Journal of Chemical Technology and Metallurgy, 56, 5, 2021, 1074-1081

IMPACT OF PROCESS PARAMETERS OF LASER WELDING ON THE MECHANICAL PROPERTIES OF Ti6Al4V

A REVIEW

Peter O. Omoniyi[1,2], Rasheedat M. Mahamood[1,3], Esther T. Akinlabi[4]

[1] *Department of Mechanical Engineering Science, University of Johannesburg*
Johannesburg, South Africa, P. O. Box 524
E-mail: omoniyi.po@unilorin.edu.ng
[2] *Department of Mechanical Engineering, University of Ilorin, Ilorin, Nigeria, P. M. B. 1515*
[3] *Department of Materials and Metallurgical Engineering, University of Ilorin*
Ilorin. Nigeria, P. M. B. 1515
[4] *Pan African University for Life and Earth Sciences Institute (PAULESI), Ibadan, Nigeria*

Received 05 May 2020
Accepted 31 July 2020

ABSTRACT

The advantage of the usage of titanium alloys in numerous engineering applications have prompted several researchers to explore alternatives to the earlier used traditional joining methods such as resistance welding, electric arc welding, etc. In order to obtain quality and faster means of welding machine components, laser welding has been largely adopted in different manufacturing industries such as aerospace, automotive and chemical industries, due to its numerous advantages such as low heat input, low distortion rate, fast welding speed, and small heat-affected zone (HAZ). Quality laser welding requires optimization of several processing parameters among which are: laser power, welding speed and defocusing distance. This article reviews the impact of these processing parameters on some mechanical properties, such as tensile strength, microstructure and hardness of the welded Ti6Al4V plate as presented in the literature and the future research direction is also presented.

Keywords: titanium, laser welding, microstructure, hardness, tensile strength, energy.

INTRODUCTION

Titanium as a rare earth metal, is highly advantageous, due to its lightweight to strength ratio, good corrosion resistance, adequate thermal properties, resulting in its use in numerous engineering fields such as biomedical, chemical, aerospace, nuclear etc. [1 - 14]. Due to the difficulty of the use of traditional machining methods and the limitations of arc and resistance welding, (which cannot be used in vacuum environment) on the material, coupled with the effect of oxidation on melted titanium alloys around 400°C [8], the use of laser welding is getting greater acceptability in industries due to its ability to penetrate thicker plates with minimum pass, its low production cost compared to other types of welding and its precision makes it the choicest welding technique in industries [15 - 16]. The weldability of titanium in annealed condition, solution heat treatment and aged conditions is also an advantage [6]. The laser beam has also been adopted for use in the area of surface processing of metals, such as surface hardening, vapour deposition and alloying.

This article aims at reviewing the impact of process parameters of laser welding on the mechanical properties of Ti6Al4V plates and objectively accessing the parameters that alter the microstructure, tensile strength and hardness of the material. It further investigates the parameters responsible for some defects in the welded portion of the material.

Laser Welding of Ti6Al4V

Joining of metals using laser welding makes use of solid-state welder for welding [17]. According to Akbari et al. [4] and Sandeep et al. [18], laser welding is categorized into two, which are continuous wave (CW) and pulsed wave (PW).

Laser power, welding speed and beam diameter are the major parameters associated with CW and are majorly used for welding of thick beams, while that of PW includes the pulse duration, pulse energy, beam diameter and are used for thin plates, the ratio of pulse energy and pulse duration determines the depth of penetration of the weld, other parameters include spot diameter, gas flow rate, and pulse frequency [19 - 20].

Joining of titanium alloy using laser welding can be autogenously or with the use of filler wire or powder [21]. Laser welding can also be of two forms based on power density, which are conduction limited welding (power density < 10^5 W cm^{-2}) and keyhole welding (power density > 10^6 - 10^7 W cm^{-2}), the advantage of keyhole production, allow for concentration of power at a small spot, thereby allowing a restricted microstructure change, as the HAZ is small [22 - 24].

The use of gas shield which is mostly the inert gases such as helium and argon has helped to reduce oxidation of melt pool during welding, thereby enhancing the mechanical properties of the material and giving quality welding [3, 10]. In order to efficiently deliver this gas to a targeted area, nozzles of different shapes have been developed, the conical-shaped nozzle is advantageous when there is need for stabilization of plasma plume, ring nozzle is mainly used to avoid ambient air contamination [9]. According to Akshay et al., [9] the height of nozzle and gas flow rate affects the seams of the weld, in which the biggest weld beads can be achieved when the angle between the side gas flow and coaxial gas flow is 40°. The use of helium and argon have also been beneficial in achieving great weld penetration, but helium has proved better at every welding speed and constant power, due to its low ionization energy.

CO_2 laser is still one of the most used in manufacturing industries, its welding principle is basically based on the use of mirrors, these mirrors focus the energy on the workpiece [25]. In solid-state lasers, neodymium-doped yttrium aluminium garnet (Nd:YAG) lasers are capable of producing more powerful laser beams at low wavelength, through the use of optic fibre, which enables its use with robots [7, 24, 26].

The use of filler wire which is of the same composition with the base metal to bridge the gap between materials to be joined has also shown improvements in the overall mechanical properties of joined metals and it compensates for vaporized metals during welding. The use of unalloyed filler metal has been approved advantageous to improve joint ductility, by reducing the level of martensitic transformation that occurs due to rapid solidification after laser welding [15]. In the use of wire filler, contaminants can be avoided through the use of continuous wire feeding, also there is a need for higher power input or reduced welding speed compared to the autogenous welding. Welding configurations can be in the form of butt weld, overlap weld, fillet lap weld and edge flange weld [8].

Numerical Evaluation of Process Parameters

Different ranges of values of process parameters for laser welding have been used by authors in order to achieve an optimum set of the parameter for quality laser welding. Fig. 1 shows the parameters required in order to achieve quality weld. Furthermore, Table 1 shows authors who have used different parameters, their optimum parameter for good quality weld, and the type of laser welding used on titanium alloys. Other contributing factors which affects the laser process are cooling rate and temperature gradient.

Effect of Processing Parameters

Effect of Peak Power

The depth of penetration is a factor of peak power and pulse duration, if peak power is small, there could be little melt pool. Akman et al. [1] observed that the higher the peak power the higher is the depth of penetration at constant pulse duration and spot diameter. This phenomenon was attributed to the increased temperature inside keyhole at higher peak power. But with higher peak power, there occur crater formation and more material loss, this could be reduced by increasing the pulse duration with constant peak power [9]. The deepest penetration observed by Akman et al. [1] was at a peak power of 3 kW and a pulse duration of 10 ms. Xinjin et al. [8] also discovered that with increasing laser power, higher welding speed is necessary. Laser power between 2 - 4 kW gave a full penetration of 3.2 mm titanium alloy plate at a welding speed of 12.5 - 125 mm s^{-1}. Also, at high laser power, lower heat input is required. The optimum weld integrity and bead geometry were reported to be a power of 3 kW and speed pf 37.5 mm s^{-1}.

Increasing the heat input and lowering the welding speed, there is an increase in the fusion zone (FZ), HAZ and the grain size [9]. Bead geometry transformation

Table 1. Input Parameters for Laser Welding.

Author (s)	Type of Laser Welding	Weld Type	Shield Gas	Focal Length (mm)	Focal Plane (mm)	Welding Mode	Max. Penetration depth (mm)	Spot Size (mm)	Welding Speed (mms^{-1})	Pulse Duration (ms)	Beam Diameter (mm)	Laser Power (kW)	Pulse Frequency (Hz)	Pulse Energy (J)	Gas Flow Rate ($Lmin^{-1}$)
[4]	Pulsed Nd: YAG Laser	Bead on plate	Ar		6	keyhole	1.7	0.7	3-9	0.2-25	3	0.75	1-250	0-40	*15
[1]	Pulsed Nd: YAG Laser	Bead on plate	He		2	keyhole	2.8	0.4	5	5-10	3	1.12-3.06	43	5.6-13.4	
[15]	4 kW Pulsed Nd: YAG Laser	Bead on plate	Ar/He		-1			0.45	28.17-50		3.2, 5.1	3, 4			**23.6/66.1
[5]	400 W Nd: YAG Laser	Bead on plate	Ar	190	0.3-2.2			0.3	35	0.5-20	1	1	20	20	*8
[6]	2 kW Nd: YAG Laser	Bead on plate	Ar						15			2			*20
[8]	4 kW Nd: YAG Laser	Butt joint	Ar/He		-1	continuous wave		0.45	12.5-125		3.2	2-4			**23.6/66.1
[11]	750 W Nd: YAG Laser	Bead on plate	Ar	2-4	-1.1	keyhole			2-4.3	6-8	3	0.15-0.24	15-20	0-40	*15

**Gas applied coaxially*

***Gas flow rate at the top/Gas flow rate at the bottom*

Ar- Argon gas   He- Helium gas

BoP-bead on plate

from V shape to hourglass geometry and to a wide near rectangle shape can also be achieved as heat input increases [27].

Fabrizia and Alessandra [3] used Artificial Neural Network (ANN) and experimental values to obtain an optimum processing parameter for a sound joint in laser welding of Ti6Al4V alloy, and obtained 117.10 W for laser power, 1.77 mm s^{-1} as optimum welding speed and 0.16 mm for defocusing distance, using a 2 kW Nd:YAG laser and 3 mm thick plate.

Effect of the Welding Speed

The welding speed has a great effect on the fusion zone (FZ), irrespective of the laser power and the welding mode, an increase in the welding speed reduces the FZ. Hardness and grain size are increased with an increase in the welding speed in Gaussian mode of welding. In Donut mode, there is an increase in hardness but a decrease in grain size with an increase in welding speed, the decrease in grain size is due to the decrease in heat input duration at faster welding speed. In summary, the welding speed is inversely proportional to the heat input [9].

Microstructure

Phase transformation within HAZ is a common phenomenon in the laser welding operation, the alpha-beta transition is a common occurrence in solid-state welding [6]. The phase transformation within the FZ is said to be proportional to the cooling rate, in which the phase transformation within the FZ is an α to β phase and that which occur during the cooling is β to α [4, 28]. The microstructure is known to be affected by cooling rate, the higher cooling rate is said to form martensitic morphology within the FZ and Heat affected zone (HAZ), and is said to provide effective strengthening methods for titanium alloys.

At a temperature of approximately 995°C, there is a transition of titanium alloys from the alpha hcp (hexagonal closed packed) to beta bcc (body centred cubic), this transition in structure further allows more strengthening in titanium alloys than other non-ferrous alloys [1, 28]. Squillace et al. [13] also observed a diffusionless transformation of β to α' martensitic structure on cooling temperature reaching the tansus temperature.

According to Akman et al. [1], Kabir et al. [15], and Jing et al. [29] the microstructure of base metal (BM) (Ti6Al4V) is observed to have the intergranular beta phase in an equiaxed alpha phase, while in the transition from HAZ to BM, there is a martensitic α', acicular α and primary α observed in the HAZ [14, 28, 30]. Furthermore, the HAZ was grouped into HAZ close to the FZ, where acicular α' martensitic and blocky α phase were observed and the HAZ close to BM, having acicular α' blocky and α phase, also, is the initial α and β phase. This phenomenon within the HAZ was attributed to the different cooling

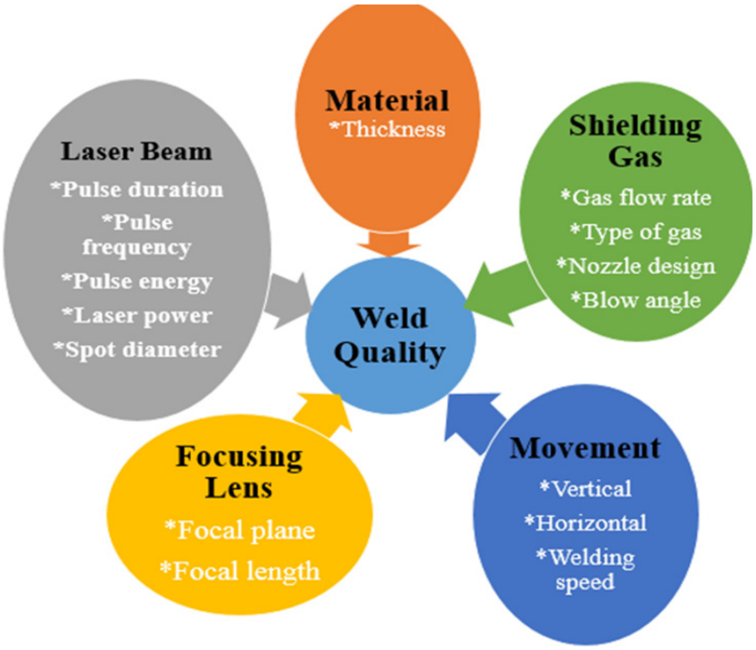

Fig. 1. Processing Parameters for Quality Weld.

rates within the Ti64 plate. In the FZ, the martensitic α transit from the β grains is observed [5, 29, 31]. There is a rise in grain size as power input increases within the HAZ and FZ, acicular martensites also form in columnar α and β grains within the weld pool [6, 8, 15]. Jing et al. [29] observed coarse grains within the FZ, which reduces towards the HAZ and BM. The average diameter of the α and interspersed β grain size within the BM range from 5 - 10 μm and 2 - 5 μm, respectively [32].

Welding speed is proportional to cooling rate and in turn proportional to phase transformation in laser-welded Ti6Al4V. In the report of Akbari et al. [4] on the effect of welding speed and cooling rate on the microstructure of 3 mm thick Ti6Al4V plate, they observed that at welding speed of 9 mm s^{-1}, the cooling rate is 100°C s^{-1} and is sufficient for martensitic formation, with critical cooling rate for α' martensitic formation defined at 410°C. For welded samples at 3 mm s^{-1}, the cooling rate was 50°C s^{-1} and was found sufficient for α martensitic formation [13, 27].

Annealed Ti6Al4V plates of 1 - 2 mm were laser welded by Cao et al. [33], the microstructure within the BM showed a β phase dominating the α phase, in which the FZ consist mainly of the α martensitic, and displays coarse columnar β grains in opposite direction of the heat flow as also observed by Squillace et al. [13], Balasubramanian et al. [14] and Casalino et al. [32]. A thin HAZ was observed, within 0.31- 0.38 mm for all thickness of the plates used.

Hardness

The FZ is observed to have higher hardness number than the HAZ than the BM, due to rapid cooling of the melt pool and martensitic microstructure formation around this region, as a result, the higher the peak power input, the longer it is for the melt pool to cool, resulting in a reduction of the hardness of material [15, 27]. As received hardness of titanium alloy was given by Kumar et al. [5] as 356 HV. Xinjin et al. [8] observed average hardness at the BM, when a laser power of 3 kW at a welding speed of 28.17 mm s^{-1} was used in welding as 312 ± 8 HV and 360 ± 4 HV at the FZ. The change in hardness between these zones was attributed towards the transformation of α and β phases of the microstructure. Jing et al. [29], also observed a hardness of 350 HV within the FZ, 320 HV within the BM, this increase in hardness within the FZ was attributed towards the formation of α' martensite, as observed also by Kumar et al. [30]. The HAZ was observed to have a lower hardness value than FZ and BM lower in hardness than HAZ, irrespective of the welding parameters [28]. Akbari et al. [4] observed a 330 ± 10 HV with the BM, which was the lowest and 385 HV with the FZ.

In relations of laser power and welding speed, there is an increase in hardness within the FZ as there is an increase in welding speed. There is also a reduction in hardness with an increase in laser power, this in turn, increases the heat input and thus affecting the microstructure within the FZ [9, 13].

Tensile Properties

Porosity is known to be one of the defects that affect the tensile strength of welded Ti6Al4V alloy, also the transition of microstructure after heat treatment from α to β causes a reduction in tensile strength [1]. Defocusing distance, which is the distance between the focal point and top surface of the workpiece, has an effect on the tensile properties of the welded plate. The change in focal point leads to a change in penetration depth and weld width. The defocusing distance can be positive or negative, negative defocusing distance has the advantage of reducing the grain growth rate, thereby increasing the tensile strength of the welded portion [3].

Xinjin et al. [8] observed a higher tensile strength within the FZ than the HAZ and BM. Kumar et al. [5] gave the tensile properties of as-received titanium alloy as 964 ± 42 MPa, yield strength of 891 ± 39 MPa and 14 % elongation. Pasang et al. [6] reported tensile strength of 1053 MPa, yield strength of 1028 MPa, percentage elongation of 12 % for laser-welded Ti6Al4V alloy.

The increase in welding speed on the tensile properties shows a reduction in tensile properties of annealed laser welded samples of 1 mm thickness, while, for the 2 mm thick plates, there was an increase in tensile properties as the welding speed increases, up to a speed of 6 m min^{-1} [33]. The tensile strength of as-received annealed sample was 950 MPa and an elongation of 14 %. Tensile strengths in the study were observed to range from 975 - 1043 MPa [33]. Martensite formation and grain size, are factors depending on cooling rate, which has an effect on tensile properties of Ti6Al4V alloy [34].

Porosity and Defects

Porosity has been attributed to gas entrapment, which is basically absorption of gases such as hydrogen, nitrogen and oxygen in the melt pools during laser welding of metals. The gas porosity can be attributed to contaminants from grease, moisture, inadequately dried electrode, dirt or oil existing within the machine, filler wire, and workpiece [8, 9, 15]. Gas entrapment of up to 1 % can cause distributed porosity, and up to 1.5 % can cause massive surface pores [35]. Porosity could also be due to the collapse of keyholes before proper solidification takes place, it exists majorly at the root of the weld [23, 25]. Welding speed also contributes to the existence of porosity in welded titanium alloy, higher welding speed reduces the level of porosity. The turbulence flow of the melted pool, due to high gas flow rate could also be attributed to porosity formation in welded joints [8, 22].

Baohua et al. [36] observed that the position of welding affects porosity, in the vertical up weld position, no porosity was observed as against numerous porosity observed in the vertical down weld at high input energy of 275 kJ m^{-1} (2200 W at 0.5 m min^{-1}). With lower heat input of about 125 kJ m^{-1} (2500 W at 1.2 m min^{-1}), there exist some pores in the vertical up weld, on the contrary, there exist lesser porosity in the vertical down weld as the energy input reduces.

Defects in welded titanium plates are caused by loss of materials from the surface of the welded joint due to evaporation. Spatter, expulsion, high energy input and fast welding speed have also been major reasons for defects or underfill [15, 23]. At high temperature, there is a reduction in surface tension of titanium alloy resulting in lack of adhesion of molten metal with the solid part, resulting in underfill, that later results in cracks from stress concentration. The maximum allowable underfill in a weld is 7 % of the sheet thickness in the aerospace industry [15].

CONCLUSIONS

The integrity of a quality joint formed by the use of laser welding depends mainly on the processing parameters irrespective of the form of welding used, so also, is the amount of porosity or defects in the form of underfill or cracks. Higher welding speed, energy input and welding power, are beneficial to the reduction of porosity, reduction of underfills, quality bead geometry and optimum hardness.

Hardness is said to be maximum within the FZ, then the HAZ and lastly the BZ due to the formation of martensite, increase in welding speed also contributed to the increase in hardness within the FZ.

The tensile properties within the FZ are also attributed to the martensite formation within the zone. Tensile strength also reduces as the grain growth increases due to an increase in heat input.

The application of shielding gas has also aided in improving the mechanical properties of laser-welded titanium alloys, with argon being predominately used by researchers, due to the fact that it enhances weld penetration.

The major microstructure of the FZ is martensitic, the microstructure of BM generally has the intergranular beta phase in an equiaxed alpha phase, while in the transition from HAZ to BM, there is a martensitic α', acicular α and primary α observed.

Peak power, laser power and welding speed have been found to be the most important parameters in obtaining a quality weld.

There are still great needs for better understanding of optimization of parameters for producing quality weld of titanium alloys. Also, further research is required in the proper mapping of the process parameters and optimum properties of the weld. This will help in establishing fact sheet for laser welding of titanium and its alloys.

REFERENCES

1. E. Akman, A. Demir, T. Canel, T. Sinmazcelik, Laser Welding of Ti6Al4V Titanium Alloys, J. Mater. Processing Technol., 209, 2009, 3705-2713.
2. A.A. Antonysamy, Microstructure, Texture and Mechanical Property Evolution during Additive Manufacturing of Ti6Al4V Alloy for Aerospace Application, University of Manchester, 2012.
3. C. Fabrizia, C. Alessandra, Investigation of Laser Welding of Ti Alloys for Cognitive Process Parameters Selection, Mater., 11, 632, 2018, 1-11.
4. M. Akbari, S. Saedodin, D. Toghraie, R. Shoja-Razavi, F. Kowsari, Experimental and Numerical Investigation of Temperature Distribution and Melt Pool Geometry During Pulsed Laser Welding of Ti6Al4V, Opt. Laser Technol., 59, 2013, 52-59.
5. U. Kumar, D. Patel, Z. Zaffar, D.K. Gope, S. Chattopadhyaya, A.K. Das, M.K. Biswal, Experimental and Numerical Investigation of Temperature Distribution and Analysis of Mechanical Properties During Pulsed Nd-YAGLaser Welding of

Thin Ti6Al4V Alloy, Proceedings of International Conference on Mechanical, Materials and Renewable Energy, Swakopmund, Namibia, 2018, 1-10.

6. T. Pasang, Y. Tao, O. Kamiya, Y. Miyano, G. Kudo, Research on Various Welding Methods on Aerospace Titanium Alloys: Collaboration between Akita University and AUT University, Int. J. Soc. Mater. Eng. Resources, 20, 1, 2014, 35-39.
7. C. Giuseppe, M. Michelangelo, P. Patrice, FEM analysis of fibre laser welding of Titanium and Aluminum, R. Teti (ed.), proceedings of the 48th CIRP Conference on Manufacturing Systems, Ischia, Italy, 41, 2016, 992-997.
8. C. Xinjin, H.K. Abu-Syed, W. Priti, G. Javad, B. Anand, C. Jonathan, M. Mamoun, Global and Local Mechanical Properties of Autogenously Laser Welded Ti-6Al-4V, Metall. Mater. Transactions A, 45A, 2014, 1258-1272.
9. G. Akshay, D. Hemant, K. Vivek, P. Akshay, V. Ankita, Review on Laser Welding of Titanium Alloy, Proceedings of International Conference on Ideas, Impact and Innovation in Mechanical Engineering, Pune, India, 5, 6, 2017, 789-795.
10. K. Tomáš, M. Ivan, K. Pavel, The Laser Beam Welding of Titanium Grade 2 Alloy, Grant J., 2012, 77-79.
11. L. Zhixiong, R. Khashayar, P. Afshin, A. Mohammad, K. Arash, R. Sara, Experimental and Numerical Study of Temperature Field and Molten Pool Dimensions in Dissimilar Thickness Laser Welding of Ti6Al4V Alloy, J. Manuf. Processes, 49, 2020, 438-446.
12. G. Xiao-Long, Z. Lin-Jie, L. Jing, Z. Jian-Xun, A Comparative Study of Pulsed Nd:YAG Laser Welding and TIG Welding of Thin Ti6Al4V Titanium Alloy Plate, Mater. Sci. Eng. A, 559, 2013, 14-21.
13. A. Squillace, U. Prisco, S. Ciliberto, A. Astarita, Effect of Welding Parameters on Morphology and Mechanical Properties of Ti–6Al–4V Laser Beam Welded Butt Joints, J. Mat. Processing Technol., 212, 2012, 427-436.
14. T.S. Balasubramanian, M. Balakrishnan, V. Balasubramanian, M.A. Muthu-Manickam, Influence of Welding Processes on Microstructure, Tensile and Impact Properties of Ti-6Al-4V Alloy Joints, Transac. Nonferrous Meter. Soc. China, 21, 2011, 1253-1262.
15. A.S.H. Kabir, X. Cao, P. Wanjara, J. Cuddy, A. Birur, M. Medraj, Use of Filler Wire For Laser Welding of Ti-6Al-4V, Adv. High Temp. Join. Mater.,51, 3, 2012, 320-327.
16. F. Fedor, F. Martin, V. Volker, A. Pedro, B. Stefan, K. Nikolai, Metallurgical Aspects of Joining Commercially Pure Titanium to Ti-6Al-4V Alloy in a T-joint Configuration by Laser Beam Welding, The Int. J. Adv. Manufac. Technol., 97, 2018, 2019-2031.
17. P.M. Chintan, P. Ketan, A Literature Review on Effect of Laser Welding Parameters on Mechanical Properties and Microstructure, Int. J. Sci. Res. Dev., 1, 10, 2013, 2102-2105.
18. S.S. Sandeep, M. Sachin, Research Developments in Laser Welding - A Review, Int. J. Innovative Research in Sci. Technol., 3, 11, 2017, 60-64.
19. B. Alex, D. Matt, S. David, D. John, N. Samih, Laser Welding of Titanium and its Alloys for Medical Applications: Current Knowledge and Future Direction, Mater. Sci. Forum, 618-619, 2009, 291-294.
20. J. Dezhi, S.A. Ali, A. Mohammad, A. Masoud, A.A. Abdulrahman, Numerical and Experimental Studies on the Effect of Varied Beam Diameter, Average Power and Pulse Energy in Nd: YAG Laser Welding of Ti6Al4V, Infrared Phys. Technol., 101, 2019, 180-188.
21. A. Jayanthia, K. Venkataramanan, K.S. Kumar, A Literature Survey on Modeling of Laser Welding and its Related Processes, IOSR J. Appl. Phys., 8, 6, 2016, 42-53.
22. F. Behzad, F. W. Steven, L. Gladius and A. Ebrahim, A Review on Melt-Pool Characteristics in Laser Welding of Metals, Adv. Mater. Sci. Eng., 2018, 1-18.
23. L. Wei, A. Yuewe, J. Ping, L. Yang, Simulation and Modeling of Shielding Gas on the Welding Defects in the Fiber Laser Keyhole Welding, Proceedings of 3rd International Conference on Materials Science and Mechanical Engineering, Windsor, United Kingdom, 2016, 31-35.
24. S. Katayama, in S. Katayama (Ed), Introduction: Fundamentals of Laser Welding, Handbook of Laser Welding Technologies, Woodhead Publishing Limited, India, 2013, 3-16.
25. J. Berkmanns, M. Faerber, Laser Welding, BOC Limited, Surrey, 2010.
26. C.A. Walsh, Laser Welding - Literature Review, Cambridge, University of Cambridge, 2002.

27. N. Kashaev, V. Ventzke, V. Fomichev, F. Fomin, S. Riekehr, Effect of Nd:YAG Laser Beam Welding on Weld Morphology and Mechanical Properties of Ti-6Al-4V Butt Joints and T-Joints, Opt. Lasers Eng., 86, 2016, 172-180.
28. K. Hong, Y.C. Shin, Analysis of Microstructure and Mechanical Properties Change in Laser Welding of Ti6Al4V with a Multiphysics Prediction Model, J. Mater. Process. Technol., 237, 2016, 420-429.
29. L. Jing, G. Xiao-Long, Z. Lin-Jie, Z. Jian-Xun, A Study of Fatigue Damage Evolution on Pulsed Nd:YAG Ti6Al4V Laser Welded Joints, Eng. Fract. Mechanics, 117, 2014, 84-93.
30. U. Kumar, D.K. Gope, R. Kumar, S. Chattopadhyaya, A.K. Das, A. Pramanik, G. Krolczyk, Investigation of Microstructure and Mechanical Properties of Titanium Alloy Sheet using Low Power Nd-YAG Laser Welding Process, Met. Mater., 56, 2, 2018, 121-129.
31. G. Xiao-Long, Z. Lin-Jie, L. Jing, Z. Jian-Xun, Porosity and Microstructure in Pulsed Nd:YAG Laser Welded Ti6Al4V Sheet, J. Mater. Process. Technol., 214, 2014, 1316-1325.
32. G. Casalino, M. Mortello, S.L. Campanelli, Ytterbium Fiber Laser Welding of Ti6Al4V Alloy, J. Manufac. Process., 20, 2015, 250-256.
33. 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, Opt. Lasers Eng., 47, 2009, 1231-1241.
34. W.K.C. Yung, B. Ralph, W.B. Lee, R. Fenn, An Investigation into Welding Parameters Affecting the Tensile Properties of Titanium Welds, J. Mater. Process. Technol., 63, 1997, 759-764.
35. J.S. Alireza, C. Isabelle, N. Håkan, Numerical Modelling of Shielding Gas Flow and Heat Transfer in Laser Welding Process, Mater. Sci., 2012, 1-8.
36. C. Baohua, Y. Zhang, P. Haitao, L. Haigang, C. Hao, D. Dong, S. Jiguo, Study of Gravity Effects on Titanium Laser Welding in the Vertical Position, Mater., 10, 1031, 2017, 1-12.