the most efficient welding mode for structural alloy VT19 (Figure 5). Here, for structural alloy VT19 it is rational to lower the degree of weld metal alloying by 20 %, and for sparsely-doped pseudo-β-alloy LCB-5.1 — by 10 %. This attributable to a greater amount of alloying element Fe which makes a large contribution to hardening of LCB-5.1 alloy.

Comparison of strength values of EB welded joints of pseudo-β-alloys led to the conclusion that the greatest hardening of welded joints compared with the metal in as-rolled condition is ensured by quenching in water and aging, and the least quenching is provided by delayed cooling at a controlled rate.

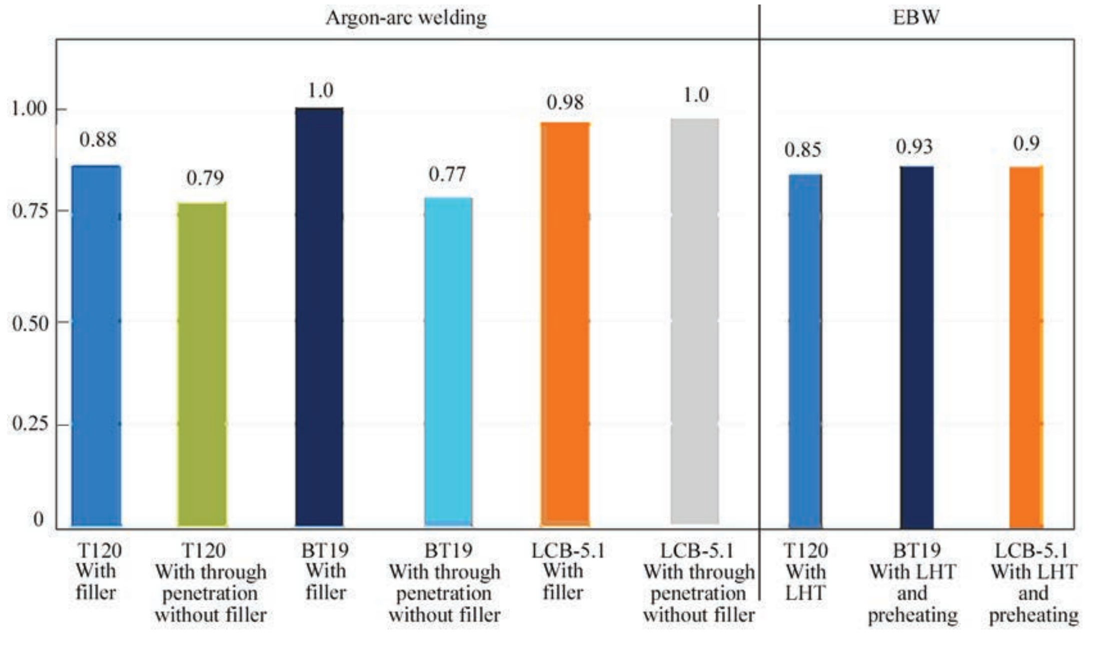

Figure 5. Quality factors of welded joints for some AAW and EBW modes in as-welded condition

CONCLUSIONS

1. It was established that the high quality of welded joints of promising high-strength titanium pseudo-β-alloys in as-welded condition can be ensured by performing EBW with application of LHT and preheating, as well as making the welded joints by AAW with the use of filler material, which allows reducing by 10–20 % the amount of alloying elements in the weld metal compared to base metal.

2. Lowering of strength of welded joints of pseudo-β-alloys is associated with increase of the amount of β-phase in the weld metal and HAZ.

3. It was determined that the highest quality factor of welded joints of structural pseudo-β-titanium alloy VT19 and (α+β)-alloy T120 is provided by AAW with feeding of unalloyed filler material VT1-00sv in the welding modes, which ensure 10 % filler metal content in the weld.

4. The highest quality factor of welded joints of sparsely-doped titanium pseudo-β-alloy LCB-5.1 is provided by EBW, which envisages application of preheating and LHT.

5. Values of quality characteristic and strength coefficient of welded joints of (α+β)-alloy T120 are inferior to the respective values of pseudo-β-alloys.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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