NARROW-GAP WELDING OF UP TO 110 mm THICK HIGH-STRENGTH TITANIUM ALLOYS

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A method was developed for narrow-gap welding of thick titanium alloys (20–110 mm), having the following advantages: decrease in requirements to edge preparation, reduction of costs for preparatory operations, lowering of angular distortions and residual welding stresses in welded joints, and saving of welding wire and electric power, while ensuring a high quality of the welded joints. Guaranteed fusion of side walls of the groove with the weld is achieved due to application of the controlling transverse alternating magnetic field.

Keywords: *TIG welding, titanium alloys, filler wire, large thickness, narrow gap, controlling magnetic field, edge fusion, structure, mechanical properties*

Substantial growth in scopes of application of titanium alloys in different industries has been observed lately. Titanium alloys have found wide acceptance in chemical engineering, in addition to traditional application in aerospace engineering and ship building. The trend is to a more extensive utilisation of high-strength titanium alloys, such as VT6, VT20 and VT23 (σ_t = = 835–1400 MPa). Many 20–110 mm thick welded joints were produced by multi-layer argon-arc U- or V-groove welding. An important drawback of this welding method is a large volume of deposited metal, the cost of the titanium wire used being much in excess of the cost of the titanium rolled stock. The narrow-gap TIG welding technology is most efficient in a number of cases to join 20–110 mm thick structures. To successfully realise this technology, it is necessary to provide the following conditions: reliable shielding of the welding zone and tungsten electrode from oxidation with air, quality formation of the weld metal and guaranteed fusion of the vertical walls of the narrow groove, viewing of the welding zone to monitor the process, and monitoring of position of tungsten electrode in the central plane of the groove during welding.

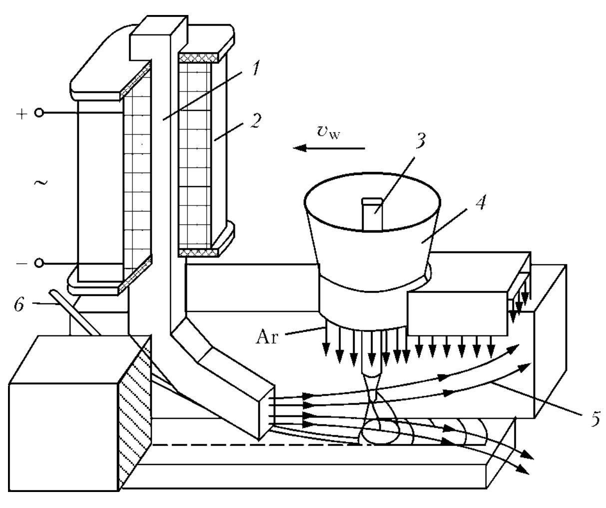

Figure 1. Schematic of the narrow-gap welding process using the controlling magnetic field: *1* — magnet limb; *2* — magnetic coil; *3* — tungsten electrode; *4* — protective nozzle; *5* — force lines of controlling magnetic field; *6* — filler wire

Narrow-gap welding of titanium is recommended to perform by two schemes: with the protective nozzle lowered into the gap [1], and with the protective nozzle located over the surface of the parts welded [2]. When using the second welding scheme, only the tungsten electrode is placed into the gap. Welding can be performed in the narrow gap with a width of 8–12 mm, which makes it possible to decrease consumption of an expensive filler metal 1.5–2 times, compared with welding by the first scheme, as well as to reduce welding strains. However, the use of the second scheme involves a problem of shielding of the welding zone and deposited metal from absorption of oxygen and nitrogen from air. The investigations conducted by the E.O. Paton Electric Welding Institute showed a high potential of the second scheme of narrow-gap welding of titanium. The AD238 unit of a cantilever type was made for welding titanium plates up to 100 mm thick and up to 2000 mm long [2].

The main problem in narrow-gap welding is to ensure a reliable and uniform fusion of vertical walls of the narrow groove with the deposited bead, as well as between the beads. In narrow-gap TIG welding without deflection of the welding arc, a substantial portion of its heat is consumed for re-penetration of the previous pass. This may cause lacks of penetration in the vertical walls of the groove. The lacks of penetration are especially frequent in a zone of intersection of the vertical walls of the groove with the surface of the previous pass, which is related to an intensive heat removal in this zone of the welded joint.

Transverse motion of the welding arc, which can be carried out mechanically (by weaving or rotating the tungsten electrode) [3] or by applying an external magnetic field, is used, as a rule, to achieve the guaranteed fusion of the side walls. This results in deflec-

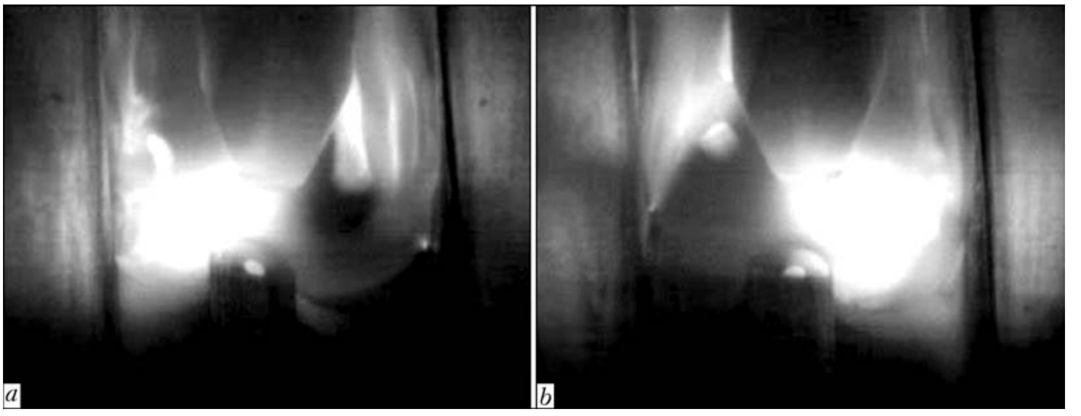

Figure 2. Video pictures of the process of narrow-gap TIG welding using the external controlling magnetic field with deflection of the arc to the left (*a*) and right (*b*) walls of the groove

tion of the welding arc [2] and displacement of its anode spot. As titanium and titanium-base alloys are non-magnetic materials, the most efficient method for ensuring the reliable and uniform fusion of the side walls of the groove is to apply electromagnetic control of deflection of the welding arc.

The magnetic coil power source BUMP-2 (Limited Liability Company «Rostock-SPARKS»), generating trapezoidal pulses with an amplitude of up to 6 A, was used to control the welding arc. In welding, the magnet limb performs the function of a magnetic core and is placed into the narrow gap (Figure 1). The current flowing through the magnetic coil induces the magnetic field within the arc zone, the force lines of the field within the arc zone being oriented mainly along the welding direction. This magnetic field is transverse with regard to the arc. Alternating deflections of the welding arc to the side walls of the groove and respective displacement of the anode spot of the arc to the side walls are provided by a change of polarity of the current flowing through the magnetic coil. Maximal induction of the controlling magnetic field within the arc zone may amount to 8 mT, the longitudinal component of induction of the controlling magnetic field being not higher than 20 %. The frequency of reversing of the magnetic field by using the BUMP-2 system developed for formation of the controlling magnetic field is adjustable from 1 to 80 Hz, the magnetic induction being adjustable from 0 to 8 mT.

Investigations of peculiarities of formation of welds on titanium alloys in narrow-gap welding using the controlling magnetic field showed that penetration of the side walls grew with increase in a transverse component of induction of the magnetic field and decrease in frequency of its reversing. The maximal depth of penetration of the surface of a previous layer was fixed at the weld centre at a frequency of reversing of the controlling magnetic field equal to more than 20 Hz. The welds made at optimal parameters are free from lacks of penetration and lacks of fusion.

The electric arc in narrow-gap welding burns under restrained conditions, the narrow gap comprising a filler wire guide and magnetic core, in addition to tungsten electrode. This hampers an operator to directly monitor the welding process. The small size video camera VK-27 equipped with a right-angle attachment was developed to visually observe the welding process and monitor the state of tungsten electrode and position of filler wire in the groove. The camera is intended for TV observation of the process of TIG welding of structures made from titanium and titanium alloys at a current of up to 500 A. The video camera comprises a light filter, objective, optical detector array and microprocessor controller based on

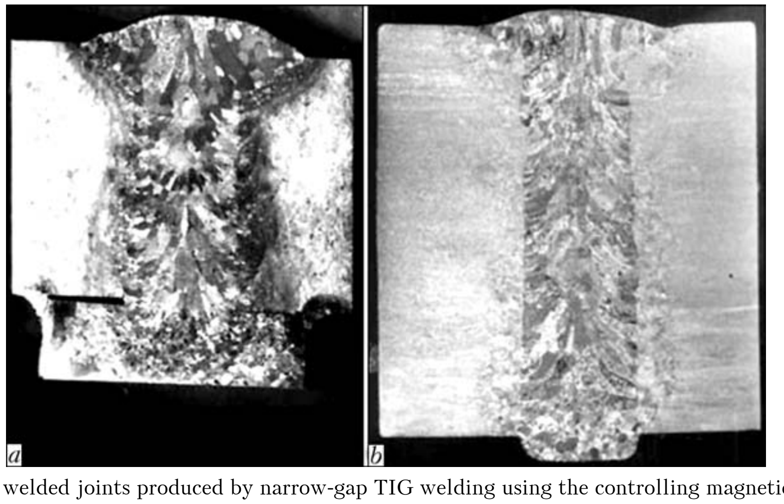

Figure 3. Macrosections of welded joints produced by narrow-gap TIG welding using the controlling magnetic field on a permanent (*a*) and forming (*b*) backing

Table 1. Content of gases in welded joints on alloy VT23, wt.%

Gas	[O]	[N]	[H]
Base metal	0.07	0.024	0.002
Filler wire SP15	0.06	0.016	0.0023
Weld metal	0.06	0.020	0.0022

Table 2. Mechanical properties of base and weld metals

Investigation object	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	ψ, %	KCV, J/cm^2
Base metal — alloy VT23	1030	980	13	30.0	35
Weld metal	1010	978	4	3.9	21
Welded joint	960	–	–	–	–

the digital signal processor. The camera generates an output video signal of the PAL format. TV viewing of the narrow-gap welding process may help to solve another problem, i.e. in-process control of position of tungsten electrode in the central plane of the groove (see Figure 2).

Two schemes of fit-up of parts for narrow-gap welding were developed, and corresponding process parameters were selected on the basis of the investigation results. The first scheme provides for the use of a backing, which is welded to the reverse side of the parts to be joined. An important drawback of this scheme for titanium alloys is that the backing should be removed, as a rule, this leaving defects on the surfaces of the parts. The second scheme of fit-up and welding using a forming water-cooled backing [4] was suggested to eliminate this drawback. In this case, the backing serves as a crystalliser for the first-pass bead, protects the reverse side of a part from oxidation with air, and functions as a current conductor. Macrosections of the welded joints produced by using the above scheme are shown in Figure 3.

As indicated by the results of determination of the content of gases in the weld metal (Table 1), it is not in excess of that in the base metal, and depends upon their content in filler wire. This proved the high quality of gas shielding in welding.

The investigations conducted evidence that strength of the welds made on titanium alloy VT6 by narrow-gap TIG welding using filler wire SPT2 in the as-welded condition is at a level of 95 % of that of the base metal (Table 2), this meeting requirements to the welds of category 1.

Examinations of structure of the welds made on two-phase titanium alloy VT23 using high-alloy filler wire SP15 revealed a coarse-acicular structure with long martensite needles present both in the central and peripheral parts of the weld at the absence of induction without oscillations of the welding arc. The martensitic structure is coarser in the peripheral part of metal of the welds made with a magnetic induction of 6 mT. However, the martensite needles in this case are shorter than in the welds made without oscillations of the welding arc.

Metal of the welds made with a magnetic induction of more than 6 mT has a homogeneous structure, no coarse martensite needles being revealed in the central and peripheral parts of the welds. Increase in the reversing frequency to above 20 Hz has almost no effect on length of the mertensite needles.

Analysis of microstructure of the narrow-gap TIG welds on titanium alloy VT23 with filler wire SP15 showed that the average length of the martensite needles at the absence of the magnetic field was 0.10–0.05 mm. In welding with a field reversing frequency of 10 Hz and magnetic induction of 6 and 12 mT, the average length of the martensite needles decreased to 0.06–0.08 and 0.04–0.05 mm, respectively. At a magnetic induction of 8 mT and frequency of reversing of the magnetic field increased from 2.5 to 20 Hz, the average length of the martensite needles decreased from 0.10–0.15 to 0.03–0.04 mm. Further increase in the frequency of reversing of the magnetic field had almost no impact on length of the martensite needles in the weld metal.

It can be concluded on the basis of the investigations conducted that magnetic control of the welding arc in welding allows decreasing the average length of the martensite needles almost 4 times and obtaining a more homogeneous and fine-acicular structure of the weld metal (Figure 4). It is the opinion of the authors

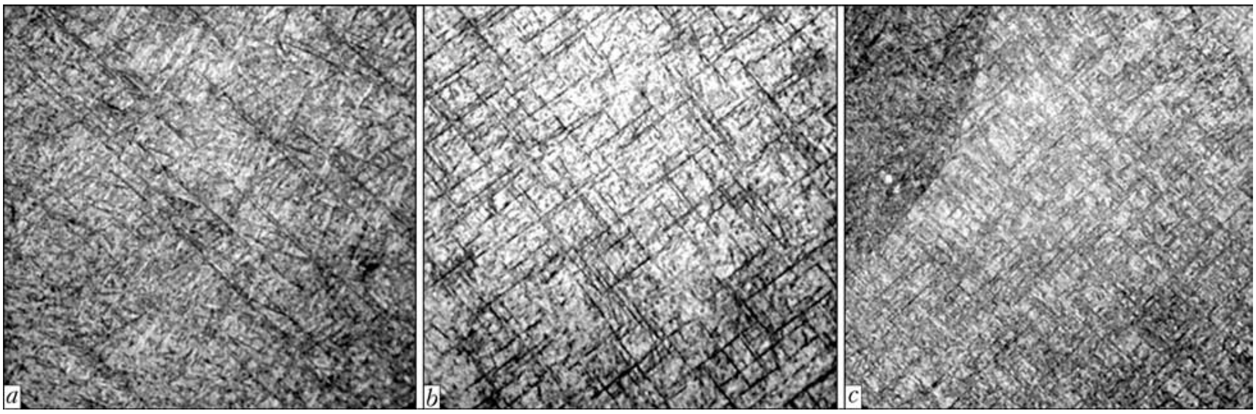

Figure 4. Microstructures (×400) of metal of the welds made without (*a*) and with the controlling magnetic field at an induction of 6 (*b*) and 8 (*c*) mT

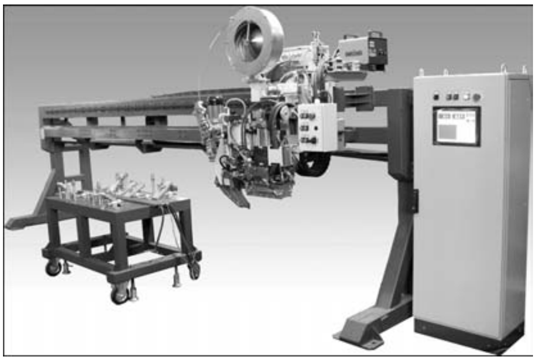

Figure 5. Gantry-type unit for narrow-gap welding of 20–110 mm thick titanium and titanium-base alloys

that improvement of the secondary structure of the weld metal on two-phase titanium alloys is related to formation of transverse oscillations of the weld pool. Transverse oscillations of the melt in a tailing portion of the weld pool are fixed on a video of the narrow-gap welding process, and show up as a change in ripples on the weld surface: distance between the ripples decreases with increase in frequency of reversing of the controlling magnetic field. Transverse oscillations of the weld pool result in a periodic incipient melting of metal at the solidification front, as well as in formation of a finely dispersed structure of the welds on two-phase titanium alloys, wherein the average size of the martensite needles decreases from 160 to 40 μm.

Solution of the above problems allowed development of a welding unit to produce joints on up to 110 mm thick high-strength titanium alloys by narrow-gap welding using magnetic control of the welding arc (Figure 5). The unit performs welding by the second scheme. The welding torch with a cylindrical protective nozzle was developed to solve the problem of shielding of the welding zone. The nozzle is located over the surface of the parts joined (Figure 6), its internal surface having a generating line with a shape close to the Vitoshinsky curve [5]. The use of this welding torch made it possible to guarantee a reliable shielding of the welding zone in production of welded joints on up to 110 mm thick titanium and titanium-base alloys.

The welding unit consists of the following main components: fixed gantry to position the welding head over the welding zone; carriage with a mechanism for movement of the welding head along the weld; welding torch with a protective spout; mechanism for vertical movement of the welding head with a system for automatic adjustment of the arc voltage; mechanism for transverse movement of the welding head; filler wire feed mechanism; system for magnetic control of the welding arc, system for TV observation of the welding process; table for welded specimens; power supply VDU-511 with arc exciter VSD-02; control cabinet with a touch display, and local control panel.

The unit control system is intended to implement the process of TIG welding of titanium alloys and provide functioning of the equipment in the following modes: «Setting up» — to check operation of all mechanisms of the unit and perform setting displacements prior to welding, and «Automatic» — for automatic control of the welding process following the preset program. Both visual observation of the welding process and fixation of its parameters, such as arc voltage and current, welding speed, wire feed speed, frequency and induction of the magnetic field, are performed by means of this control system.

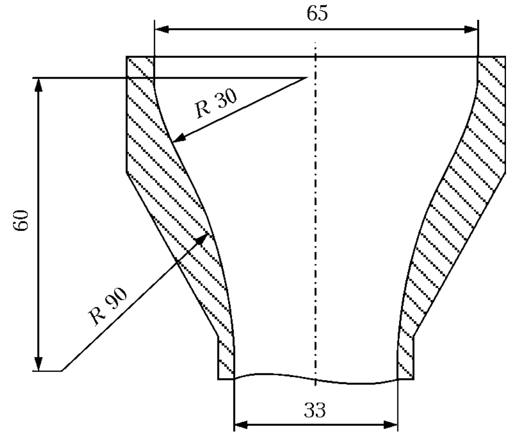

Figure 6. Schematic of protective nozzle for narrow-gap welding of titanium and titanium-base alloys

The welding unit performs multi-pass welding in the automatic mode, providing welded joints on 20–110 mm thick and 4000 mm long commercial titanium and titanium-base alloys by narrow-gap straight-line welding, thickness of the deposited layer per pass being 5–7 mm.

The developed welding technology and unit provide a high quality of the welded joints.

CONCLUSIONS

1. Based on the investigations conducted, the technology was developed for narrow-gap welding of high-strength titanium alloys using the external controlling magnetic field. The technology provides a high quality of the welded joints and their mechanical properties at a level of not less that 90 % of those of the base metal.

2. Narrow-gap welding of two-phase titanium alloys using the controlling magnetic field provides the weld metal with a finely dispersed structure, the average size of martensite needles being decreased 4–5 times (from 160 to 40 μm), compared with the weld metal produced without the controlling magnetic field.

3. The gantry-type unit was developed for multi-pass narrow-gap straight-line welding of 20–110 mm thick and up to 4000 mm long titanium and titanium-base alloys in the automatic mode, providing a high quality of the resulting welded joints.

1. Mikhajlov, V.I., Sakharov, I.Yu. (2006) Welding of structures of thick titanium alloys (problems of technology). In: *Proc. of Int. Conf. on Ti-2006 in CIS* (21–24 May 2006, Suzdal, Russia). Kiev: Naukova Dumka, 109–111.
2. Paton, B.E., Zamkov, V.N., Prilutsky, V.P. (1996) Narrow-groove welding proves its worth on thick titanium. *Welding J.*, **4**, 37–41.
3. Grinin, V.S., Shtrikman, M.M. (1982) High-productivity automatic narrow-gap welding. *Svarochn. Proizvodstvo*, **7**, 21–23.
4. Belous, V.Yu. (2009) TIG welding of thick titanium plates by using forming backing. *The Paton Welding J.*, **10**, 32–34.
5. Ardentov, V.V., Fedorenko, G.A. (1973) Influence of design of the flow part of torches on characteristics of gas shielding. *Svarochn. Proizvodstvo*, **10**, 24–26.