PECULIARITIES OF LASER-ARC WELDING OF TITANIUM ALLOYS

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Methods were developed, and parameters were selected for hybrid laser-arc welding. It was established that hybrid laser-arc welding allows producing joints on low and medium titanium alloys with properties that are not inferior to those of the base metal. Impact toughness of the hybrid laser-arc welded joints on high titanium alloy T110 is much higher than that of the laser welded joints.

Keywords: *hybrid laser-arc welding, laser radiation, tungsten-electrode arc, titanium alloys, experiments, parameters, metallography, structures, mechanical properties*

At present titanium alloys are applied for fabrication of critical structures operating in aerospace engineering, chemical industry, instrument making and ship building. They are used to manufacture such critical parts as stringer panels for aircraft, rocket components, tanks for chemical industry, casing parts, etc. [1]. Often the design solutions these parts are based on require the use of welding processes. In practice, more than 90 % of all the welds are made by argon-arc and electron beam welding [2].

However, these welding methods have drawbacks of both technological (low power density in the arc discharge plasma) and economical character (high cost even at small dimensions of the majority of vacuum chambers for electron beam welding). Laser welding has been gaining acceptance lately, which is due to its advantages, such as high power density in the laser beam, high productivity and precision of processing [3]. A substantial drawback of the process of laser welding is a high cost of the equipment involved. As shown in study [4], one of the ways of reducing this indicator is partial replacement of the laser power by the arc one. Moreover, laser welding also has some technological limitations related to a high reflection power of surfaces of many structural metals and alloys. However, it can be overcome by using the hybrid laser-arc process.

The work on hybrid laser-arc welding of steels and aluminium alloys has been performed for about three decades (e.g. [5]). The discussions are underway for the last ten years concerning the possibility of applying it for titanium alloys [6], and corresponding experimental data have been accumulated. The issue of the highest current importance is determination of the effect of the thermal cycle of hybrid laser-arc welding on properties of the joints on high-strength titanium alloys, for example, such as T110. In particular, under conditions of the experiment described in study [7], laser welding of alloy T110 led to deterioration of its mechanical properties compared to the base metal.

The purpose of the present study was to investigate peculiarities of laser-arc welding of joints on titanium alloys, such as low titanium alloy VT6 and high-strength alloy T110, as well as to evaluate mechanical properties of the resulting welded joints.

To solve this problem, the authors implemented the flowchart of the hybrid laser-arc welding process shown in Figure 1. The radiation source was Nd:YAG-laser DY 044 (Rofin Sinar, Germany) with a power of up to 4.4 kW and wavelength of 1.06 μm, and the welding current source was power supply VDU-601 UZ for automatic TIG welding. According to this flowchart, the tungsten electrode is located ahead of the laser beam. This combination of laser and TIG welding makes it possible to increase the penetrating power of the welding process and permits a simple feed of the filler wire to the welding zone. To implement this flowchart, a welding head was developed to provide feed of laser beam *1* focused by the lens (focal distance — 300 mm) and tungsten electrode *7* (diameter — 5 mm, sharpening angle — 30°) to a certain point on the surface of specimen *5* being welded. The distance from the electrode tip to the surface of the welded specimen was set at about 3 mm. The distance from the exit section of the lower part of the welding head to the specimen was the same. Deepening of the focal plane of the laser

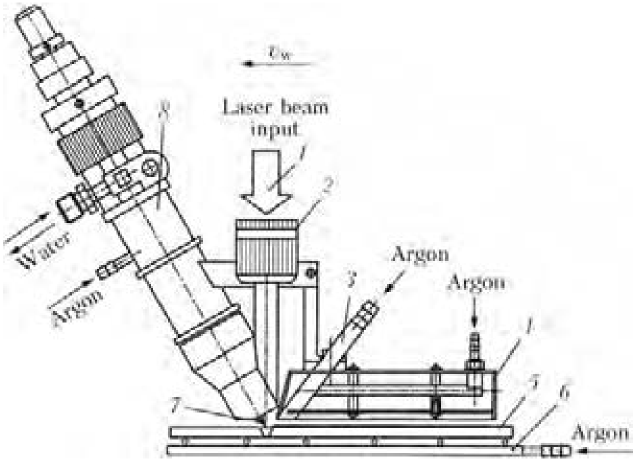


Figure 1. Flowchart of the hybrid laser-arc welding process: *1* — laser beam; *2* — focusing device; *3* — device for additional feed of shielding gas; *4* — device for shielding of the welding zone and cooling weld and HAZ metals; *5* — welded specimen; *6* — device for shielding of reverse side of the joint; *7* — tungsten electrode; *8* — welding head for TIG welding of titanium

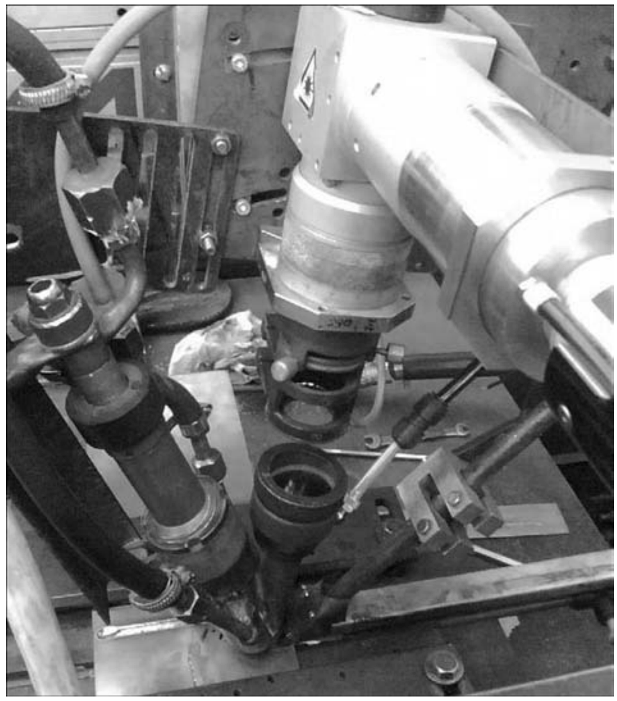


Figure 2. Appearance of the welding head for laser-arc welding of titanium alloys

beam to under the surface of the welded specimen was varied within 0–5 mm, depending on its thickness. The angles between the normal to the surface welded and axes of the laser beam and electrode were chosen to be as small as possible. The experiments showed that to provide the hybrid effect in welding the distance between the laser beam axis and the electrode tip should be 1.0–1.5 mm. Melting and fracture of the tungsten electrode tip take place at a distance between the laser beam axis and the electrode tip less than 1 mm. If this distance is more than 3 mm, after the effect exerted by the tungsten electrode arc the solidified weld metal is subjected to repeated penetration by the laser beam, no substantial increase in the penetrating power of the laser-arc process being fixed in this case.

Increase in the penetration depth was achieved when the tungsten electrode welding arc was the first in the direction of welding (Figure 2), which provided augmentation of the laser radiation absorbed by metal, as the molten metal has a better absorptive capacity than the cold one [8]. In the experiments the welding current was varied within 200–450 A, the radiation power of the Nd:YAG-laser being 4.4 kW. Titanium alloys VT1, VT6 and T110 with thickness δ = 10–13 mm were used as specimens. The shielding gas (argon) was fed both from top and bottom of a specimen. To ensure quality shielding of the welding zone, the welding head was fitted with a device for additional blowing of the tailing part of the weld pool with argon (Figure 1, pos. *3* and *4*).

The experiments conducted made it possible to establish that the laser-arc method can be applied to weld 12 mm thick titanium alloys with through penetration at a speed of 22–24 m/h, radiation power of 4.4 kW, welding current of 400 A and voltage of 12–14 V (Figures 3, *a*; 4, *a*; 5, *a*). The weld bead deposited on the same alloys under the above conditions separately by the laser and arc methods had a depth of about 6 and 5 mm, respectively (Figures 3, *b*; 4, *b*; 5, *b*). Comparison of cross section areas of these welds with the welds made by the hybrid method allows a conclusion that the hybrid effect takes

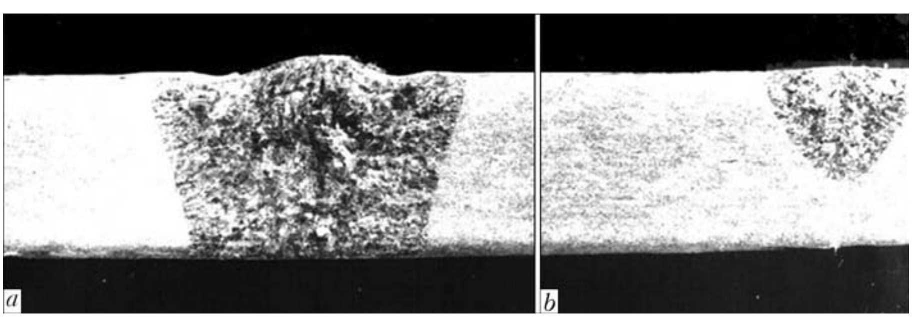


Figure 3. Macrostructures of welds on titanium alloy VT6 (δ = 10 mm): *a* — laser-arc welding; *b* — laser welding

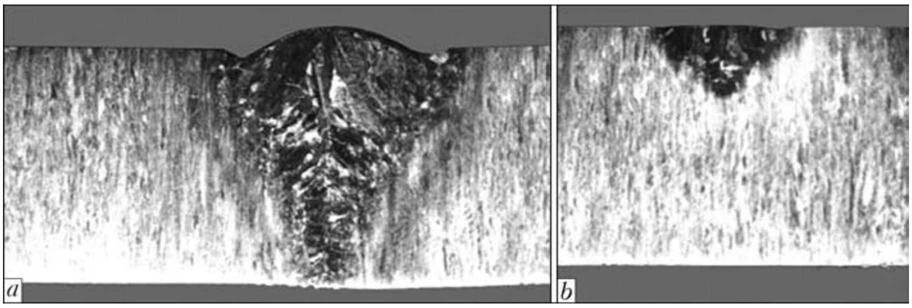


Figure 4. Macrostructures of welds on titanium alloy VT6 (δ = 13 mm): *a* — laser-arc welding; *b* — laser welding

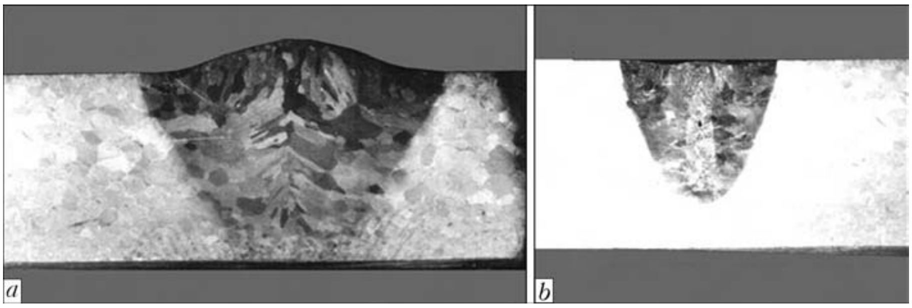


Figure 5. Macrostructures of welds on titanium alloy T110 (δ = 13 mm): *a* — laser-arc welding; *b* — laser welding

place in the laser-arc welding process. It shows up in non-additivity of the sum of the cross section areas of the welds made by the laser and arc methods, compared to the areas of the welds made by the hybrid method. Parameters of the welds on alloys VT6 and T110 in laser and laser-arc welding are given in Table 1.

Main drawbacks of the methods of laser and hybrid laser-arc welding of titanium alloys include the probability of formation of internal pores in the cast weld metal and unsatisfactory formation of the upper reinforcement bead. The latter defect consists in formation of undercuts on two sides of the weld and some increase in the reinforcement bead proper.

Metallographic examinations of the welds on alloys VT6 and T110 made by laser welding showed a clearly defined dendritic structure with primary β-grains seen against its background, the grains being elongated in a direction of heat removal or equiaxed. The substructure was fixed too. In laser-arc welding of alloys VT6 and T110, mostly β-grains elongated in a direction of heat removal were formed in the weld, while relatively

Table 1. Parameters of the welds and HAZ in laser and laser-arc welding

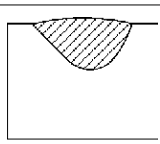
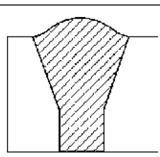
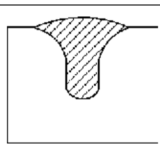
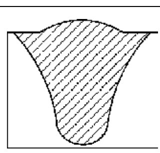
Alloy	Welding method	Weld shape	Penetration depth, mm	Weld width, mm			HAZ width, mm		
				Upper part	Midsection	Root part	Upper part	Midsection	Root part
VT6	Laser		4.0	7.0	2.5	–	1.2	1.8	0.7
	Laser-arc		13.0 (through)	12.0	5.0	2.3	1.8	4.3	2.3
T110	Laser		6.9	8.0	1.5	1.9	1.2	3.3	0.9
	Laser-arc		11.0	12.0	5.4	3.4	2.3	4.5	2.5

Table 2. Mechanical properties of alloy VT6 and its laser-arc welded joints

Material	Tensile strength, MPa	Ductility limit, MPa	Elongation, %	Reduction in area, %	Impact toughness, J/cm^2	
					Weld	HAZ
Base metal VT6 (δ = 13 mm)	888	815	13.6	30	39	
Welded joint	911	–	–	–	54	32

Table 3. Mechanical properties of alloy T110 and its laser and laser-arc welded joints

Material	Tensile strength, MPa	Ductility limit, MPa	Elongation, %	Reduction in area, %	Impact toughness, J/cm^2	
					Weld	HAZ
Base metal T110 (δ = 13 mm)	1130	999	6	5	38	
Welded joint:						
laser-arc	1180	–	–	–	15	23
laser	1131	–	–	–	6	13

fine equiaxed grains were fixed only in the upper part of the weld near the surface.

In contrast to the welded joints on alloy T110 made by laser welding, no substructure was detected either in the weld or in the HAZ of the laser-arc welded joints, the microstructure being more homogeneous and uniform. Examination of microstructure of transverse sections of the welded joints showed that the laser welds had pores with a diameter of 0.010–0.035 mm, whereas the laser-arc welds were free from pores.

As shown by mechanical tests, the tensile strength values of the laser and laser-arc welded joints on alloys VT6 and T110 were 2–4 % higher than those of the base metal (Tables 2 and 3), which, in the authors' opinion, can be explained by the presence of the dendritic structure in the weld metal, which is characteristic of a cast metal. Measurements of impact toughness of the laser-arc welded joints on titanium alloy T110 showed the satisfactory values.

Because of peculiarities of laser and laser-arc welding characterised by an evaporating mechanism of the keyhole formation, the welded joints were investigated to determine the content of alloying elements in the cast weld metal and compare it to the content of such elements in the base metal. Investigations of chemical microheterogeneity in specimens of alloy T100 welded by the laser and laser-arc methods were carried out to determine the content of aluminium, niobium, zirconium, molybdenum, vanadium and iron by using CAMECA scanning microscope-microanalyser SX-50. The instrument comprised an electron probe consisting of an electron beam 1 μm in diameter. The volume of the determined mass was 1–3 μm^3, depending on the depth of penetration of the probe into the material studied. It was found that both in laser welding and in hybrid welding the deviation of the content of the investigated elements was within the permissible scatter for alloying elements in the grade composition of the alloy. Therefore, in welding under the indicated conditions there is no risk of burning out of individual alloying elements of the alloy.

CONCLUSIONS

1. The welding head was designed for hybrid laser-arc welding (beam + TIG) of titanium alloys, wherein the laser beam was located behind the welding arc. This welding head provides the satisfactory quality of shielding of the welding zone and cooling weld metal.

2. The use of the proposed flowchart of laser-arc welding at a laser beam power of 4.4 kW and welding current of 400 A was found to provide a twofold increase in the penetration depth, compared to the results of using only laser welding performed at a power of 4.4 kW. Both in laser welding and in laser-arc welding there is no risk of burning out of alloying elements.

3. The technological approaches were developed, and parameters of laser-arc welding were selected to provide through penetration of specimens of titanium alloys VT6 and T110 with thickness of up to 13 mm at a laser beam power of 4.4 kW and welding speed of 22–24 m/h.

4. Tensile strength of the laser and laser-arc welded joints on titanium alloys VT6 and T110 was 2–4 % higher than that of the base metal.

5. Laser-arc welding is characterised by a higher penetrating power compared to welding only with the laser beam, and provides the welded joints on high titanium alloys with satisfactory ductility and impact toughness.

6. As shown by the investigations, hybrid laser-arc welding allows producing the welded joints on low and medium titanium alloys with properties that are not inferior to properties of the base metal.

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CORROSION-FATIGUE STRENGTH OF 12Kh18N10T STEEL T-JOINTS AND METHODS OF ITS IMPROVEMENT

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Results of fatigue testing the T-joints of stainless steel 12Kh18N10T in air and in corrosion medium are given, and the effect of surface strengthening on improvement of strength properties and fatigue life of welded elements of hydrofoil wing ship assemblies is also determined.

Keywords: *arc welding, MMA welding, TIG welding, stainless steel, welded joints, corrosion medium, fatigue strength, fatigue life, surface strengthening, residual stresses*

The stainless steel of the austenite class of the grade 12Kh18N10T is widely used in manufacture of different welded structures which in process of operation are subjected to influence of the alternate loads. They include foil systems (FS) of foilcrafts (FC), rollers of heating furnaces of metallurgy enterprises, welded components of products of chemical and power machine building.

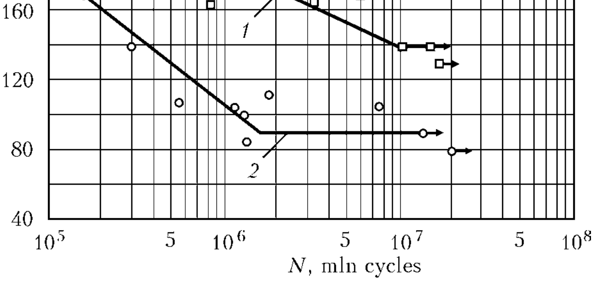

Figure 1. Curves of fatigue of manual welded T-joints: *1* — initial state after welding; *2* — after strengthening using BPS

In this study the results of fatigue tests of T-joints of steel 12Kh18N10T in air and sea water both in as-welded state, as well as after strengthening treatment applying ball-pin strengthener (BPS).

The experience of service of vessels of the type «Kometa» showed [1, 2] that in FS the cracks are formed on the planes of wings, at the places of joining the bracket with the wing plane, in brackets of propeller shafts. During operation under conditions of the Azov sea, the cracks in ships «Kometa» and «Kolkhida» are formed during 1.5–2 months after repair and after 2–3 weeks under the conditions of the Black Sea. They have to be eliminated by grooving and re-welding of defective places that is accompanied by significant expenses connected both with the repair itself, and also at taken the ship from the service in the navigation period.

The fatigue life of FS can be increased by the new constructive solutions or by technological operations, which include in particular the strengthening treatments which create compressive stresses in the surface layers [3, 4].

The purpose of this work is to evaluate the effect of strengthening treatment on the fatigue life and strength of FS of the ships of the «Kometa» type.

For this purpose the specimens with T-joints were manufactured of sheet rolled metal of steel