TECHNOLOGICAL PECULIARITIES OF ELECTROSLAG NARROW-GAP WELDING OF TITANIUM

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The aim of the work consisted in development of technology for electroslag narrow-gap welding of titanium billets of 120 mm thickness using consumable nozzle, investigation of technological and metallurgy peculiarities of the process and formation of welded joint. The billets of commercial titanium VT1 of the size 120 × 120 × 270 mm were subjected to welding. The consumable nozzles of commercial titanium with two channels for electrode wires of 5 mm diameter were applied. As a slag, the flux AN-T4 was applied. The experiments were realized with the standard size of a gap between the edges of 30 mm and 22 mm into a narrow gap. The modes of welding processes, thermal cycles, macrosections of welded joints and parameters of molten metal pool were analyzed. The results of experiments showed that decrease of welding gap results in increase of welding speed by 13 %, decrease of specific energy input of the process by 23 % and reduction in area of heat-affected zone. The penetration of the edges being welded is decreased on average from 12 to 5.5 mm (by 54 %). The investigation of parameters of molten metal pool showed that width of a pool in electroslag narrow-gap welding decreased from 54 to 33 mm, at decrease of depth of a pool from 22 to 19 mm. According to the results of investigations the technology was developed and the modes of electroslag narrow gap welding of titanium were recommended providing the stable running of the process with a good formation of welded joint, without lacks of penetration, pores, cracks and other defects. 10 Ref., 1 Table, 9 Figures.

K e y w o r d s : *electroslag welding, narrow gap, titanium, thermal cycle of welding, weld metal, macrostructure, weld pool*

The electroslag welding (ESW) is the efficient method for joining of structures of titanium and titanium alloys of large thicknesses [1–4]. One of its main advantages is high productivity and possibility of joining the metal of 30–400 mm thickness in one pass without edge preparation. The weld metal is characterized by high density, lack of defects in the form of micro- and macropores, lacks of fusion, etc. The technological advantages of ESW of titanium can also be relative simplicity and reliability of the equipment being in use, easy technology of welds making, additional protective and refining action on the liquid slag metal [1–3].

The disadvantages of ESW of titanium alloys limiting its practical application are undesired structural transformations in near-weld zone under the action of thermal cycle of welding and formation of a rough, coarse-grain structure of weld metal which negatively influences the operational properties of welded joints.

In work [5] the rationality of application of complex methods of influence on ESW process is shown based on thermal and hydrodynamic mechanisms of control of formation of welded joints. The thermal methods can be based on decrease of energy input of welding and redistribution of heat evolution in the volume of a pool which allows decreasing the overheat and non-uniformity of penetration of the base metal and meantime exclude the non-desirable structural transformations in it. The hydrodynamic methods consist in contact-free power influence on weld pool using external magnetic fields to control the processes of heat mass transfer and crystallization of weld metal.

It is very difficult to control the thermal cycle of welding in ESW as far as this process is characterized by large energy inputs and volumes of molten slag and metal. One of the methods allowing decrease of energy input of welding and reduce the width of HAZ is narrow-gap welding. Such investigations were conducted in the 1970s in USSR, England, Japan, USA, Canada and other countries [6–8]. It was shown that narrow-gap welding is characterized by the decrease of volume of slag pool, filler material and increase of welding speed.

According to the standards accepted for ESW of steels, the gap between the edges in the place of welding for metal of 81–160 mm thickness should be 30 mm in the lower part of the edges and 33–49 mm in the upper one [9]. Such sizes are accepted judging from the conditions of guaranteed penetration of the edges being welded and exclusion of the possibility of short-circuiting of the electrodes (consumable nozzle) to the base metal. The similar gaps of 30–32 mm are recommended also in welding of titanium alloys [1].

The possibility of decrease of welding gap in ESW of steels down to 19 ± 1 mm as applied to the tasks of bridge construction is given in work [8]. It is noted that new technology of narrow-gap ESW provides improved fatigue characteristics and impact toughness of weld metal and HAZ. The mentioned effects are achieved due to decrease of heat input, optimization of a shape of metal pool, application of welding wire which improves the structure of metal.

The aim of present work consisted in development of narrow-gap ESW technology of titanium billets of 120 mm thickness using consumable nozzle, investigation of technological and metallurgy peculiarities of the process and formation of welded joint. The obtained results are planned to be used in carrying out the further investigations in ESW with external electromagnetic effects.

The billets of commercial titanium VT1 of the sizes 120 × 120 × 270 mm were subjected to welding. The experiments were carried out using installation A-1494 with transformer TShP-10000/1 (Figure 1). The consumable nozzles of commercial titanium with two channels for electrode wires of 5 mm diameter were applied. As a slag the flux AN-T4 was applied. The welding was performed with the standard gap between the edges of 30 mm and in narrow gap — 22 mm. In the first case the welded-on titanium cover plates were used as run-in and run-out pockets, in the second case the copper water-cooled forming straps were used. To investigate the thermal cycle of welding the thermocouples of the chromel-alumel type were used which were arranged in welding specimens at the distance of 30, 40, 50, 60 mm from the edges. The hot junctions of thermocouples were fixed in the holes of the base metal at the depth of 20 mm with application of capacitor-type welding. For registration and processing of the process parameters the program packages LabView and PowerGraph were used. From the produced welded joints the longitudinal and transversal templates for the analysis of metal structure, parameters of welds and HAZ were manufactured.

As it was stated above, the technology of narrow-gap welding requires application of additional measures directed to prevention of short-circuiting of the electrodes to the edges being welded and guaranteed penetration of the base metal. For this purpose the consumable nozzle was used, the design of which was selected coming from the conditions of the uniform penetration of edges being welded (Figure 2, *b*). The thickness of nozzle was reduced to 12 mm, and channels for electrode wires were shifted to the edges of the nozzle to increase the heat evolution in the region of water-cooled forming straps. To prevent the short-circuiting of a nozzle to the edges being welded, especially in welding with longitudinal welds, it is rationally to apply insulators manufactured of material similar to the used flux (Figure 3). On fusion of nozzle the insulators are melted compensating the consumption of a slag on formation of skull crust on the weld surface. The insulators can be fixed on the nozzle using welded-on titanium rings (Figure 3,

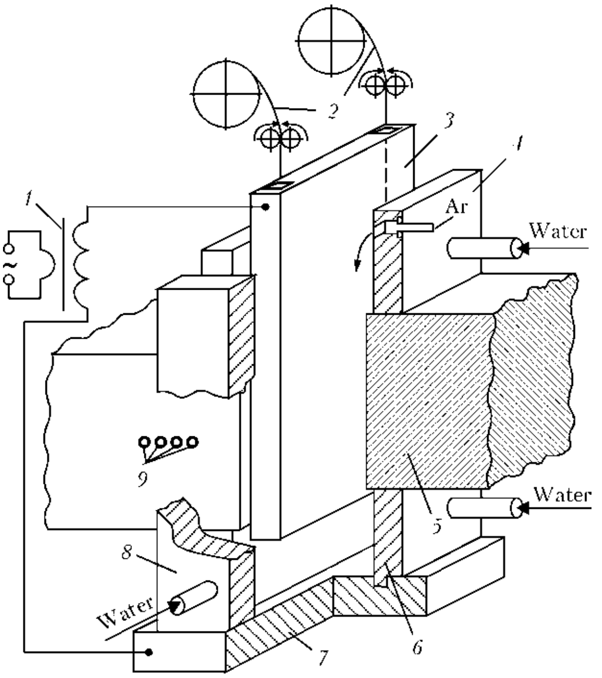

Figure 1. Scheme of assembly of specimens for ESW: *1* — power source; *2* — welding wire; *3* — consumable nozzle; *4* — run-out water-cooled forming strap; *5* — specimen being welded; *6* — run-in water-cooled forming strap; *7* — bottom plate; *8* — side forming device; *9* — holes for thermocouples

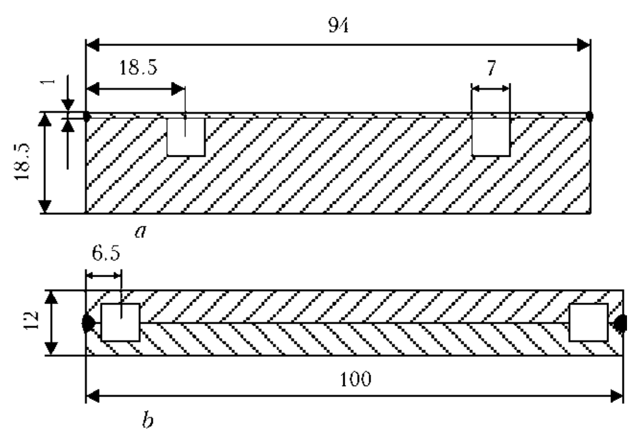

Figure 2. Design and geometry of consumable nozzles used during standard method of ESW (*a*) and in narrow-gap ESW (*b*)

Parameters of ESW of titanium billet ($\delta_{b.m}$ = 120 mm)

Process	Gap size, mm	Welding current, A	Voltage, V	Welding speed, m/h	Specific energy input of welding, kJ/cm^2	Value of penetration of edges, mm	Depth of molten metal pool, mm	Width of molten metal pool, mm	Coefficient of pool shape	Angle of intersection of crystallites of a weld (see Figure 9), deg
Traditional ESW	30	$\frac{3000–4000}{3500}$	$\frac{23–25}{24}$	2.2	$\frac{93–135}{114}$	$\frac{10–14}{12}$	22	54	2.5	120
Narrow-gap ESW	22	$\frac{2500–3500}{3000}$	$\frac{24–26}{25}$	2.5	$\frac{70–106}{88}$	$\frac{4–7}{5.5}$	19	33	1.7	160

a) or pressed-in (cast) into special holes in it (Figure 3, *b*, *c*).

The welding parameters and basic results of investigations are given in the Table and in Figures 4–9.

In both cases (standard ESW and narrow-gap ESW) the electroslag process was stable, without splashes of a slag pool, short circuits and arc discharges. The welds had giterring, smooth side surface (Figure 4). The macrostructure of weld metal was dense, without slag inclusions, pores, cracks and other defects (Figures 5 and 6). Hardness *HB* in the height of a weld was distributed uniformly. Across the width of a weld the increase of hardness in the fusion zone was observed on average by 10 %.

The penetration of edges of the base metal in the cross section in narrow-gap welding was relatively uniform (see Figure 6). The negligible decrease of penetration in the central part of a weld (4 mm) was observed as compared to periphery areas (7 mm) which was connected with heat evolution in the pool, in the place of fusion of electrode wires.

The results of experiments show that decrease of welding gap from 30 to 22 mm results in increase of welding speed (productivity of the process) by 13 % and decrease of specific energy input of the process on average by 23 %. The value of penetration of the edges being welded is decreased on average from 12 to 5.5 mm (by 54 %). The mentioned effects are first of all achieved due to decrease of volume of the deposited metal and optimization of heat mass transfer in the pool.

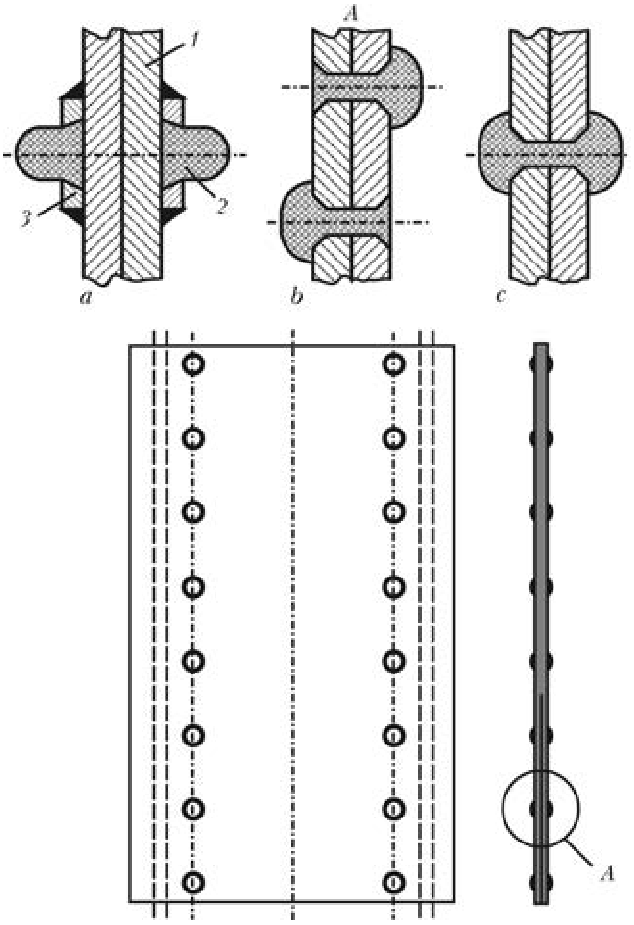

Figure 3. Design of electric insulators of consumable nozzle for ESW of titanium: *a* — fixed insulator; *b*, *c* — pressed-in (cast) insulators; *1* — consumable nozzle; *2* — electric insulator; *3* — titanium washer

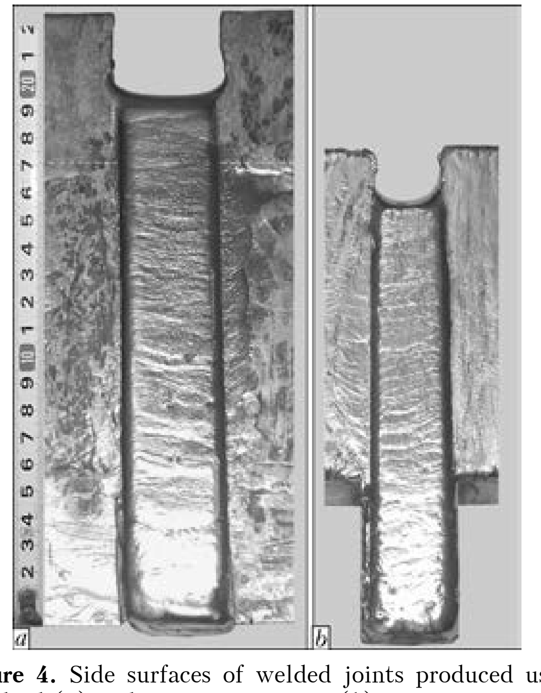

Figure 4. Side surfaces of welded joints produced using standard (*a*) and narrow-gap ESW (*b*)

Figure 5. Macrostructures of welded joints (longitudinal section) produced using standard (*a*) and narrow-gap ESW (*b*)

Figure 6. Macrostructure of welded joint (cross section) produced using narrow-gap ESW

The analysis of thermal cycles of welding (Figures 7 and 8) shows that during decrease of welding gap the maximal temperature of preheating the base metal at the distance of 30 mm from the edge being welded is decreased from 1250 to 640 °C. The width of a heating zone of the metal is higher than the temperature, for example, 840 °C (minimal temperature of start of polymorphous transformations for $(\alpha + \beta)$-titanium alloys [10]) in narrow-gap ESW decreased more than twice (from 32 to 14.5 mm). The effect of reduction in area of HAZ is achieved due to a number of factors, first of all decrease in specific energy input of welding and decrease in the volumes of slag and molten metal pools, and also increase in welding speed. The given circumstance decreases the probability of running of the processes of undesirable structural transformations in the base metal.

The investigations of the parameters of molten metal pool show that width of a pool in narrow-gap ESW decreased from 54 to 33 mm at decrease of a pool depth from 22 to 19 mm. Respectively, the coefficient of shape of a pool decreased from 2.5 to 1.7, and angle of crossing the crystallites along the axis of a weld increased from 120 to 160° (Figure 9). Such changes of coefficient of shape of the weld and directions of growth of crystallites can negatively influence the mechanical properties of welded joints, especially along the axis of a weld. Therefore, to reorient the direction of growth of crystallites it is necessary to decrease the depth of metal pool, which can be achieved, for example, by decrease of welding voltage to 19–22 V.

It should be noted that only by change of welding conditions it is impossible to control the solidification of deposited metal to achieve the formation of a weld with homogeneous fine-grain structure. Besides, excessive reduction of a gap and energy input of welding can result in non-stable penetration of base metal and the welding process itself. This requires application of additional mechanisms of influence on heat mass transfer in weld pool and solidification of weld metal, in particular, using external magnetic fields [2, 5]. Such investigations applying pulse electromagnetic effects are planned to be carried out in future.

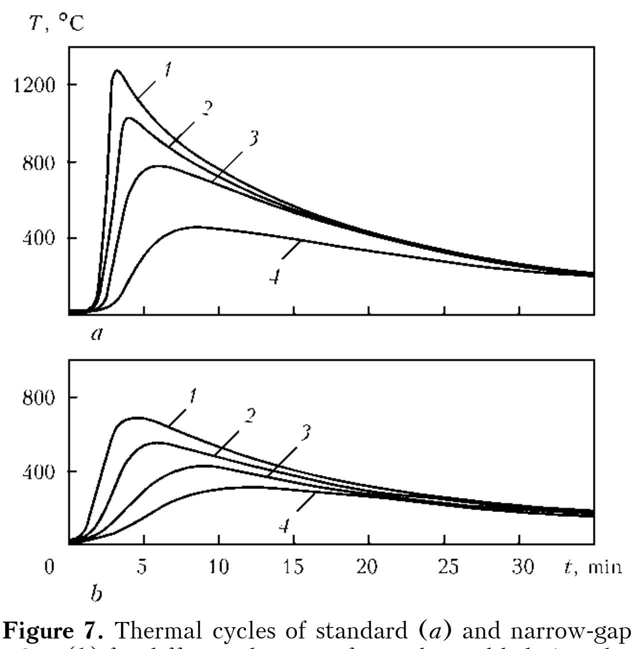

Figure 7. Thermal cycles of standard (*a*) and narrow-gap ESW (*b*) for different distances from edge welded: *1* — *l* = = 30; *2* — 40; *3* — 50; *4* — 60 mm

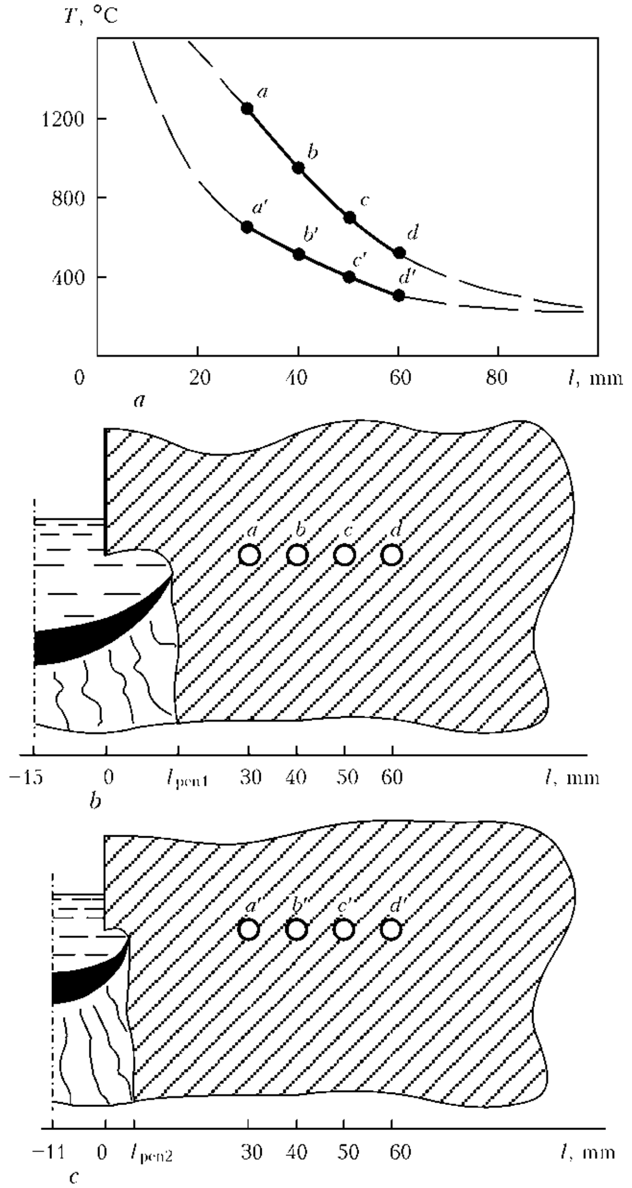

Figure 8. Maximal temperatures in welding specimen (*a*) depending on the distance to edge being welded in standard (*b*) and narrow-gap ESW (*c*): *a*–*d* (*a*′–*d*′) — spots where thermal couples are located

Conclusions

1. It was shown that it is possible to decrease the welding gap to 22 mm in consumable nozzle ESW of titanium billets of 120 mm thickness.

2. The technique and conditions of narrow-gap ESW of titanium were developed providing stable running of electroslag process with good formation of welded joint, without lacks of penetration, pores, cracks and other defects.

3. It was established that decrease of welding gap from 30 to 22 mm results in increase of welding speed (process efficiency) by 13 % and decrease of specific energy input of welding on average by 23 %. The thickness of molten metal pool is decreased from 54 to 33 mm, and depth — from 22 to 19 mm.

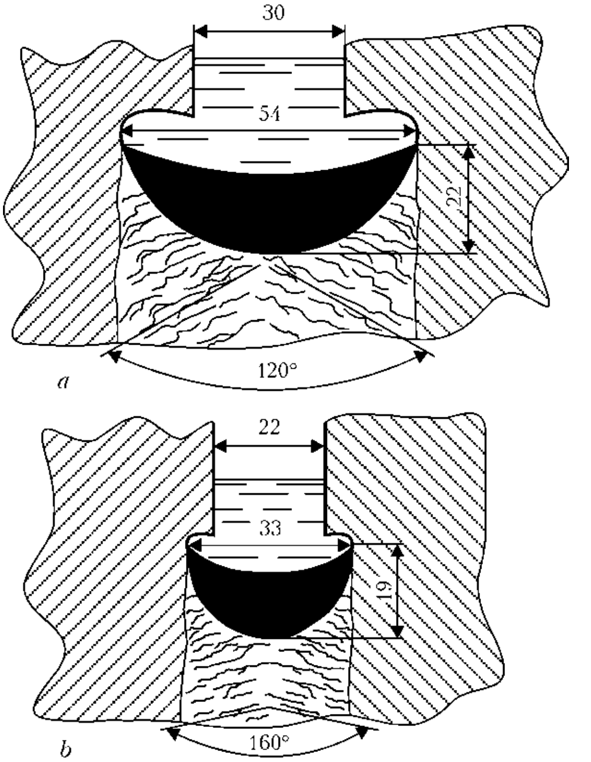

Figure 9. Scheme of molten metal pool in standard (*a*) and narrow-gap ESW (*b*)

4. The decrease of energy input in narrow-gap ESW results in decrease of width of HAZ and decreases the probability of proceeding of undesired structural transformations in base metal.

5. The formation in ESW of rough, coarse-grain structure of weld metal, decreasing mechanical properties of welded joint, requires application of additional mechanisms of effect on solidification of metal which can be based on application of external magnetic fields.

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Received 15.10.2012