Laser-TIG Welding of Titanium Alloys

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Abstract. The article presents the results of investigation the technological opportunity of laser-TIG welding of titanium alloys. The experimental stand for implementation of process with the capability to feed a filler wire was made. The research of the nature of transfer the filler wire into the welding pool has been demonstrated. The influence of distance between the electrode and the surface of the welded plates on the stability of the arc was shown. The relationship between welding velocity, the position of focal plane of the laser beam and the stability of penetration of plates was determined.

1. Introduction

Titanium and its alloys are indispensable construction materials because they have unique physical properties: high specific strength comparable to steel. However, they have a density in two times less than steels. The titanium alloys have a high melting point and corrosion resistance in aggressive chemical environments, atmosphere and water.

Technology of welding titanium has the distinctive features. The titanium interacts actively with atmospheric gases, such as oxygen, hydrogen, nitrogen during the heating more than 350^0C; because of this, the mechanical properties of joint weld significantly decrease. Titanium alloys are sensitive to thermal cycle due to a heavy increase of grains during heating and cooling in the area of β phase. Therefore, the welding should be done in the atmosphere of inert gas with minimum heat input. For the formation of joint weld from titanium and its alloys in the world practice using various welding methods: TIG welding, friction welding, electron beam welding. However, each of these methods has its own significant imperfection. TIG welding have a low productivity. The friction welding has a narrow field of application, as the dimensions of the welding parts are limited. The electron beam welding has a limitation on the overall dimensions of the weld workpieces and it is a labour intensive process due to there is the necessity of creating a vacuum in the working chamber. The welding of titanium by laser radiation is the most promising. Analysis of the articles of other researchers revealed a wide range of researches in this direction. There are researches with using of laser radiation of solid-state laser in a pulse mode [1], with the aim of reducing residual welding deformations, and in continuous mode for welding thick sheets of titanium (16mm) [2]. In addition, there are researches with using of laser radiation of CO_2 laser. Separate work are devoted to the description of results of the research of laser welding with filler wire [3, 4], other about laser welding of titanium sheets overlap [5]. However, the most advantageous welding process of titanium alloy is laser-arc welding. The main advantages are minimal welding deformation (comparable to the deformations formed at laser

welding), high welding speed, high depth of penetration, the capability of welding with gap, and the capability of varying the chemical composition of the weld metal [6-8].

The aim of this work was to evaluate the technological opportunity of laser-TIG welding (LTW) of titanium alloys Ti-1.5Al-1.0Mn and Ti-6Al-4V with a thickness of 5 mm.

Researches in this area are mainly represented with using of electron-beam welding, but also there is the interest to the use of laser welding by a CO_2 laser [9, 10] or solid-state laser [11].

The influence of the parameters of LTW on the formation of the joint weld was investigated during research; also, the analysis of the microstructure and mechanical properties of joint weld was produced.

2. The experimental researches

2.1. Welding equipment

The experimental researches of laser -TIG welding have been carried out with using a laser-arc technological complex with fiber ytterbium laser LS-5 (IPG). It works in continuous mode and has wavelength of radiation of 1070 nm and maximum output power of 5 kW.

The laser beam has been focused with a focal length of 300 mm in a spot with a diameter of 200 microns. The TIG welding source AC/DC TRITON 220 AC/DC Power Sinus (EWM) with the maximum welding current and floating voltage 220A and 45V, respectively, has been used as arc source. The feeder PDGO-601 («ITW») got the filler wire.

2.2. Welding materials

Plates from titanium alloys grade Ti-1.5Al-1.0Mn и Ti-6Al-4V with dimensions 200x400x5 mm were used in the experiments. The welding wire Ti-1.5Al-1.0Mn with a diameter of 1.6 mm has been used as the filler wire.

Chemical composition of titanium alloys are presented in table 1.

Table 1 - Chemical composition of titanium alloys

	Fe	C	Si	Mn	V	N	Ti	Al	Zr	O	H	others
Ti-1.5Al-1.0Mn	< 0.3	<0.1	< 0.15	0.7 - 2		< 0.05	94.138 - 98.3	1 - 2.5	< 0.3	< 0.15	< 0.012	0.3
Ti-6Al-4V	< 0.3	< 0.1	< 0.15		3.5 - 5.3	< 0.05	86.485 - 91.2	5.3 - 6.8	< 0.3	< 0.2	< 0.015	0.3

The argon and helium have been used as shielding gases for prevention of oxidation of the welding pool and metal, heated to a temperature more than 350^0C

2.3. Methods of quality control of the welds, test methods, test equipment

All welds have been subjected to visual inspection for existence of defects. For further study of geometry, internal defects and microstructure of joint weld were made microsections. Researches of the nature of transfer the filler wire into the welding pool and stability of the arc have been carried by high-speed video camera CENTURIO C100, with the video frequency of 3000 frames/sec.

3. Experimental results and discussions

LTW have been carried in a lower position in one pass. The process is performed with maximum output power of laser radiation of 5 kW for getting maximize productivity.

3.1 Melting of a filler wire

During the LTW process filler wire was applied along the seam from the side of the arc at the smallest possible angle relative to the surface plate 10-15^0, figure 1.
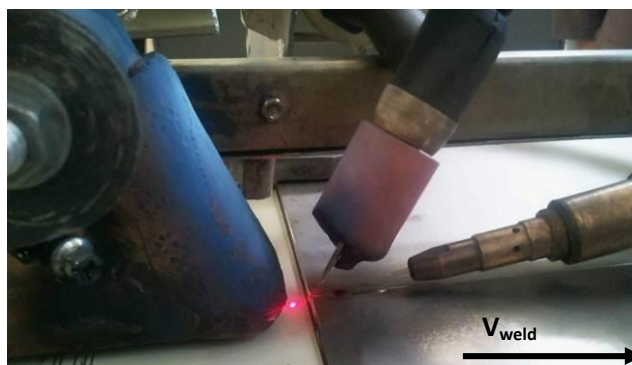

Figure 1 – Scheme of location of sources of heat and filler wire in LTW

For researches of the nature of melting of filler material was used a high-speed video. The frames of high-speed video are shown in figure 2.
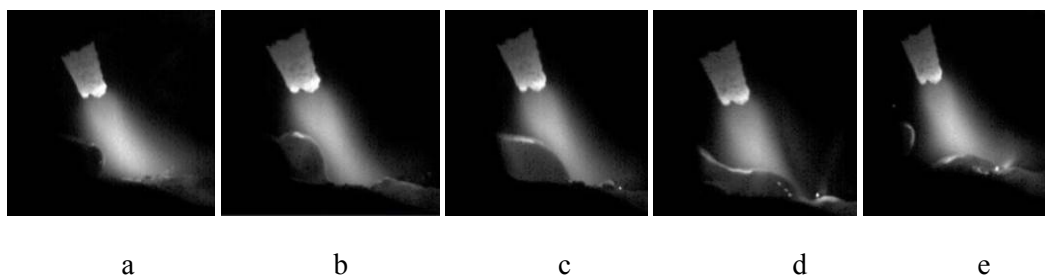

a   b   c   d   e

Figure 2 – Transferring of filler material in the welding pool: laser output power (P_L) - 5kW, velocity of LTW (V_{weld}) - 0.9 m/min, current of arc (I) - 140A, arc voltage (U_{arc}) to 18V,   filler wire feed speed (V_{wire}) - 1.1 m/min; the distance from the end of the electrode to the surface of the sheet (h) - 3 mm.

As can be seen from figure 2, the process of melting the filler wire can be divided into several stages. The heating of wire in front of by the arc and melting with the formation at the expense of forces of surface tension of a spherical droplet at its end is shown in figure 2a. The growth of a spherical droplet due to the melting of new portions of the filler wire and hold it on the end of the wire due to the forces of surface tension are shown in figure 2b. The amount of molten metal filler wire and the mass of droplet increase and due to the action of gravity, the drop changes its shape (figure 2c). The drop is stretched out (figure 2d) and is separated from the end of filler wire and flowing into the welding pool (figure 2e) when it approaches to the weld pool and increasing the pressure of the arc on the surface.

The cyclical nature of this process provides a uniform transfer of molten filler metal to the welding pool. The melting of the filler wire by arc component of LTW helps to use of costly laser radiation on the penetration of the plates. Arc also provides pre-heating of the plates, increasing their absorption of laser radiation.

3.2. The influence of the distance between the electrode and the surface of the welded plates on the stability of arcing

LTW has been carried with the distance between the electrode and the surface of the plates in the range from 2 to 3 mm. It helps to determine the optimal location of the electrode. The process of LTW

has been recorded by high-speed video camera. The frames of high-speed video are presented in figure 3.
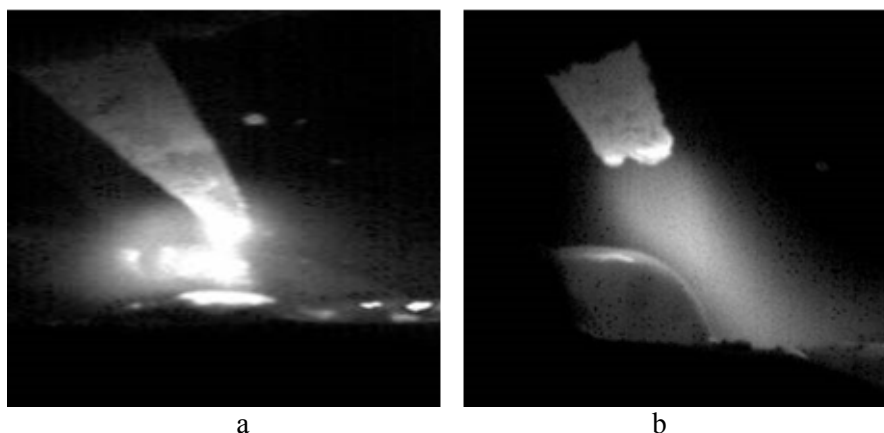

a   b

Figure 3 – Influence the distance between the electrode and the surface of the plates h on the stability of arcing: a – h=2 mm, b – h=3 mm, (P_L=5kW, V_{weld}=0.9 m/min, I=140A, U_{arc}=18V, V_{wire}=1.1 m/min)

According to the results of experimental studies of the nature of melting of filler wire (figure 2) the melt droplet during its growth increases in volume with keeping a spherical shape. At some point of time the diameter of the spherical drop is increased to 2 mm, sufficient for the circuits of the arc gap (figure 3a). At the time of short circuit the arc goes out. The shape of drops changes because size of drops, its mass increase, and the pressure of arc on the surface also increase. Thus, the melt droplet at the end of filler wire has not time to reach a diameter of 3 mm and flows into the molten pool via the mechanism described in the previous section (figure 3b), because of this, a short circuit is not formed, and the arc burns steadily.

3.3. The influence of welding speed on the formation of a welded joint

The investigation of the influence of speed of LTW on the formation of a joint weld has been performed in the range of 0.72 to 1.5 m/min. The electrode was positioned at a 30^0 angle from the vertical. The distance between the axis of the laser radiation and the electrode on the surface of the plates was 3 mm. LTW has been carried without filler wire and without the protection of the weld root. The top side of the welding pool and the weld metal were protected by argon with flow rate of 30 l/min. The welding has been carried out at the following mode settings: laser power: 5 kW, embedding of the focal plane of laser beam is 1 mm, the power arc current: 160A, arc voltage: 18V. The appearance of the result of the experiment with stable full-penetration of plates are presented in figure 4.

Front side   Backside

Figure 4 – The appearance of joint weld performed at LTW with welding velocity V_{weld} = 0.72 m/min

The results of welding performed at high speeds and, consequently, low heat input had not stable full penetration. The joint weld formed at a velocity of 0.72 m/min and the maximum welding heat input had the highest stability of full penetration. The results of this study it was decided to perform further experiments of LTW at a welding velocity of 0.72 m/min.

3.4. The influence of deepening the focal plane of laser radiation on the formation of a joint weld

LTW with an embedding of focal plane Δf from 1 to 7 mm relative to the surface of the plates has been performed with the aim of getting a stable full penetration. The welding has been carried out on selected in the previous sub-section velocity with the same values of the other parameters of the mode.

The welding process was carried out without filler wire and without the protection of the weld root. The electrode was positioned at a 30^0 angle from the vertical. The distance between the axis of the laser radiation and the electrode on the surface of the plates was 3 mm. The top side of the welding pool and the weld metal were protected by argon with flow rate of 30 l/min. Appearance of joint weld with stable penetration is presented in figure 5.
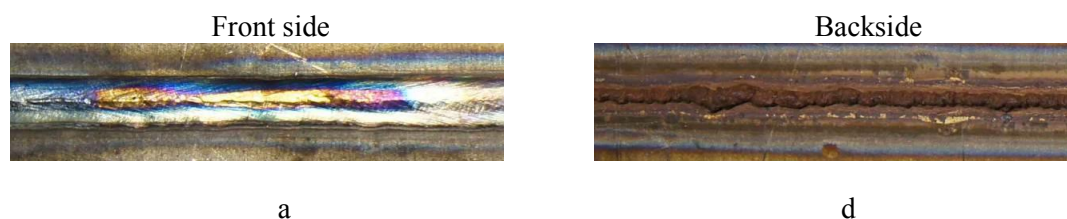
Front side	Backside

a	d

Figure 5 – Appearance of joint weld, Δf =1 mm

The top weld beads had annealing colours (Figure 5a). It shows about to the poor protection during the welding process. Bottom weld beads had a rough surface and a brown color (Figure 5b). It shows about the absence of protection of the weld metal. The reduction of the width of the bottom weld bead and increase the width of the top weld bead at the embedding of the focal plane of the laser beam was found during of visually control of geometry of joint weld.

The stable formation of a bottom weld bead (full penetration) was detected at the deepening of the focal plane relative to the top surface of the plate by 1 mm.

Then LTW with the filler wire was performed. The mode of parameters are presented in table 2. The welding pool and the metal is heated to a temperature above 350^0C were protected by argon. The appearance of welded joints is presented in figure 6.

Table 2 – The mode of parameters of LTW

№	P_L, kW	V_{weld}, m/min	Δf, mm	I, A	U_{arc}, V
8	5	0.72	-1	160	18

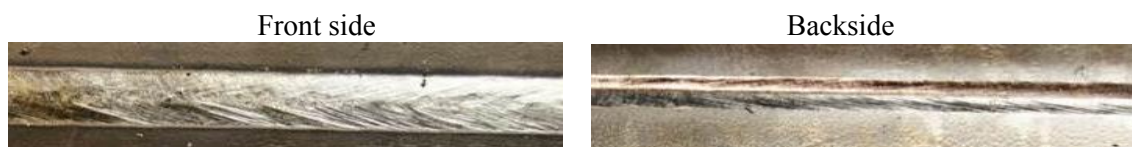| Front side	Backside

Figure 6 – Appearance of joint weld with filler wire

Any visual defects have been not detected by visual control of joint weld. The joint weld had a stable full penetration. The colour of top weld bead changed from light silver to light straw. The bottom weld bead had a light silver color. It indicates about a uniform quality protection.

3. Metallographic tests

During visual control of the cross section of a joint weld by optical microscope, the increase in the width of weld in the upper and lower parts has been found. The main contribution to end-to-end

penetration introduces laser radiation; the energy of the arc is used for melting the filler material and the upper layers of the plate.

3.1. The microstructure of the joint weld

The titanium alloys investigated in this work belong to different groups: Ti-1.5Al-1.0Mn - pseudo-α alloy containing β phase and Ti-6Al-4V – the alloy of the martensitic type, similar to the pseudo α alloy.

The alloys Ti-1.5Al-1.0Mn and Ti-6Al-4V have been welded between each other with application of welding wire with a chemical composition corresponding to Ti-1.5Al-1.0Mn and the resulting structure of the weld metal composed of martensite α' – phase.

Three characteristic areas were found in the HAZ of the joint weld:

the area with big size of grains (overheating), where the temperature varies from the melting temperature to 1300°C;

the area with full recrystallization, where upon cooling, the structures are similar to those that occur at the area with big size of grains;

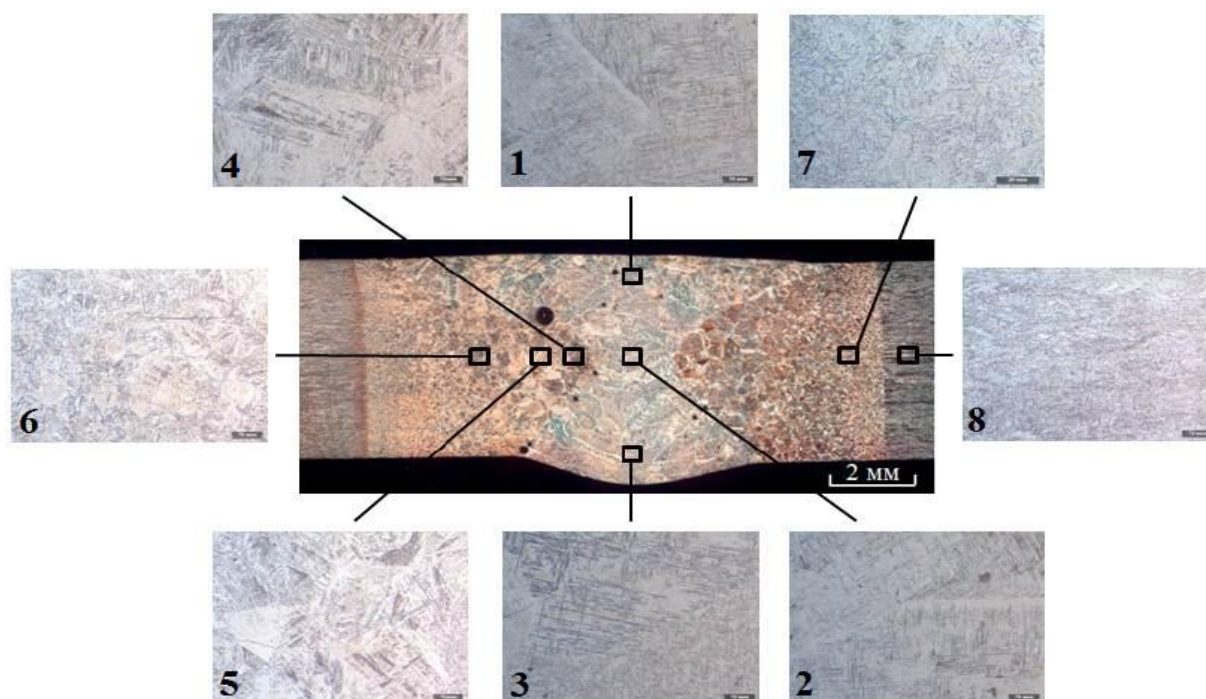the area of incomplete recrystallization (figure 7).

Figure 7 – Microstructure of the joint weld

4. Mechanical tests

4.1. Static tension

From the weld joint were manufactured samples for tests on static stretching according to GOST 1497-84 "Methods of tensile tests". According to test results, the value of temporary resistance ranged from 653 to 661 MPa, and the fracture of specimen occurred in the base metal. This proves that the parameters of the mode of LTW provide a generation a joint weld with the strength simmilar to base metal.

4.2. The microhardness tests

The microhardness tests have been carried out according to the scheme presented in figure 8.
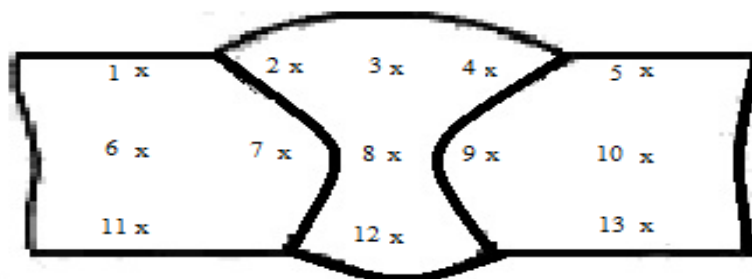

Figure 8 - Scheme of microhardness measurement.

The results of measurement of microhardness are presented in table 3.

Table 3 – The results of measurement of microhardness

№	1	2	3	4	5	6	7	8
HV	283.3	282.9	253.9	272	231.1	272.4	273.8	264.4
	9	10	11	12	13			
	211	213.2	264.6	247.9	214.2			

The weld seam had a hardness middle between Ti-6Al-4V (numbers 1, 6, 11) and Ti-1.5Al-1.0Mn (numbers 5, 10, 13) about 260 HV.

The study of the chemical composition of the weld metal detected that it is formed of filler material Ti-1.5 Al-1.0Mn. The presence of V is not detected in the composition of the weld metal. It indicates about a minimum amount of Ti-6Al-4V in the composition of the weld metal.

Conclusion
During the research, the nature of transport of metal filler wire into the weld pool has been investigated. The melting of it in front of the weld pool by arc with a uniform drop transport mechanism has been detected. The minimal distance between the end electrode and the surface of the welded plates, providing steady-state combustion of arc is 3 mm. The devices providing reliable protection of the molten metal and metal heated over a temperature of 350^0C, from the atmosphere have been made. The relationship between welding velocity, the position of focal plane of the laser beam and the stability of penetration of plates was determined.

According to the results of research the technology laser-TIG welding with the filler wire of titanium alloys Ti-1.5Al-1.0 Mn and Ti-6Al-4V with a thickness of 5 mm has been developed. The welded joints with satisfactory mechanical properties were obtained.

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