Archives of Materials Science and Engineering

Volume 58
Issue 2
December 2012
Pages 209-218

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Welding of titanium alloy by different types of lasers

A. Lisiecki*
Welding Department, Silesian University of Technology,
ul. Konarskiego 18a, 44-100 Gliwice, Poland
* Corresponding e-mail address: aleksander.lisiecki@polsl.pl

Received 12.10.2012; published in revised form 01.12.2012

ABSTRACT

Purpose: of this paper was focused on comparing the welding modes during laser welding of butt joints of titanium alloy Ti6Al4V sheets 1.5 and 2.0 mm thick with direct diode laser and Disk solid state laser.

Design/methodology/approach: Bead-on-plate welds were produced at different parameters of laser welding, different welding speed, different output laser power resulted in different heat input of laser welding process. The test welds were investigated by visual test, metallographic observations including macro and microstructure analysis. Additionally mechanical test were carried out such as tensile tests and technological bending test of the joints. The influence of basic laser welding parameters on the penetration depth, shape of fusion zone, width of welds and width of heat affected zones were studied. Additionally the phenomena of laser heating and melting of the welded sheets were analyzed.

Findings: It was found that the mechanism of HPDL laser welding of titanium alloy differs distinctly from the mechanism of Disk laser welding. The test welds produced by HPDL laser were high quality. Welds produced by the Disk laser are characterized by a columnar shape of fusion zones, very narrow with narrow and fine structure heat affected zone.

Research limitations/implications: In further investigations of laser welding of titanium alloys applying the key-hole welding mode a special care must be taken to the shielding of the weld zone and protection the weld pool and weld metal against the harmful gases from air atmosphere.

Practical implications: Results of investigations presented in this paper may be applied directly for welding high quality butt joints of titanium alloy with the HPDL laser. In a case of laser welding with the Disk laser practical application requires further study, especially concentrated on the effectiveness of gas protection of the welding area including the key-hole, weld pool and surrounding regions of metal.

Originality/value: This paper describes results of investigation concerning laser welding of the most common used titanium alloy Ti6Al4V by two unique and modern lasers. The investigations were carried out using the high power diode laser with a rectangular laser beam spot and also using a new generation of Disk laser characterised very high power density of the laser beam spot.

Keywords: Laser welding; Diode laser; HPDL laser; Titanium alloy; Ti6Al4V

Reference to this paper should be given in the following way:

A. Lisiecki, Welding of titanium alloy by different types of lasers, Archives of Materials Science and Engineering 58/2 (2012) 209-218.

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Titanium and titanium alloys are widely used in space, aerospace, ship and chemical, nuclear energy and medical industries, because of many advantages compared to other materials e.g. steel, aluminium, magnesium alloys, and even some composites, cermetals [1-17]. 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 [1,18-20]. 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) [1-3,18,19]. 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) [1,2,18-19]. The grove 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 results 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 [1,2,18]. 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 ω 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 [1,21].

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 [1,2,18-19,21].

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 [1,2,18,19].

Laser welding of titanium alloys, as well as other metals and 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 [1,2,18-22]. The disadvantages of laser butt welding is the difficulty of the joint fit up, which requires extreme precision along the edges to be welded.

In recent years, the development of laser devices, generators, gain medium types is very dynamic [1,2,23-25]. There are many new types and modified lasers, leading to rapid development of laser technology, including laser welding technology [1-3,5,7,13].

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 [1,2,18-25].

Therefor two types of modern lasers with different characteristics were used for study of titanium welding.

2. Materials and experimental procedures

Mill-annealed sheets of 1.5 and 2.0 mm thick of Ti6Al4V (Grade 5 according to ASTM B265) were used for laser welding of butt joints (Tables 1, 2). The study of laser welding phenomena were carried out by means of a High Power Diode Laser ROFINH SIANR DL 020 with a rectangular beam spot and by a Disk laser TRUMPF TRUDISK 3302 with a circular beam spot (Tables 3,4). The HPDL ROFIN DL 020 is a direct diode laser which emits at 808 nm (very near infra-red range IR) and the minimum area of the rectangular beam spot of the laser is 1.8×6.8 at 82 mm focal length or 1.8×3.8 mm at 32 mm focal length (with an extra focusing lens). Maximum output power of the HPDL ROFIN DL 020 is 2.2 kW and the energy distribution across the beam spot is very even (multimode TEM) (Table 3). The maximum power density of HPDL laser beam, at maximum power of 2200 W and spot size 1.8x3.8 mm, reaches $3.2\cdot10^4$ W/cm^2 (Table 3, Fig. 1.)

The Disk laser TruDisk emits a circular high quality laser beam at the wave length 1.03 μm. The laser beam is delivered into the focusing optics via fibre core of 200 μm 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 is < 8.0 mm·mrad, which indicates very high quality of the laser beam. According to the configuration of the optics diameter of the laser beam spot is 200 μm, (Table 4, Fig. 2). Maximum power density of the Disk laser beam, at 3300 W, is $1.05\cdot10^7$ W/cm^2, significantly higher compared to the HPDL laser (Table 4).

In a case of HPDL laser welding of titanium alloy Ti6Al4V sheets, preliminary welding tests indicated that cylindrical nozzle of dia. 12 mm with argon flow at 12-15 l/min provides full protection of the weld face and no trailing shield is needed (Fig. 1).

On the other hand, in a case of Disk laser welding of titanium alloy Ti6Al4V sheets, protection of the weld pool, and also the surrounding regions of the joint against the harmful influence of atmospheric air is significantly more difficult (Fig. 2). Therefor in a case of the Disk laser study of titanium alloy Ti6Al4V welding a special multi nozzle system was applied (Fig. 2). The high purity argon was delivered via multi nozzle system, including trailing shield 40.0 mm wide and 90.0 mm long, and also the beck side of joint (weld root) was protected by high purity argon flow (Fig. 2).

The specimens 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 (Figs. 1, 2).

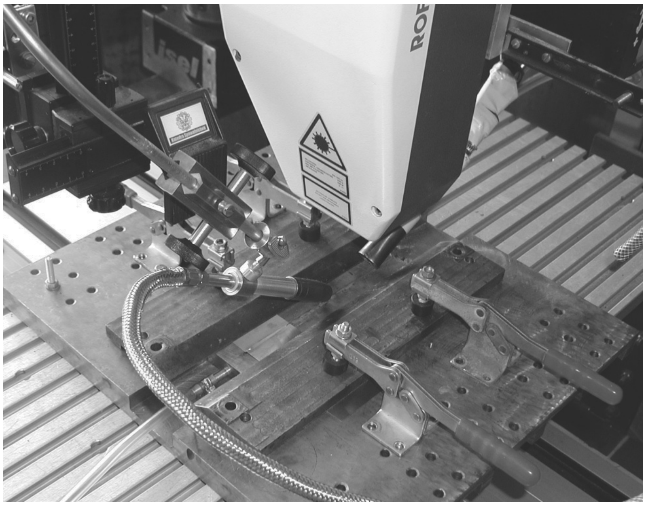
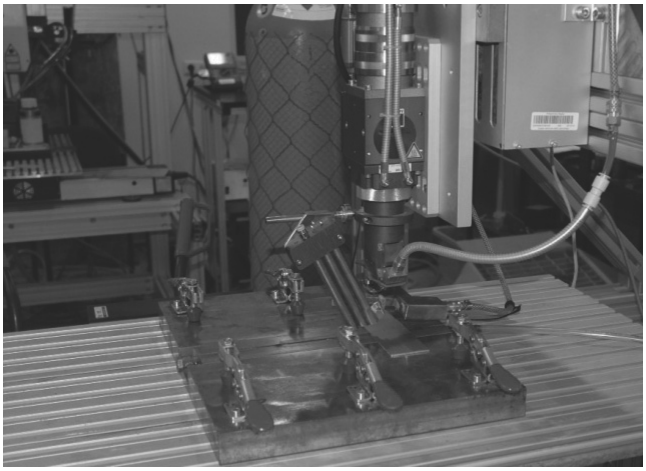


Fig. 1. A view of the experimental setup with the HPDL ROFIN DL020 laser head and clamping system used for welding the butt joints of titanium alloy Ti6Al4V 1.5 mm thick (Table 3)

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 (Tables 5, 6). 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 (Figs. 3, 4, 7, 8). In a case of HPDL laser welding study the titanium alloy Ti6Al4V sheets 1.5 mm thick were used and the laser beam was focused on the topsurface of sheets to be welded. Additionally the rectangular laser beam spot of HPDL laser 1.8x6.8 mm was set along the welding direction (Fig. 1). In a case of Disk laser welding study the 2.0 mm thick sheets were used and the circular laser beam was focused on the top surface of the joints (200 μm spot diameter) (Fig. 2).

Results of metallurgical and mechanical examinations of the bead-one-plate and test joints are given on the (Figs. 3 to 17).



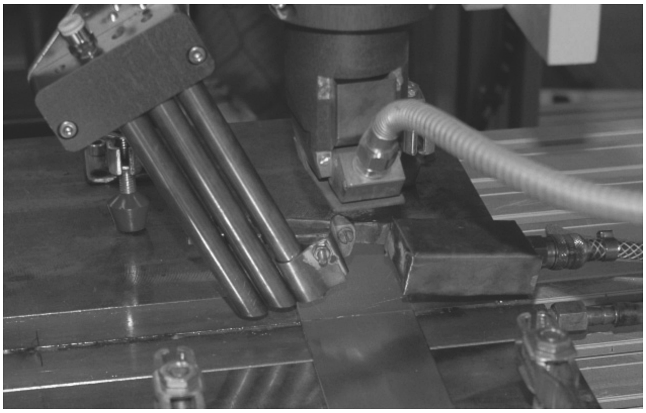


Fig. 2. A view of the experimental setup with the TRUMPF TruDISK 3302 laser, welding head and shielding gas system with multi nozzle protection, including trailing nozzle and grove protective nozzles (Table 4).

Table 1.
Chemical composition of titanium alloy Ti6Al4V (Table 2)

Alloying element	Al	V	Fe	C	Si	Mn	Mo	Cu	B	Zr	Sn	O	H
Content, %	6.29	4.12	0.18	0.14	0.1	0.01	0.1	0.02	0.01	0.1	0.01	0.19	0.0032

Table 2.
Physical properties of titanium alloy Ti6Al4V (Table 1)

Property	Density g/cm^3	Melting point °C	Specific heat J/kg·K	Thermal expansion coefficient	Electrical resistance Ω·cm	Thermal conductivity W/m·K
Value	4.42	1649	560	$8.6 \cdot 10^{-6}$	170	7.2

Table 3.
Technical data of high power diode laser HPDL ROFIN SINAR DL 020 (Fig. 1)

Parameter	Value
Wavelength of the laser radiation - nm	808
Maximum output power of the laser beam (cw) - W	2200
Range of laser power - kW	0.1-2.2
Focal length - mm	82/32
Laser beam spot size - mm	1.8×6.8/1.8×3.8
Maximum power intensity - W/cm^2	$3.2 \cdot 10^4$

Table 4.
The technical data of the TRUMPF TruDISK 3302 and the laser optics (Fig. 2)

Parameter	Value
Wave length, nm	1030
Output power, W	3300
Laser beam Divergence, mm·mrad	8.0
Fibre core diameter, µm	200.0
Collimator focal length, mm	200.0
Focusing lens focal length, mm	200.0
Bem spot diameter, µm	200.0
Fibre length, m	20.0

Table 5.
Parameters of bead-on-plate and butt joint laser welding of the titanium alloy Ti6Al4V (Grade 5) sheet 1.5 mm thick with the HPDL ROFIN SINAR DL 020 (Table 3, Fig. 1)

Weld no.	Welding speed mm/min	Output laser power W	Heat input J/mm	Remarks
P1	**400**	**1500**	**225**	**NC, SF, NH, LR, PW**
P2	**400**	**1800**	**270**	**NC, SF, NH, LR, PW**
P3	400	2000	300	NC, SF, WH
P3	400	2200	330	NC, SF, WH

Remarks: laser beam spot size 1.8x6.8 [mm], focal length 82 [mm], argon flow rate via the cylindrical nozzle 12.0 [l/min], argon flow rate from the root side 4.0 l/min
NC - no crack, US - uneven surface, HR - high roughness of the weld face, LR - low roughness of the weld face, UW - uneven width of the weld, SF - smooth surface of the weld, WH - wide heat affected zone, NH - narrow heat affected zone, PW - parameters set for butt joint welding

Table 6.
Parameters of bead-on-plate and butt joint laser welding of the titanium alloy Ti6Al4V (Grade 5) sheet 2.0 mm thick with the TRUMPF TruDISK 3302 (Table 4, Fig. 2)

Weld no.	Welding speed, mm/min	Laser beam power W	Heat input, J/mm	Remarks
W1	**500**	**500**	**60**	**NC, US, HR, UW, NH, PW**
W2	500	600	72	NC, UW
W3	**500**	**800**	**96**	**NC, NH, PW**
W4	500	400	48	NC, UW
W5	1000	1000	60	NC, UW
W6	**800**	**1000**	**75**	**NC, NH, PW**
W7	900	1000	66	NC, UW
W8	1200	1000	50	NC, HR
W9	1500	1000	40	NC, NP

Remarks: laser spot diameter 200 µm, argon flow rate via cylindrical nozzles 15 l/min, argon flow rate via trailing shield 40.0 mm wide and 90.0 mm long 25 l/min, argon flow rate from the root side 4.0 l/min
NC - no crack, US - uneven surface, HR - high roughness of the weld face, LR - low roughness of the weld face, UW - uneven width of the weld, SF - smooth surface of the weld, WH - wide heat affected zone, NH - narrow heat affected zone, NP - no penetration, PW - parameters set for butt joint welding

a) b)

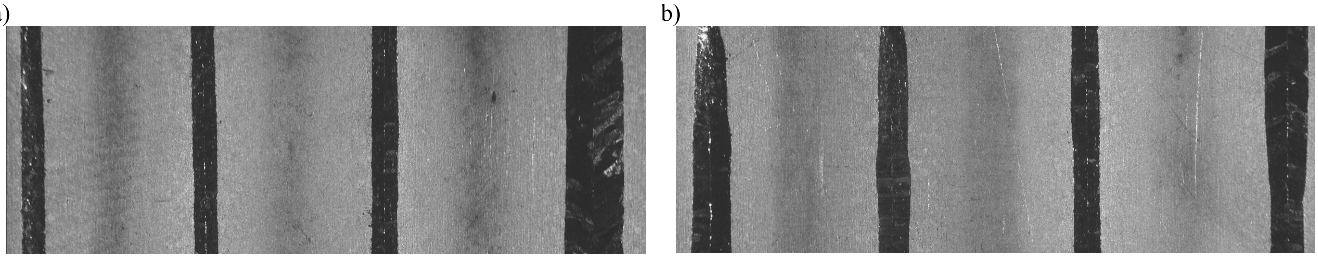
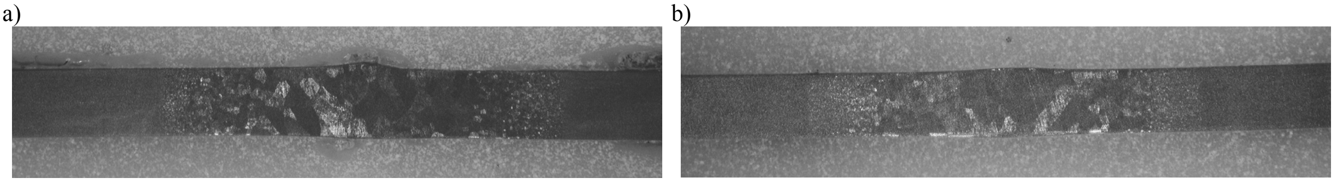


Fig. 3. A view of bead-on-plate welds on titanium alloy Ti6Al4V sheet 1.5 mm thick laser welded with the HPDL ROFIN SINAR DL 020 (Table 5); a) face of the welds (P1 from left), b) root of welds (P1 from left)

a) b)



c) d)

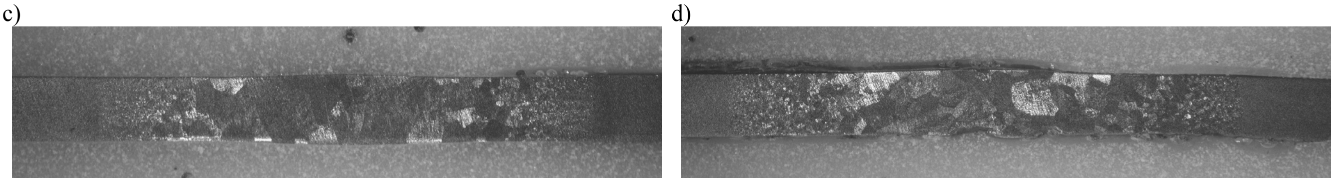


Fig. 4. Macrograph of the cross section of bead-on-plate welds of titanium alloy Ti6Al4V sheets 1.5 mm thick laser welded with the HPDL (Table 5); a) weld no. 1, b) weld no. 2, c) weld no. 3, d) weld no. 4

a) b)

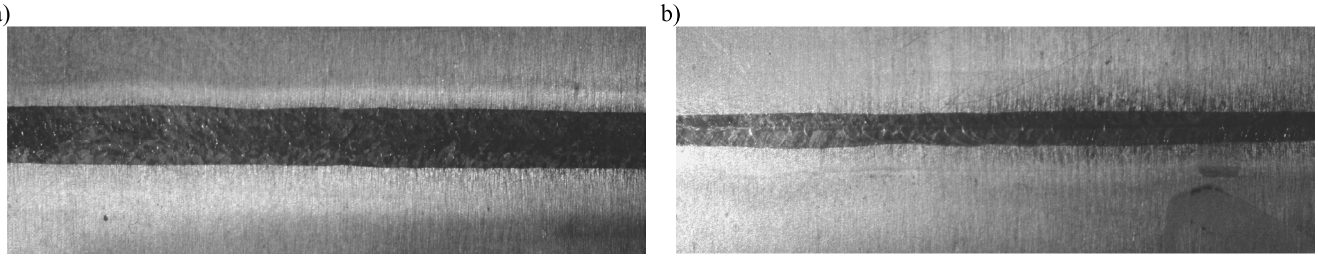


Fig. 5. A view of butt joints of titanium alloy Ti6Al4V sheets 1.5 mm thick laser welded with the HPDL laser, weld no. 1 (P1) (Table 5); a) weld face, b) weld root

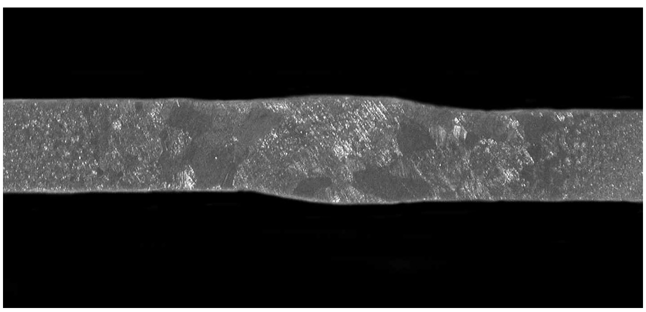


Fig. 6. Macrograph of the cross section of butt joint of titanium alloy Ti6Al4V sheets 1.5 mm thick laser welded with the HPDL laser, joint no. 1 (P1) (Table 5)

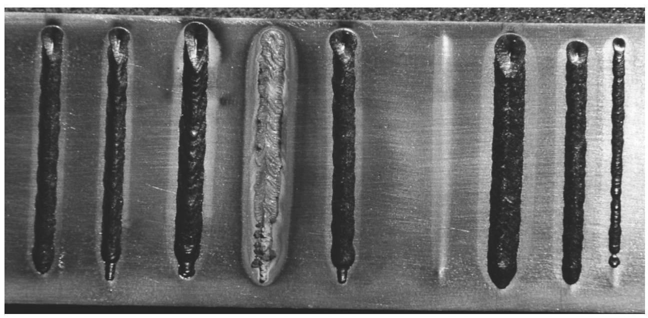


Fig. 7. A view of bead-on-plate welds on titanium alloy Ti6Al4V sheet 2.0 mm thick laser welded with the TRUMPF TruDISK 3302 (Table 6)

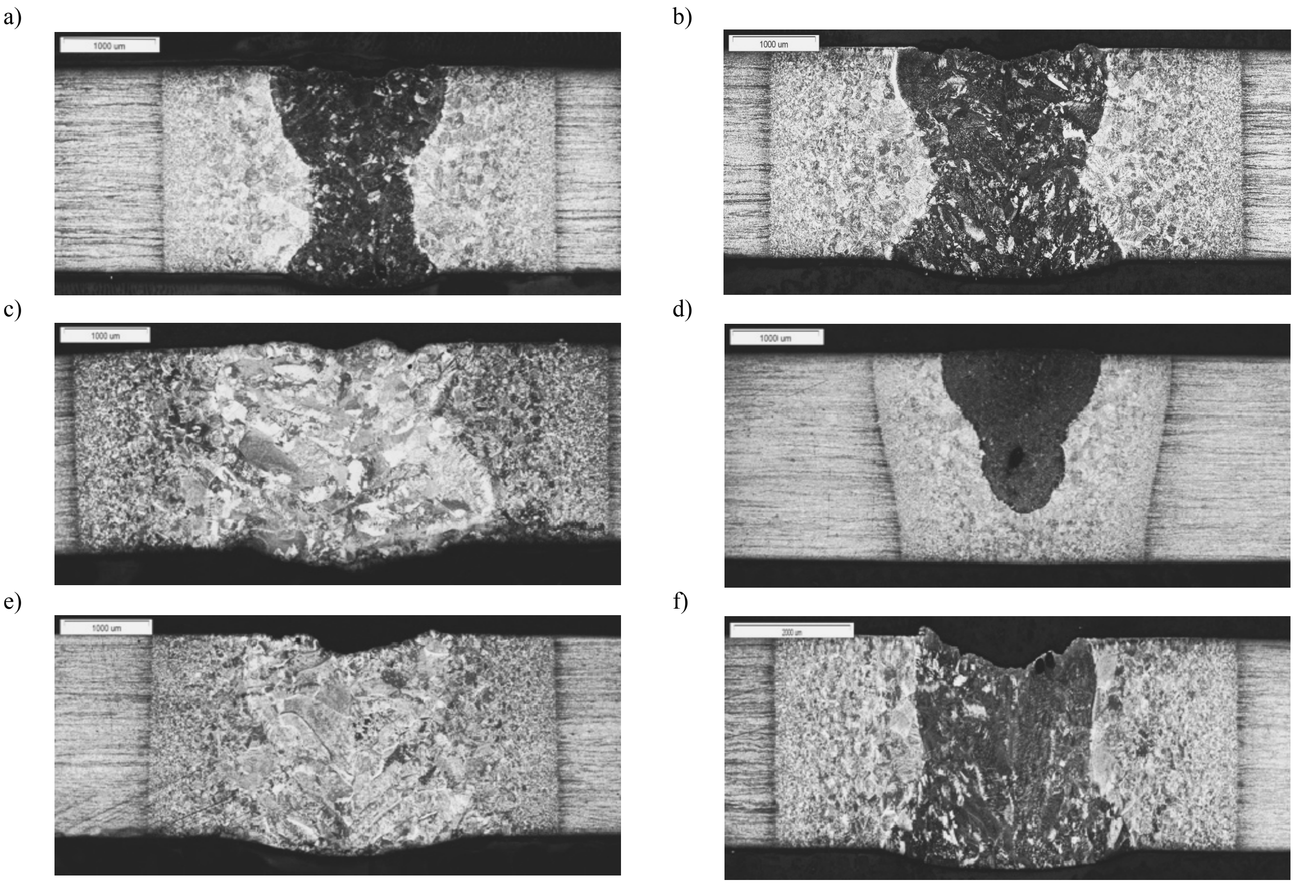


Fig. 8. Macrograph of the cross section of bead-on-plate welds of titanium alloy Ti6Al4V sheets 2.0 mm thick laser welded with the TRUMPF TruDISK 3302, Table 6; a) weld no. 1, b) weld no. 2, c) weld no. 3, d) weld no. 4, e) weld no. 6, f) weld no. 7

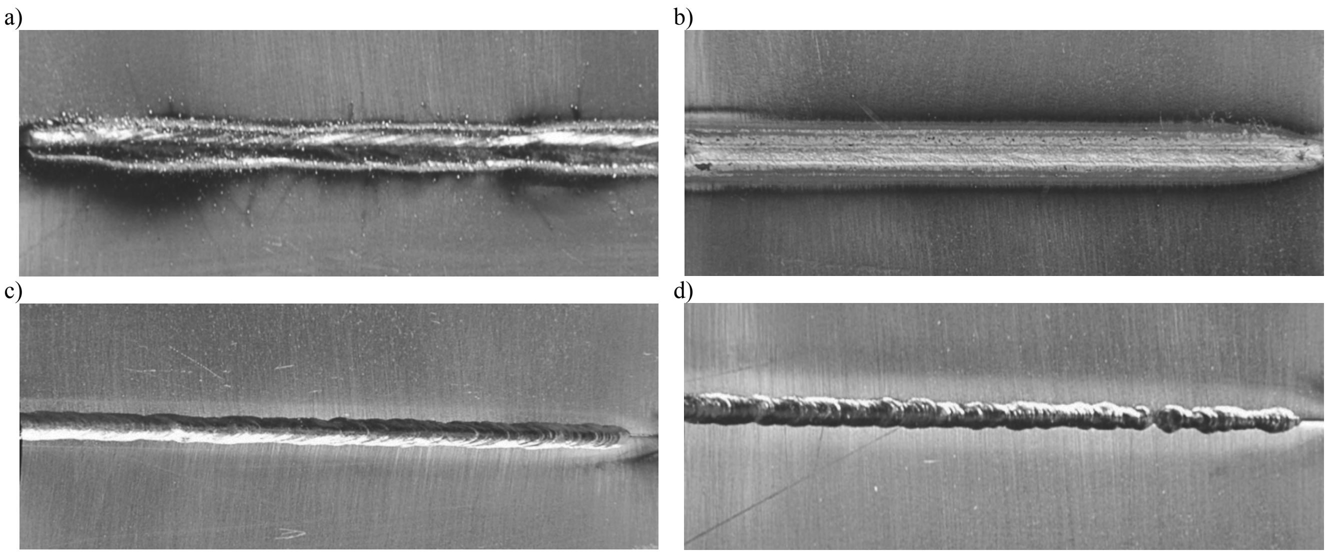


Fig. 9. A view of butt joints of titanium alloy Ti6Al4V sheets 2.0 mm thick laser welded with the TRUMPF TruDISK 3302 (Table 6); a), b) weld face and grove of the W3 joint, c),d) weld face and grove of the W6 joint

a) b)

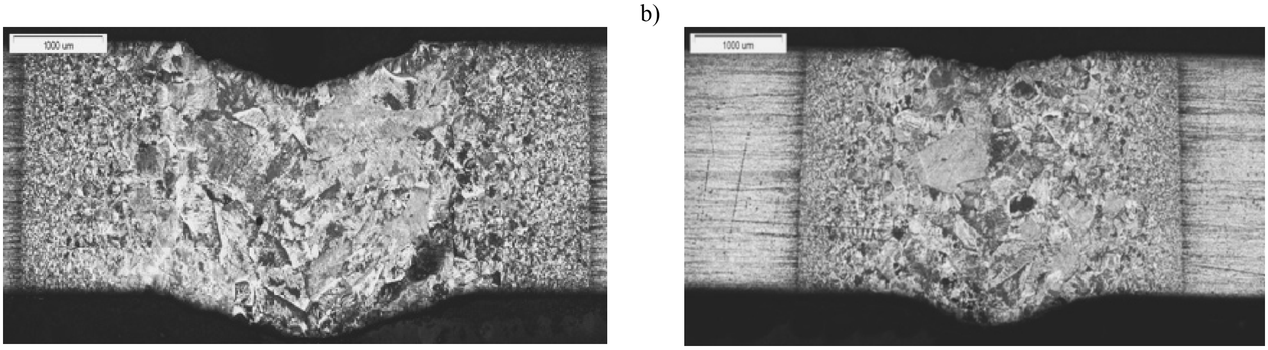


Fig. 10. Macrograph of the cross section of butt joint of titanium alloy Ti6Al4V sheets 2.0 mm thick laser welded with the TRUMPF TruDISK 3302, (Table 6); a) W3 joint, b) W6 joint

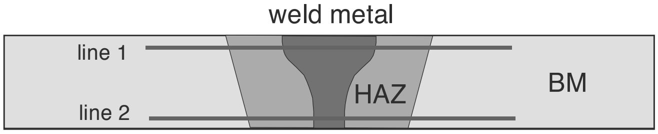


Fig. 11. Scheme of the hardness and micro hardness measurement procedure

a) b)

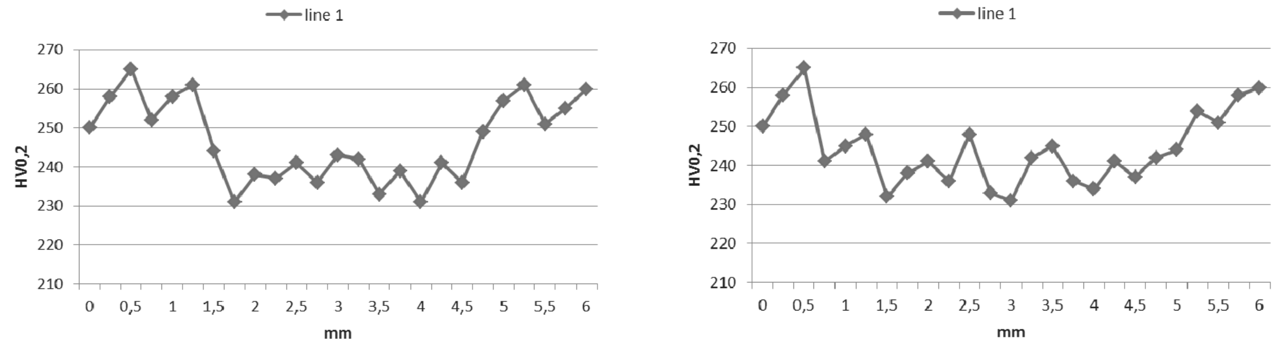


Fig. 12. Micro hardness HV0,2 distribution on the cross section of titanium alloy Ti6Al4V butt joint 1.5 mm thick laser welded with the HPDL laser (Table 5); a) joint no. 1 (P1), b) joint no. 2 (P2)

a) b)

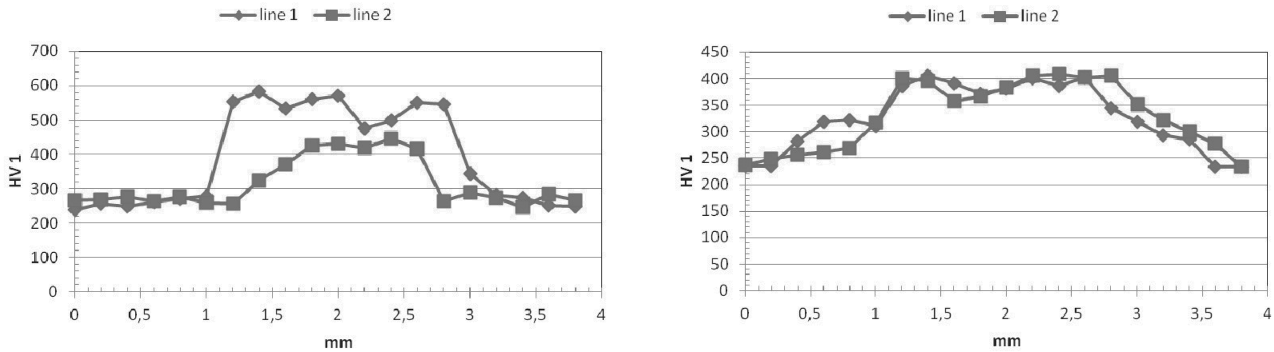


Fig. 13. Hardness HV 1 distribution on the cross section of titanium alloy Ti6Al4V butt joint 2.0 mm thick laser welded with the Disk laser (Table 6); a) W3 joint, b) W6 joint

a) b)

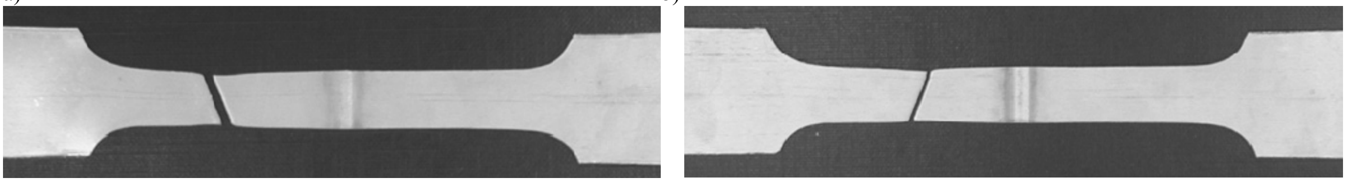


Fig. 14. A view of samples after tensile test of the titanium alloy Ti6Al4V butt joints 1.5 mm thick laser welded with HPDL laser, tensile strength of the welded joints 961-994 MPa (Table 5); a) joint no. 1 (P1), b) joint no. 2 (P2)

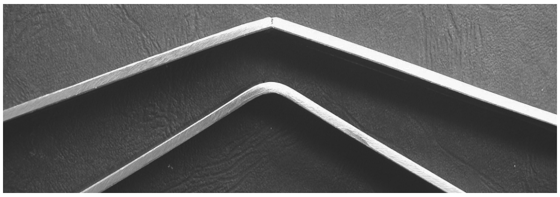


Fig. 15. A view of the samples after bend test of the titanium alloy Ti6Al4V butt joints 1.5 mm thick laser welded with the HPDL laser, bending angle 37°-56° (Table 5); a) joint no. 1 (P1), b) joint no. 2 (P2)

a)

b)

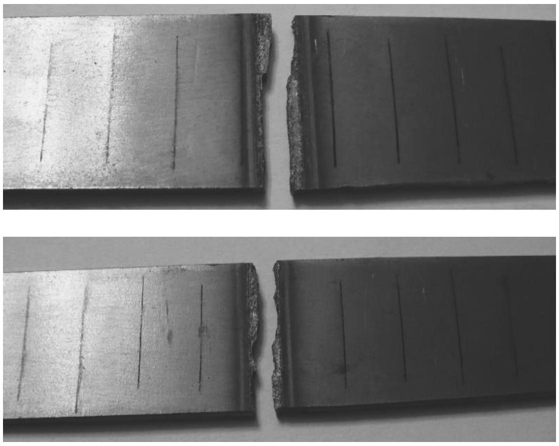


Fig. 16. A view of the samples after tensile test of the titanium alloy Ti6Al4V butt joints 2.0 mm thick laser welded with the Disk laser, Table 6; a) joint no. W3, b) joint no. W6

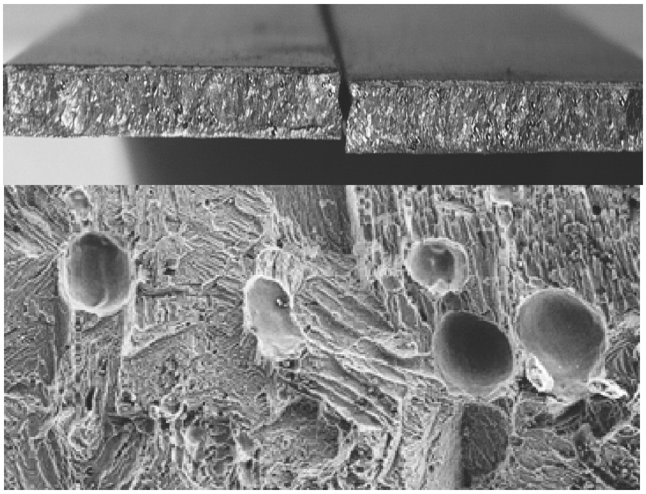


Fig. 17. Fracture surface (brittle fracture, porosity) of the titanium alloy Ti6Al4V butt joint no. W3 after bend test (Table 6)

3. Results and discussion

In the first stage of investigations, bead-on-plate welds were produced on the titanium alloy Ti6Al4V (Grade 5 according to ASTM B265) sheets 1.5 mm thick by the High Power Diode Laser and on the 2.0 mm thick sheets by the Disk laser (Figs. 1, 2). Bead-on-plate welds were produced at different laser power and welding speed to simulate the butt joint welding without an additional material (filler material) to analyze the phenomena of laser heating, melting and solidification, and also to determine the range of laser welding parameters for high quality and fully penetrated joints (Tables 5, 6).

The results of investigations have proved that the mechanism of HPDL welding of titanium alloy Ti6Al4V butt joints with a rectangular laser beam spot at wave length 808 nm differs distinctly from very well known and described mechanisms of conventional CO_2 and Nd:YAG lasers welding, especially key-hole laser welding technique. Shape of the analyzed bead-on-plate welds, as well as the width/depth ratio of fusion zone (FZ) in a range from 3 to over 4 clearly show that the welds were produced at conduction mode welding (Figs. 4, 6).

In whole range of the investigated parameters of HPDL bead-on-plate and also butt joints welding the energy of diode laser radiation at 808 nm is absorbed on the top surface of the titanium alloy sheet in a region of the laser beam spot effect (Figs. 3-6). The surrounding regions, as well as the metal under the top surface, are heated and next melted during the conduction mode (conduction of heat) welding. The investigated bead-on-plate welds are characterized by an elliptical fusion line, and relatively low penetration depth (Figs. 4, 6). Moreover the cross sections of the investigated bead-on-plate welds, as well as butt joints showed that the width of the welds is higher than the penetration depth, in every case and whole range of investigated parameters of HPDL welding of the 1.5 mm thick titanium alloy Ti6Al4V sheets (Figs. 4, 6). The depth/width ratio of the investigated welds is typical for conduction welding mode (Figs. 4, 6). The reason of this phenomenon is a uniform energy distribution and multimode of the laser beam TEM, and simultaneously low power density of the diode laser beam, which doesn't exceed $3.2 \cdot 10^4$ W/cm^2, not enough to produce a key-hole, (Table 3, Figs. 3, 6). On the other hand the heating and melting of the joint surface by HPDL laser beam is very stable and easy to protect by argon flow via a single cylindrical nozzle, Fig. 1. The protection of argon flow at 12 l/min was very effective and sufficient for full protection of the weld area (Fig. 3). Welds are high quality, with flat and smooth faces, as well as roots, and meet all requirements of PN-EN 970 standard for visual inspection (Figs. 3-6). There is no evidence of defects such as porosity, undercut, burn through and humping (Figs. 3-6).

Metallographic examinations of the test butt joints of titanium alloy Ti6Al4V 1.5 thick sheets welded by HPDL laser showed that the fusion zone is characterized by coarse structure (Figs. 4, 6). Additionally significant grain growth was observed in the heat affected zones HAZ of the test welds (Figs. 4, 6). On the other hand no internal imperfections were found (Figs. 4, 6). It was found that the lower heat input of the HPDL laser welding the lower grain growth occurs in the HAZ, and also in the FZ (Fig. 4).

Measurement of micro hardness conducted across the welded butt joints revealed that the fusion zones as well as the HAZ are softened compared to the base material BM of the titanium alloy Ti6Al4V (Figs. 11, 12). Micro hardness measured in the fusion zone of the test welds is in a range 230-250 HV0.2 and the micro hardness of HAZ is about 240-255 HV0,2 (Fig. 12). High quality of the test joints welded by HPDL laser and excellent plasticity were proved by mechanical testing (Figs. 14, 15).

The tensile strength of the test joints is not lower than the tensile strength of the base material titanium alloy Ti6Al4V sheet 1.5 mm thick about 961-994 MPa, because every test sample were broken in the base material (Fig. 14).

The technological bending test of the butt joints welded by the HPDL laser confirmed high plasticity of the test joints because the average bend angle was over 45° (Fig. 15), but it was found that the heat input have a strong influence on the mechanical performance of the investigated joints (Fig. 15).

The studies showed that the grain coarsening in heat affected zone (HAZ), and also the grain size of FZ, leads to reduction of the mechanical performance of weld joint dramatically, in particular significant drop of plasticity was observed during the bend tests (Fig. 15).

In turn 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. 2).

Shape of the analyzed bead-on-plate welds in “V” or “X” (hour-glass shape) configuration, as well as the width/depth ratio of FZ about 1/2 clearly indicate that the welds were produced at key-hole mode welding (Figs. 8, 10). Faces of the bead on-on-plate welds are even and sooth without any external defects, however in the case of welded joints humping and slight undercuts were observed (Figs. 7-10).

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. It was found that the plasma plum over the key-hole disrupt the shielding gas (high purity argon) flow and significantly decreases the effectiveness of shielding (Fig. 7).

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, the heat input of 50 J/mm is required at least, at laser beam power 400 W and welding speed 500 mm/min (Fig. 8, Table 6).

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 (Figs. 8, 10).

Weld bead faces and grooves produced in the range of investigated parameters are smooth and flat, Figs. 7, 9. 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) (Figs. 8, 10).

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. 8). 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. 8). Additionally in a case of the weld produced at too high heat input cracks and porosity occur (Fig. 8).

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) (Figs. 11, 13). 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. W3 (Fig. 13).

The tensile strength of the base material of titanium alloy Ti6Al4V sheet 2.0 mm thick, determined experimentally, is about 820 MPa (Table 2). The tensile tests of the laser welded joints showed that the tensile strength of the joints welded is mainly in a range 630 to 710 MPa, that is about 25% lower than the tensile strength of BM (Fig. 16). These joints were broken in the weld metal (Fig. 16).

The technological bending test of the butt joints laser welded at heat input over 70 J/mm reveled high brittleness of the joint, because the joint were suddenly broken during bending test at the bend angle 20-25° (Fig. 17). 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 plum formed over the key-hole.

4. Conclusions

In whole range of HPDL welding parameters, conduction mode melting of titanium alloy Ti6Al4V sheets was observed. The laser beam energy is absorbed on the top surface of the titanium alloy sheet (joint) and conducted into the surrounding regions of the base metal. The depth/width ratio of the investigated welds (3 to 4) is typical for conduction welding mode with elliptical shape of fusion zone and width of the welds significantly higher than the penetration depth (joint thickness) (Figs. 4, 6). The conduction mode of HPDL welding of the titanium alloy sheets resulted in very stable heating, melting and weld pool. Therefore a full and effective protection of the weld pool and surrounding regions may be achieved by simply argon flow via a single cylindrical nozzle (Fig. 1). The test welds produced by HPDL laser were high quality, excellent plasticity and with no internal imperfections, but heat input of the laser welding have a strong influence on the mechanical performance of the joints (Figs. 4, 6). In a case of the titanium alloy Ti6Al4V welding by the Disk laser a different mode of welding was observed. The small area of the laser beam spot of Disk laser and significantly higher power density, compared to HPDL laser, resulted in very intensive heating of the metal, partially evaporating of the metal and formation of a key hole. Welds produced by the Disk laser are characterized by a columnar shape of fusion zones ("X" or "V" configurations), are very narrow with narrow and fine structure heat affected zones (Figs. 8, 10). However, the key-hole welding resulted in plasma plume formation over the weld pool, which disrupt the shielding gas (high purity argon) flow, and significantly decreases the effectiveness of shielding. Although applying a special multi nozzle system for protection of the weld pool and weld metal during Disk laser welding of the titanium alloy, the test joints show high brittleness, as a result absorption of harmful gases from the atmosphere (air) (Figs. 16, 17).

References

[1] A. Lisiecki, Laser welding of titanium alloy Ti6Al4V using a disk laser, International Virtual Journal Machines, Technologies, Materials 7 (2012) 53-56.

[2] A. Klimpel, D. Janicki, A. Lisiecki, Z. Wilk, Laser welding technologies: High power diode laser application examples, Welding International, Volume 24, Issue 9, September (2010) 689-698.

[3] A. Lisiecki, A. Klimpel, Diode laser surface modification of Ti6Al4V alloy to improve erosion wear resistance. Archives of Materials Science and Engineering, Vol. 32, (2008) 5-12.

[4] A Klimpel, LA Dobrzański, D Janicki, A Lisiecki, Abrasion resistance of GMA metal cored wires surfaced deposits, Journal of materials processing technology, 164 (2005) 1056-1061.

[5] LA Dobrzański, K Labisz, M Piec, A Klimpel, A Lisiecki, Influence of vanadium carbide ceramic powder on structure and properties of hot work tool steel alloyed with HPDL laser, Proceedings of the 2nd International Conference "Manufacturing Engineering" ICMEN, (2005) 185-191.

[6] A Klimpel, A Lisiecki, et al., Robotized GMA surfacing of cermetal deposits, Journal of Achievements in Materials and Manufacturing Engineering, 18 (1-2) (2006) 395-398.

[7] A. Grabowski, et al., Optical and conductive properties of AlSi-alloy/SiCp composites, application in modeling CO_2 laser processing of composites, Optics and Lasers in Engineering 43 (2005) 233-246.

[8] M. Adamiak, J. Górka, T. Kik, Comparison of abrasion resistance of selected constructional materials, Journal of Achievements in Materials and Manufacturing Engineering, 37/2 (2009) 375-380.

[9] M. Adamiak, J. Górka, T. Kik, Structure analysis of welded joints of wear resistant plate and constructional steel, Archives of Materials Science and Engineering 56/2 (2010) 108-114.

[10] A. Kurc, E. Kalinowska-Ozgowicz, The influence of the martensite α' phase occurring in the structure of cold rolled austenitic Cr-Ni steel on its mechanical properties, Archives of Materials Science and Engineering 37/1 (2009) 21-28.

[11] M. Kciuk, A. Kurc, J. Szewczenko, Structure and corrosion resistance of aluminium AlMg2.5, AlMg5Mn and AlZn5Mg1 alloys, Journal of Achievements in Materials and Manufacturing Engineering 41/1-2 (2010) 74-81.

[12] W. Kwaśny, Predicting properties of PVD and CVD coatings based on fractal quantities describing their surface, Journal of Achievements in Materials and Manufacturing Engineering 37/2 (2009) 125-192.

[13] K. Labisz, T. Tański, L.A. Dobrzański, HPDL laser alloying of heat treated Al-Si-Cu alloy, Archives of Materials Science and Engineering 54/1 (2012) 13-21.

[14] K. Janerka, J. Jezierski, J. Szajnar, Quality and properties of the cast iron produced on the steel scrap base, Archives of Materials Science and Engineering 53/2 (2012) 92-101.

[15] L.A. Dobrzański, E. Jonda, K. Labisz, M. Bonek, et al., The comparision of tribological properties of the surface layer of the surface layer of the hot work tool steels obtained by laser alloying, Journal of Achievements in Materials and Manufacturing Engineering 42 (2010) 142-147.

[16] D. Pakuła, L.A. Dobrzański, A. Križ, M. Staszuk, Investigation of PVD coatings deposited on the Si_3N_4 and sialon tool ceramics, Archives of Materials Science and Engineering 46/1 (2010) 53-60.

[17] G. Matula, Carbon effect in the sintered high-speed steels matrix composites - HSSMC, Journal of Achievements in Materials and Manufacturing Engineering 55/1 (2012) 90-107.

[18] E. Akman, A. Demir, et al., Laser welding of Ti6Al4V titanium alloys, Journal of Materials Processing Technology 209 (2009) 3705-3713.

[19] X. Cao, M.Jahazi, Effect of welding speed on butt joint quality of Ti–6Al–4V alloy welded using a high-power Nd:YAG laser, Optics and Lasers in Engineering 47 (2009) 1231–124.

[20] Cui Li, Kutusna Muneharua, et al., Fiber laser-GMA hybrid welding of commercially pure titanium, Materials and Design 30 (2009) 109–114.

[21] I. Szczygieł, A. Fic, T. Kruczek, A. Sachajdak, Verification of temperature distribution in the system for pad welding by means of infrared thermography, Proceeding of the 9^{th} International Conference "Quantitative InfraRed Thermography", Cracow, 2008.

[22] A. Klimpel, A. Lisiecki, Laser welding of butt joints of austenitic stainless steel AISI 321, Journal of Achievements in Materials and Manufacturing Engineering 25 (2007) 63.

[23] J. Bodzenta, A. Kazmierczak-Balata, et al., Analysis of influence of Yb concentration on thermal, elastic, optical and lattice parameters in YAG single crystal, Journal of Alloys and Compounds 473/1-2 (2009) 245-249.

[24] Cheolhee Kim, Junghak Kim, et al., Investigation of laser remote welding using disc laser, Journal of materials processing technology, 201 (2008) 521–525.

[25] L. Quintino, A. Costa, et al., Welding with high power fiber lasers - A preliminary study, Materials and Design 28 (2007) 1231–1237.