

# LASER WELDING OF TITANIUM ALLOY Ti6Al4V USING A DISK LASER

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**Abstract:** Study of butt joints welding of titanium alloy sheets Ti6Al4V (Grade 5 according to ASTM B265) using a new generation disk laser TRUMPF TRUDISK 3302 were carried out, and the results are presented in this paper. Butt joints of the titanium alloy sheets 2,0 mm thick were laser welded without an additional material at a flat position, using a specially designed system for shielding gas (high purity argon). The influence of laser welding parameters on weld quality and mechanical properties of test joints was studied. The quality and mechanical properties of the joints were determined by means of tensile and bending tests, hardness and micro hardness tests, and also metallographic examinations.

**Keywords:** LASER, WELDING, TITANIUM ALLOY, Ti6Al4V, GRADE5

## 1. Introduction

Titanium and titanium alloys are widely used in space, aerospace, ship and chemical, nuclear energy and medical industries, because of many advantages such as low specific weight, high strength, excellent corrosion resistance, attractive fracture behavior and high melting point [1÷5]. Weldability of commercial pure titanium and most titanium alloys is good in general, although special cares must be taken during the welding process because pure titanium and titanium alloys are highly susceptible to contamination from atmospheric gases [1,4,6,7]. Pure titanium is extremely chemical reactive at high temperature and it is easy to absorb harmful gases from the ambient atmosphere (oxygen, hydrogen and nitrogen) therefore the titanium may be exposed to contamination during the welding process and also during the subsequent cooling phase, till the temperature of titanium surface decrease below 300 °C (or 600 °C in a case of some titanium alloys) [1,6,7]. When the shielding is insufficient the heated titanium surface absorbs gases from the air atmosphere and additionally titanium forms brittle carbides, nitrides and oxides causing hardness increasing and simultaneously reducing the fatigue strength and notch toughness of the welded joint and heat-affected zone (HAZ). The groove of the weld also must be perfectly protected by shielding gas. Additionally any surface impurities can diffuse into the titanium, causing porosity and brittleness, thus the joint area must be decreased and cleaned precisely. The content of carbon in the pure titanium should not exceed 0,1 %, but even very low content of carbon may result in titanium carbides formation which have very high hardness up to 900 HV, and additionally in a case of even low content of oxygen the carbon oxide and/or carbon dioxide may be formed causing weld porosity. The electrical and thermal conductivity (16,4 W/m·K) of titanium is relative low, and significantly affects the thermal cycle of welding, thus the cooling rate of weld metal and heat affected zone (HAZ) is relative low. The low cooling rates usually leads to grain growth of weld metal and HAZ as well. In a case of overheating of the joint, when the heat input of welding is too high, the brittle  $\omega$  phases may be formed at the stage of low rate cooling resulting in hardness, brittleness increase. Additionally, as a result of high temperature gradients, significant stresses in the weld metal and HAZ may occur and sometime even cracks [1,6,7,9].

In most cases of titanium welding, especially high strength titanium alloys, the high quality of joints may be achieved just using heat sources with high power density, enabling welding at high speeds and low heat input [1,6,7].

The Ti6Al4V titanium alloy is one of the most widely used titanium alloys. It is a two phase  $\alpha+\beta$  alloy, with aluminum as the alpha stabilizer and vanadium as the beta stabilizer. The Ti6Al4V titanium alloy is characterized by satisfactory properties up to about 300 °C, that is why the alloy is widely used for manufacturing of turbine disks, compressor blades, air frame and space capsule structural components, rings for jet engines, pressure vessels, rocket engine cases, helicopter rotor hubs, fasteners and also medical and

surgical devices. This alloy can be strengthened by heat treatment or by thermo mechanical processing [8÷13].

Laser welding of titanium alloys is advantages because of low heat input, especially compared to arc welding processes, resulted in low distortion, minimizing the shrinkage and residual stress of joints and ensuring excellent mechanical properties of joints. The disadvantages of laser butt welding is the difficulty of the joint fit up, which requires extreme precision along the edges to be welded. Laser welding is one of the most modern of all metals and alloys joining processes and, thanks to its technological and economical features, laser welding becomes more and more competitive to conventional arc welding processes, even to electron beam welding.

Laser welding consist in melting of the contact area of the parts to be welded by the laser beam which is delivered and focused on the welding area. Two techniques of laser welding can be use: melt in (conduction heat welding) or keyhole welding with or without additional material [1,6,7,10,13].

## 2. Material and experimental procedure

Mill-annealed sheets of 2,0 mm thick Ti6Al4V (Grade 5 according to ASTM B265) were laser welded using a fully automated experimental stand with a Disk laser TRUMPF TRUDISK 3302, Fig. 1,2. The specimens for fully penetrated I-joint welding, without additional material (filler), were cut from a 2,0 mm thick sheet into pieces in dimension of 60,0 x 100,0 mm. The microstructure of the base material (BM) is well recrystallized and composed of a  $\beta$  phase dispersed in a dominating  $\alpha$  matrix, Fig. 3÷5.

The laser beam emitted at 1,03  $\mu\text{m}$  wave length was delivered into the focusing optics via fibre core of 200  $\mu\text{m}$  in diameter. The laser welding head (focusing optics) was equipped with a 200 mm collimator lens and a 200 mm focusing lens. The beam parameter product (BPP) of the laser beam was  $< 8.0 \text{ mm}\cdot\text{mrad}$ . The laser beam was focused on the top surface of specimens (200  $\mu\text{m}$  spot size), Fig. 1.

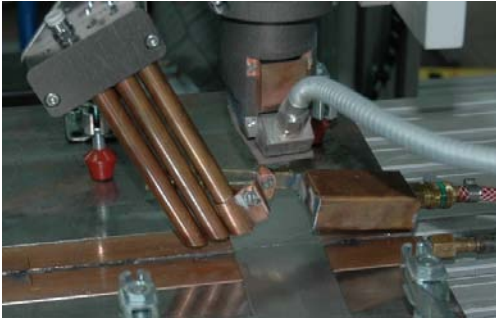
To protect the weld pool, and heated surface of the joint as well, against the harmful influence of atmospheric air the top of the joint and weld as well (weld face and surrounding areas) was protected by high purity argon flow via multi nozzle system, including trailing shield 40,0 mm wide and 90,0 mm long, and also the back side of joint (weld groove) was protected by high purity argon flow, Fig. 1.

The specimen surfaces were brushed with stainless steel wire brush and chemically cleaned by methanol prior to welding (to eliminate surface contamination) and next mounted in the stiff clamping device to eliminate any distortion or displacement during welding, Fig. 1,2.

To investigate the effect of the laser welding parameters on the weld geometry, microstructure and mechanical properties of the butt joints, the test welds were produced at different welding speed and laser power. In the initial stage of experiments, bead-on-plate welds were produced at different parameters of laser malting, to

determine the ranges of parameters for fully penetrated joint welding, Fig. 2,3.

Results of metallurgical and mechanical examinations of the bead-one-plate and test joints are given on the Fig. 2 to 11, and in the Table 3 to 5.



**Fig. 1** A view of the laser welding head and shielding gas system with multi nozzle protection, including trailing nozzle and groove protective nozzles

**Table 1.** The technical parameters of the Trumpf TruDISK 3302 and the laser optics

Parameter	Value
Wave length, nm	1030
Output power, W	3300
Laser beam Divergence, mm-mrad	8.0
Fibre core diameter, $\mu\text{m}$	200,0
Collimator focal length, mm	200,0
Focusing lens focal length, mm	200,0
Bem spot diameter, $\mu\text{m}$	200,0
Fibre length, m	20,0

**Table 2** The composition of Ti6Al4V (Grade 5) and Commercial Pure Ti (Grade 2) wt.%, according to ASTM B265 standard

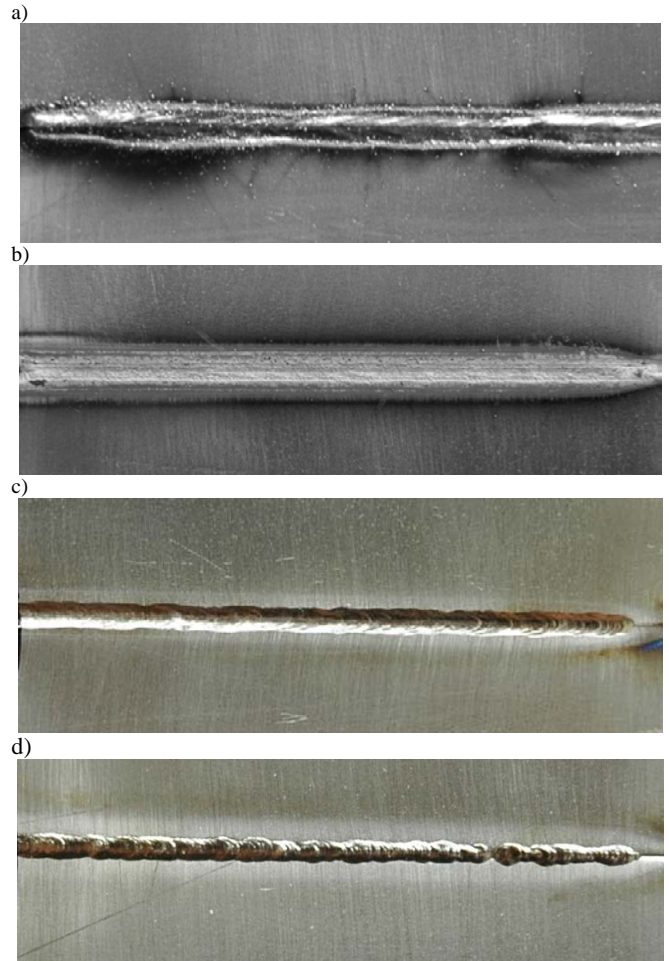
Element	Ti6Al4V	CP Ti
	Content	
C	< 0.08	< 0.08
Fe	<0.25	<0.3
O	<0.2	<0.25
Al	5.5÷6.76	-
V	3.5÷4.5	-
N	<0.05	<0.03
H	<0.015	<0.015
Ti	Balance	Balance

**Table 3** Parameters of bead-on-plate laser melting of the titanium alloy Ti6Al4V (Grade 5) sheet with the Trumpf TruDISK 3302

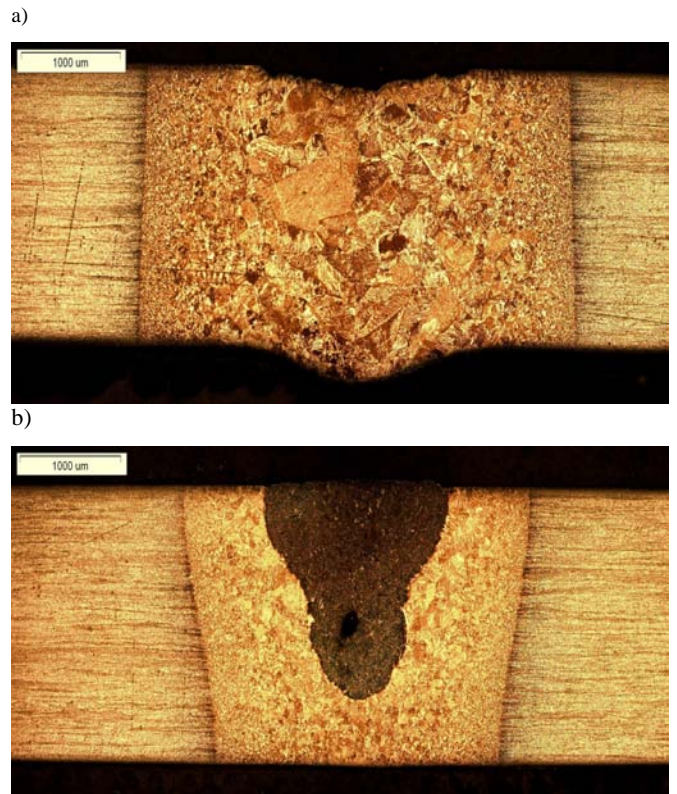
Weld bead no.	Laser beam power W	Melting speed, mm/min	Heat input, J/mm
1	500	500	60
2	600	500	72
3	800	500	96
4	400	500	48
5	1000	1000	60
6	1000	800	75
7	1000	900	66
8	1000	1200	50
9	1000	1500	40

**Table 4** Parameters of laser welding of the titanium alloy Ti6Al4V (Grade 5) butt joints with the Trumpf TruDISK 3302

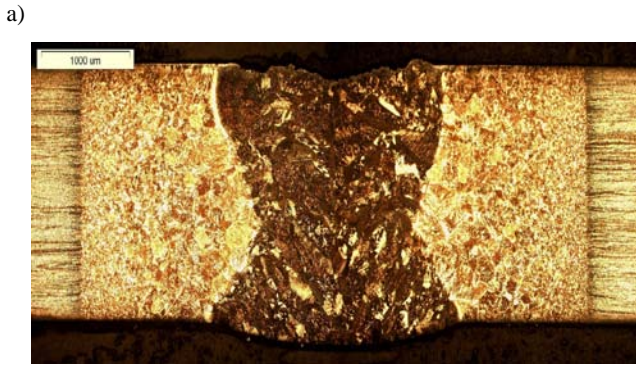
Joint no.	Laser beam power, W	Welding speed, mm/min	Heat input, J/mm
Z1	800	500	96
Z2	1000	800	75
Z3	500	500	60



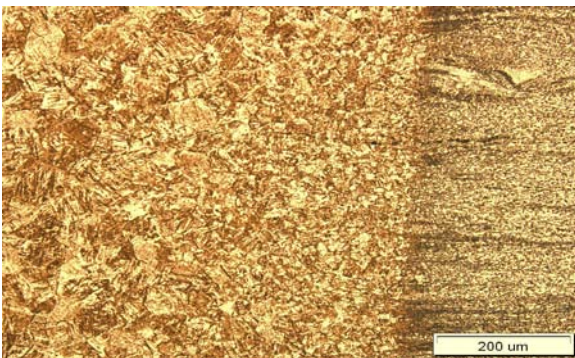
**Fig. 2** A view of butt joints of titanium alloy Ti6Al4V sheets 2.0 mm thick laser welded with the Disk laser; a),b) weld face and groove of the Z1 joint, c),d) weld face and groove of the Z3 joint, Table 4



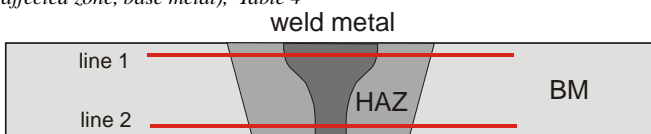
**Fig. 3** Macrograph of the cross section of bead-on-plate welds of titanium alloy Ti6Al4V sheets; a) weld bead no. 6, b) weld bead no. 9, Table 3



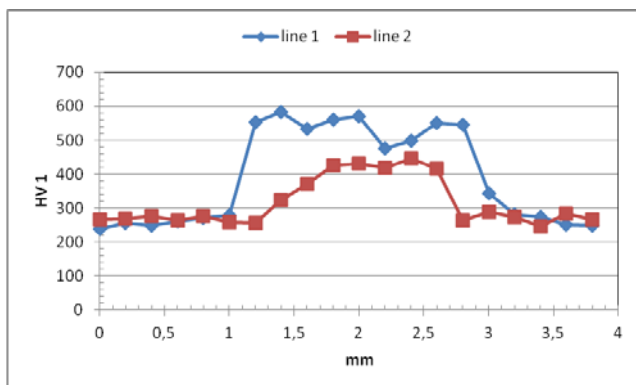
**Fig. 4** Macrograph of the cross section of butt joints of titanium alloy Ti6Al4V sheets 2.0 mm thick laser welded with the Disk laser; a) joint no. Z2, b) joint no. Z3, Table 4



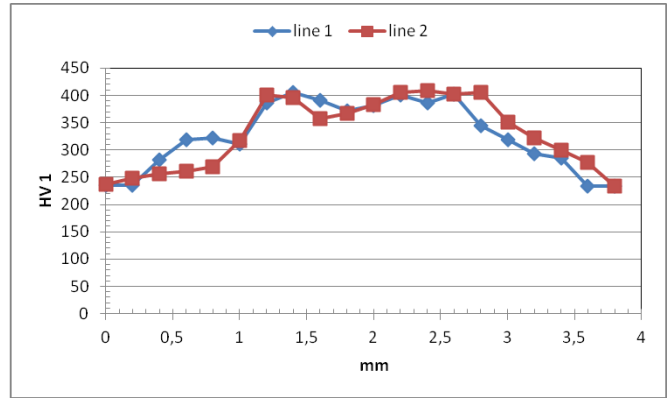
**Fig. 5** Microstructure of the Z3 butt joint of titanium alloy Ti6Al4V sheets 2.0 mm thick laser welded with the Disk laser (from left : weld metal, heat affected zone, base metal), Table 4



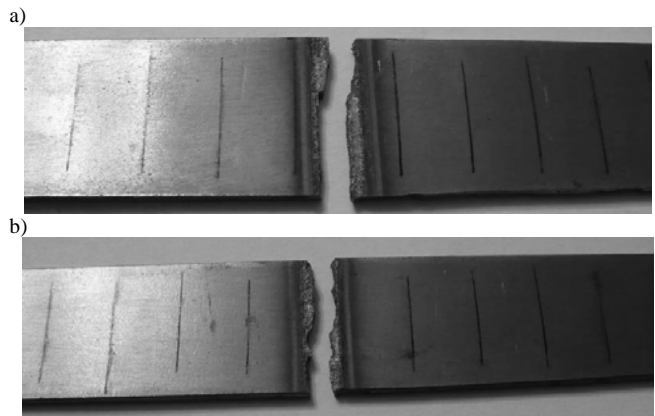
**Fig. 6** Scheme of the hardness HV1 measurement procedure



**Fig. 7** Hardness HV1 distribution on the cross section of titanium alloy Ti6Al4V butt joint 2.0 mm thick laser welded with the Disk laser; joint no. Z1, Table 4



**Fig. 8** Hardness HV1 distribution on the cross section of titanium alloy Ti6Al4V butt joint 2.0 mm thick laser welded with the Disk laser; joint no. Z1, Table 4



**Fig. 9** A view of the samples after tensile test of the titanium alloy Ti6Al4V butt joints 2.0 mm thick laser welded with the Disk laser; a) joint no. Z1, b) joint no. Z2, Table 4



**Fig. 10** A view of the titanium alloy Ti6Al4V butt joint Z3 after tensile test, Table 4

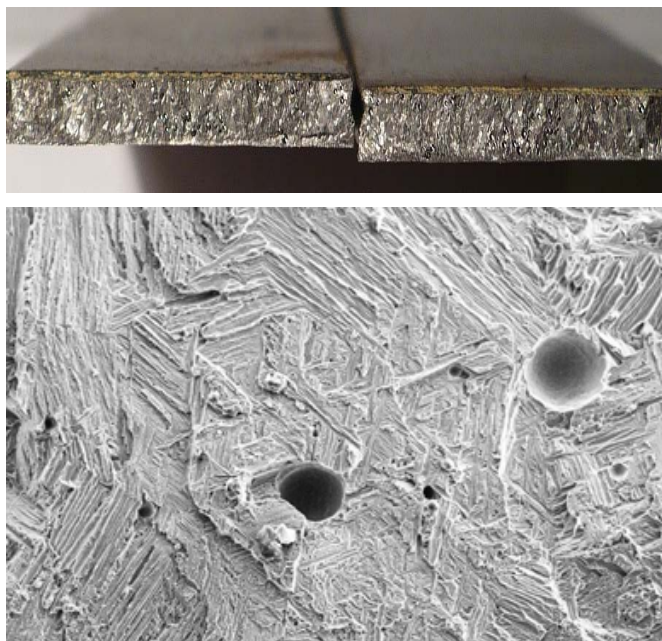
**Table 5** Results of the Technological Bend Test of butt joints of titanium alloy Ti6Al4V sheets 2.0 mm thick laser welded with the Disk laser, Table 4

Joint no. / sample no.	Test type	Bending angle	Remarks
Z1 / Z1L	Face bend	18°	Brittle fracture
Z2 / Z2L	Face bend	23°	Brittle fracture
Z3 / Z3L	Face bend	37°	A crack about 4,5 mm long
Z3 / Z3G	Root bend	56°	A crack about 3,0 mm long

### 3. Results and discussion

In the first stage of investigations, the bead-on-plate weld beads were produced on the titanium alloy Ti6Al4V (Grade 5 according to ASTM B265) sheets 2.0 mm thick at different laser power and melting speed to simulate the butt joint welding without additional material (filler) and to determine the range of laser welding

parameters for high quality and fully penetrated joints, Table 3. The initial test of bead-on-plate laser welding of the titanium alloy sheets with the Disk laser TRUMPF TRUDISK 3302 revealed that the providing of an effective and proper shielding of the joints is difficult, therefore special system for shielding gas was applied, including multi nozzle weld pool protection, trailing nozzle, and groove protection as well, Fig. 1,2. In the range of investigated parameters of bead-on-plate laser welding and butt joint laser welding of the titanium alloy Ti6Al4V sheets the mechanism of melting and welding is a key-hole welding, resulted in plasma plume formation, Fig. 3. It was found that the plasma plume over the key-hole disrupt the shielding gas (high purity argon) flow and significantly decreases the effectiveness of shielding.



**Fig. 11** Fracture surface (brittle fracture, porosity) of the titanium alloy Ti6Al4V butt joint no. Z2 after bend test, Table 4

For full penetration of the titanium alloy Ti6Al4V sheets 2.0 mm thick with the Disk laser beam focused on the top surface of the sheet, a heat input 50 J/mm is required at least, at laser beam power 400 W and welding speed 500 mm/min, Fig. 3, Table 3.

Bead-on-plate laser welding of the titanium alloy Ti6Al4V sheets 2.0 mm thick in a range of the heat input from 50 to 80 J/mm resulted in columnar shape of the weld bead with symmetric and parabolic fusion lines, typical for key-hole mode laser welding and melting as well, Fig. 3.

Weld bead faces and grooves produced in the range of investigated parameters are smooth and flat, Fig. 2. The width of weld faces does not exceed 1,0 mm, simultaneously the heat affected zones (HAZ) are very narrow with fine structure (low grain size), Fig. 3.

Increasing the heat input over 80 J/mm during laser bead-on-plate welding of the titanium sheet resulted in significant increase of the weld width and HAZ as well, and also significant grain growth in weld metal and HAZ, Fig. 2,3. Additionally the excessive heat input leads to weld face collapsing and excessive penetration, and also overheating of the weld face, groove and surrounding regions, Fig. 2,3. Additionally in a case of the weld produced at too high heat input cracks and porosity occur, Fig. 2,3.

The hardness of base material (BM) of the titanium alloy Ti6Al4V, measured on the surface of sheet 2.0 mm thick, is from 240 HV1 to 260 HV1 (about 23.5 to 25.5 HRC), Fig. 7,8. Hardness measurements conducted on the cross sections of bead-on-plate welds and butt joints revealed that the hardness in a HAZ region is similar as the hardness of BM, but significant increase of hardness occurs in the melt zone (weld metal) up to 430 HV1 or even up to 580 HV1 in a case of joint no. Z1, Fig. 7,8.

The tensile strength of the base material of titanium alloy Ti6Al4V sheet 2.0 mm thick, determined experimentally, is about 820 MPa, Fig. 10. The tensile tests of the laser welded joints showed that the tensile strength of the joints welded at heat input over 70 J/mm is in a range from 630 to 710 MPa, that is about 25% lower than the tensile strength of BM, Fig. 9. These joints were broken in the weld metal, Fig. 9. On the other hand, the test butt joint welded at the lowest heat input 60 J/mm, characterized by very narrow and fine structure HAZ, was broken in the BM, so the tensile strength of the joint is not lower than the tensile strength of BM, Fig. 10.

The technological bending test of the butt joints laser welded at heat input over 70 J/mm revealed high brittleness of the joint, because the joint were suddenly broken during bending test at the bend angle 20÷25°, Table 5, Fig. 11. The brittleness of the test butt joints, is most probably caused by the nitrogen, oxygen and hydrogen absorbed by the weld metal from the ambient as a result of the shielding argon flow disruption by the plasma plume formed over the key-hole. The test joint laser welded at the lowest heat input 60 J/mm is characterized by significantly higher plasticity because the bend angle reached 37° in a case of weld face bending and 56° in a case of groove bending, Table 5.

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