https://doi.org/10.15407/tpwj2019.10.01

HYBRID LASER-MICROPLASMA WELDING OF SHEET Ti–Al–V TITANIUM ALLOY*

I.V. KRIVTSUN[1], **V.Yu. KHASKIN**[2], **V.M. KORZHYK**[1,2], **I.M. KLOCHKOV**[1], **V.V. KVASNYTSKYI**[3], **O.A. BABICH**[1,2], **CAI DETAO**[2], **LUO ZIYI**[2] and **HAN SHANGUO**[2]
[1]E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua
[2]E.O.Paton Chinese-Ukrainian Welding Institute, Guangzhou, China
[3]National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
37 Peremohy Prosp., Kyiv-56, Ukraine

The process of hybrid laser-microplasma welding of sheet Ti–Al–V titanium alloy of TC4 grade (up to 3.0 mm) was studied. The recommended technological parameters and conditions of laser-microplasma welding in an argon medium, physical and mechanical properties of welded joints were determined, and the presence of hybrid effect was established. 5 Ref., 3 Tables, 7 Figures.

Keywords: *laser-microplasma welding, Ti-Al-V titanium alloy, heat input, strength, elongation, hybrid effect*

Welded products from sheet titanium alloys are becoming ever wider accepted in modern industry. Such products are characterized by high strength under the impact of mechanical loads, light weight and high corrosion resistance under operation conditions. Examples of such products can be structures which are applied in aerospace, nuclear, chemical and food industries, and marine engineering when operating in marine climate or at higher humidity (for instance, tanks, filters), etc. A wide range of such structures are made of titanium alloys up to 3.0 mm thick with application of butt welded joints. As a rule, resistance, argon-arc or electron beam welding are used to solve such tasks [1].

However, such welding processes often do not completely meet the requirements as to cost-effectiveness and adaptability to fabrication of such structures and by far not always allow making the physical and mechanical characteristics of welded joints as similar as possible to those of base metal. High requirements as to geometrical accuracy of products from sheet titanium alloys require application of measures and joining technologies, which provide the minimum level of residual welding deformations. One of the best welding methods today in terms of minimizing the residual deformations, and producing high-quality and durable welded joints of such alloys is electron beam welding [2]. Recently, however, there have been attempts to replace this method by laser welding, as a more efficient one that does not require application of vacuum chambers [3]. This method, however, has not yet become widely accepted, because of comparatively high cost of laser equipment. One of the ways to reduce the cost of laser equipment is lowering the radiation power due to its partial replacement in the welding process by plasma-arc component. Such a process is called hybrid laser-plasma welding [4]. Application of the process of hybrid laser-plasma welding at preservation of quality characteristics of welded joints on the level of those in laser welding opens up a prospect for creation of a new advanced welding technology. Therefore, this work is devoted to studying the capabilities of hybrid laser-microplasma welding of sheet titanium alloys, in the case of a rather widely accepted alloy of Ti–Al–V alloying system of 1.0 and 3.0 mm thickness and is actual.

The objective of the work is optimization of basic techniques of hybrid laser-microplasma welding of sheet Ti–Al–V titanium alloy of TC4 grade (VT6 analog), selection of recommended technological param-

Table 1. Chemical composition (wt.%) of TC4 alloy produced in PRC (VT6 analog)

Ti	Fe	C	Si	V	N	Al	Zr	O	H	Additives
86.45–90.9	≤0.6	≤0.1	≤0.1	3.5–5.3	≤0.05	5.3–6.8	≤0.3	≤0.2	≤0.015	Other — up to 0.3

*Published by the materials of the paper presented at the International Conference «Innovation Technologies and Engineering in Welding and Related Processes — POLYWELD», May 23–24, 2019, NTUU «Igor Sikorsky KPI», Kyiv, Ukraine.

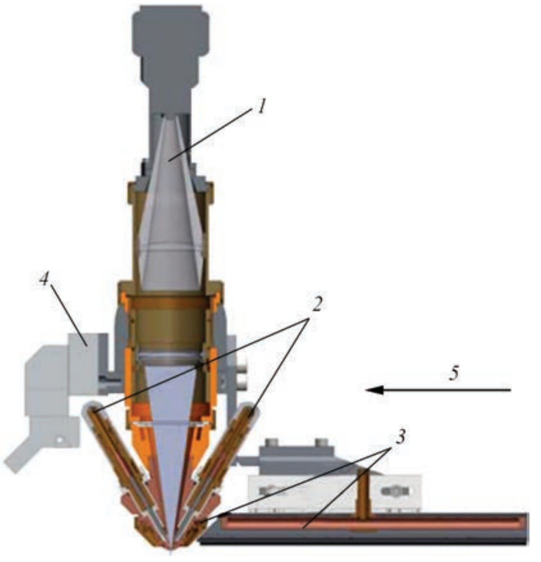

Figure 1. Diagram of integrated plasmatron and experiment performance: *1* — laser radiation feeding of power P = 0.3–1.2 kW; *2* — cathode assemblies; *3* — gas shielding; *4* — fastening to robot arm; *5* — welding direction

eters of the process and welding conditions, as well as determination of physical and mechanical characteristics of the produced joints.

Technological studies of the process of hybrid laser-microplasma welding of the mentioned titanium alloy were conducted using a unit described in [5], the circuit of integrated hybrid plasmatron of which is given in Figure 1. Disk laser with radiation wavelength λ = 1.03 μm was used during the experiments, the power of which was changed in the range of 0.3–1.2 kW. Focal spot diameter was equal to about 0.4 mm. In the integrated coaxial direct action plasmatron of original design applied for studies the laser radiation was combined with the constricted low-ampere arc of up to 2.3 kW power [5]. In this plasmatron the focused laser radiation and constricted arc were output jointly through a common nozzle of 2.5 mm diameter to the sample being welded, which

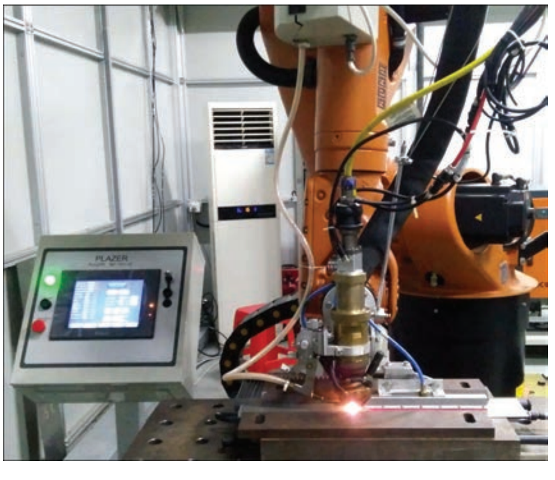

Figure 2. Process of laser-microplasma welding by integrated plasmatron, fastened on the arm of KUKA KR30HA robot

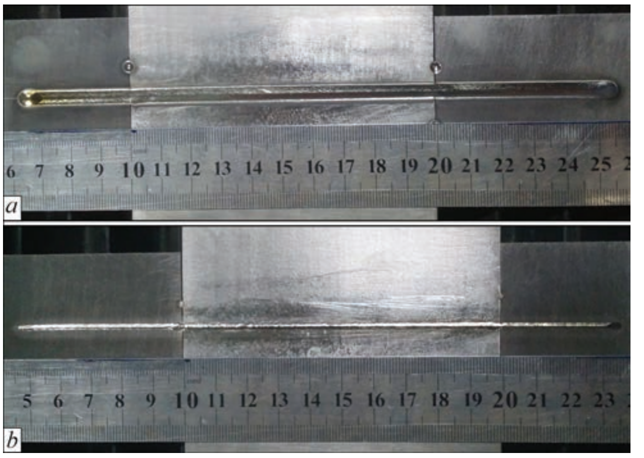

Figure 3. Appearance of plates of TC4 titanium alloy (δ = = 3.0 mm) butt welded without a gap between the edges by laser-microplasma process (radiation power P = 1.0 kW, welding current I = 50 A, voltage U = 26 V, welding speed v = 36 m/h): face (*a*) and reverse (*b*) side

was located at approximately 3 mm distance from the nozzle tip. The focal plane of laser radiation was positioned at the depth of approximately 0.5 mm relative to sample surface. Straight polarity continuous arc was used in the experiments. The arc current in integrated microplasmatron was smoothly adjusted up to 80 A at up to 28 V arc voltage. Sheets of TC4 alloy of (200–300)×100×δ mm dimensions, where δ = 1.0 and 3.0 mm (Table 1) were used as samples for butt welding and bead deposition. Movement of integrated plasmatron relative to the sample being welded was performed by an anthropomorphic robot KUKA KR30HA (Figure 2).

Conducted experiments demonstrated the high stability of the process of laser-microplasma welding. Positive results were obtained (Figures 3, 4) in the case of hybrid butt welding of sheets of TC4 titanium alloy (δ = 1.0 and 3.0 mm) with up to 0.1 mm gap between the edges being welded. Here, the speed of the hybrid process was 30 to 40 % higher than that of laser welding and approximately two times higher than that of plasma welding (Table 2).

Performance of a number of experiments enabled determination of parameters of the modes of sound (absence of undercuts, lacks-of-penetration and sag-

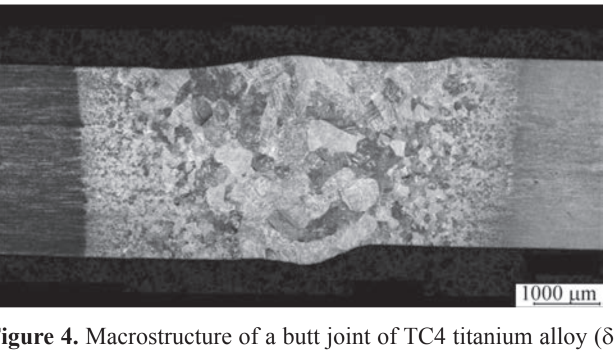

Figure 4. Macrostructure of a butt joint of TC4 titanium alloy (δ = 3.0 mm), produced by laser-microplasma welding in argon

Table 2. Modes and results of laser, plasma and laser-microplasma welding of TC4 titanium alloy in argon

Batch No.	δ, mm	Radiation power, W	Welding current, A	Arc voltage, V	Welding speed, m/h	Heat input, J/mm	Result
1	1.0	600	40	24	60	80	Hybrid welding, penetration, presence of undercuts
2	1.0	600	40	24	51	100	Hybrid welding, penetration, good weld formation, absence of undercuts
3	1.0	600	–	–	30	70	Laser welding, penetration, presence of undercuts
4	1.0	–	40	24	24	115	Microplasma welding, penetration
5	3.0	1200	50	26	42	190	Hybrid welding, penetration, presence of undercuts
6	3.0	1000	50	26	36	200	Hybrid welding, penetration, good weld formation, absence of undercuts
7	3.0	1000	–	–	24	150	Laser welding, penetration, presence of undercuts
8	3.0	–	50	26	18	210	Microplasma welding, penetration

Table 3. Modes and result of hybrid laser-microplasma welding of a sound joint of TC4 titanium alloy (δ = 3.0 mm)

Mode of laser-microplasma welding			
Laser power P, W	1000	Welding speed v, m/h	0.6
Arc current I, A	50	Distance from the part to the nozzle, mm	3
Plasma gas flow rate (argon) Q_{pl}, l/min	10	Flow rate of additional shielding gas (argon), $Q_{ad.sh}$, l/min	20
Shielding gas flow rate (argon) Q_{sh}, l/min	10	Flow rate of gas (argon) for weld root shielding Q_{rev}, l/min	20
Dimensions of the produced weld			
Width of face (top) side of the weld, mm	4.8	Width of weld reverse side (root), mm	1.5
Face side convexity, mm	0.1	Convexity of weld reverse side (root), mm	0.2

ging of the weld) hybrid butt welding of TC4 titanium alloy sheets with protection of the weld pool and hot (more than 200 °C) part of the weld by argon (Table 3). These parameters were used to produce welded joints of TC4 alloy 1.0 and 3.0 mm thick, from which samples of XIII (XIIIa) type were later cut out (GOST 6996–66) to perform mechanical testing.

Three series of 3 samples each were cut out in order to perform mechanical testing of base and welded joint metal of TC4 alloy (δ = 1.0 and 3.0 mm) butt welded by laser-microplasma method in argon atmosphere. Tensile testing machine of MTS Criterion 45 type was used to perform static tensile testing of butt welds to determine the ultimate strength σ_t (MPa) and relative elongation δ (%). Results measured for each test series were averaged. The obtained averaged values were used to plot the respective diagrams (Figure 5). The derived results demonstrated that the strength of joints of titanium alloy TC4, produced by hybrid laser-microplasma welding, is equal to approximately 85–90 % of base metal strength, relative elongation of the thus welded samples is not much higher than 40 % of that of base metal (δ ≈ 4.5 for the joints

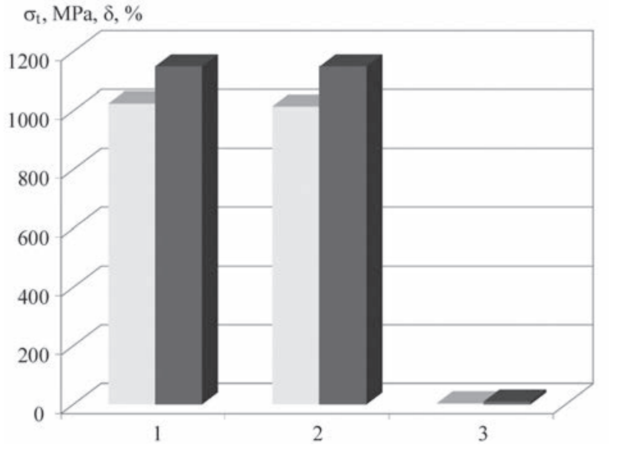

Figure 5. Comparative results of mechanical testing of samples of TC4 titanium alloy (light grey colour) welded by laser-microplasma method and base metal (dark-grey colour) at their static tension: 1, 2 — averaged ultimate strength σ_t (MPa) for samples of 1.0 (*1*) and 3.0 (*2*) mm thickness; 3 — relative elongation δ (%) for all the cases

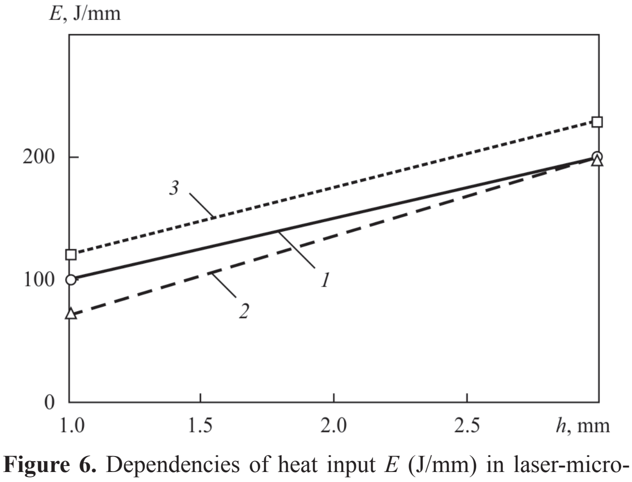

Figure 6. Dependencies of heat input E (J/mm) in laser-microplasma (*1*), laser (*2*) and plasma (*3*) welding on thickness h (mm) of welded sheets of TC4 titanium alloy

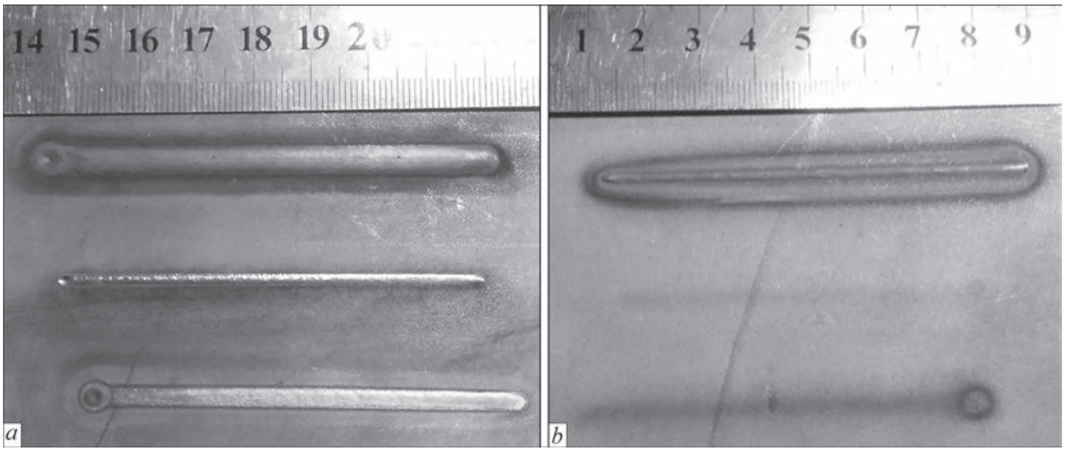

Figure 7. Appearance of face (*a*) and reverse sides (*b*) of the beads in a plate of TC4 alloy of thickness δ = 3.0 mm (from top to bottom): hybrid, laser, microplasma

at δ ≈ 10 % for base metal). The given values are acceptable for most of the welding tasks.

During analysis of the conducted technological studies, the process heat input (*E*, J/mm) was determined as a sum of powers of laser (*P*, W) and microplasma (0.8*IU*, W) components, related to welding speed (*v*, mm/s). Calculation results were used to plot the dependencies of the change of heat input of laser-microplasma and laser welding at the same process speeds (Figure 6). Comparison of curves *1*, *2* and *3* showed that the heat inputs of all the considered welding processes are rather close. Note that the energy input of plasma process is the greatest in all the cases, the laser process ensures the lowest energy input in welding sheets 1.0 mm thick, and in case of welding 3.0 mm thick sheets the hybrid and laser processes become close as to the input energy.

The following experiment was performed in order to compare the results of the laser, microplasma and hybrid laser-microplasma welding. Laser-microplasma welding in argon atmosphere was applied to ensure guaranteed penetration of plate from TC4 alloy (δ = 3.0 mm) in the following mode: P = 1000 W, I = = 50 A, U = 26 V, v = 36 m/h. Then, the same speed with the same mode parameters was used to deposit two beads by the laser and microplasma processes (Figure 7). Here, the sum of heat inputs of the process components corresponded to the heat input of hybrid welding. Examination of transverse sections of these beads showed that the depth of hybrid welding penetration is approximately by 25 to 30 % greater than the sum of penetration depths of laser and microplasma welding. This led to the conclusion about the availability of a pronounced hybrid effect in the case of laser-microplasma welding by the considered process.

Conclusions

1. In the course of this work, hybrid laser-microplasma welding of sheet titanium alloy TC4 in argon was studied. It was determined that in the case of abutment of the edges to be welded with up to 0.1 mm gap, hybrid welding allows producing sound welded joints without the need for filler wire application, without undercuts or sagging, characteristic for laser welding. Here the speed of the hybrid process is higher than that of the laser one by 30–40 %, and that of the plasma process is higher approximately two times.

2. Analysis of the results of mechanical testing of welded joints of TC4 titanium alloy, made by hybrid laser-microplasma welding, shows that their static tensile strength is equal to approximately 85–90 % of that of the base metal, and relative elongation is higher than 40 %. These values are acceptable for most of the welding tasks.

3. Comparison of heat inputs of the considered welding processes showed that their values are quite close. In all the cases, the energy input is the highest in the plasma process. In welding 1.0 mm thick sheets the lowest energy input is ensured by the laser process, and in case of welding 3.0 mm thick sheets the hybrid and laser processes are comparable in terms of the input energy.

4. Comparative studies of beads deposited on samples of TC4 alloy by laser, microplasma and hybrid processes showed that the penetration depth with the hybrid method is approximately 25–30 % greater than the sum of penetration depths in laser and microplasma welding. Here, the sum of heat inputs of the process components corresponds to the heat input of hybrid welding. This is indicative of the availability of the hybrid effect in the case of application of laser-microplasma welding.

Note. The work was performed under project No. 2018GDASCX-08-03 «Research and development of laser and plasma technologies for hybrid welding and cutting», Guangzhou, China, as well as under special project No. 2017GDASCX-0411 «Capacity — Building of Innovation — Driven Development for Special Fund Projects of the Programs of the Academy of Sciences of Guangdong Province (PRC) «Investigations of physico-chemical processes at interaction of vapour plasma with metal surface and development of scientific fundamentals of the technology of water-air plasma cutting of sheet steels to produce welded joints».

1. Gurevich, S.M., Zamkov, V.N., Blashchuk, V.E. et al. (1986) *Metallurgy and technology of welding of titanium and its alloys*. 2nd Ed. Kiev, Naukova Dumka [in Russian].
2. Nazarenko, O.K., Kajdalov, A.A., Kovbasenko, S.N. et al. (1987) *Electron beam welding*. Kiev, Naukova Dumka [in Russian].
3. Grigoryants, A.G., Shiganov, I.N. (1988) *Laser technique and technology*. In: 7 books. Book 5: Laser welding of metals. In: Manual for higher education inst. Ed. by A.G. Grigoryants. Moscow, Vysshaya Shkola [in Russian].
4. Krivtsun, I.V., Shelyagin, V.D., Khaskin, V.Yu. et al. (2007) Hybrid laser-plasma welding of aluminium alloys. *The Paton Welding J*., **5**, 36-40.
5. Krivtsun, I.V., Korzhik, V.N., Khaskin, V.Yu. et al. (2017) Unit of new generation for laser-microplasma welding. In: *Proc. of 8th Int. Conf. on Beam Technologies in Welding and Processing of Materials*. Ed. by I.V. Krivtsun. Kiev, International Association Welding, 2017, 95–100.

Received 01.07.2019