Influence of temporal and spectral profiles of lasers on weld quality of titanium

Antaryami Mohanta*, Matthias Leistner, Marc Leparoux

Empa–Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Advanced Materials Processing, Feuerwerkerstrasse 39, Thun CH–3602, Switzerland

ARTICLE INFO

Keywords:
Titanium
Laser welding
Laser processing
Optical emission spectroscopy
High-speed imaging

ABSTRACT

The effect of interaction of lasers having different spectral and temporal profiles with titanium on the weld surface quality is investigated by high-speed imaging and optical emission spectroscopy at atmospheric pressure in argon environment. High-speed imaging of the plume reveals that plume is produced during the laser pulse. Decrease in plume size and expansion rate is observed for those lasers whose spectral profiles overlap with more neutral atomic titanium transitions (Ti I) owing to increasing rate of reabsorption of the laser pulse primarily by the neutral titanium atoms present in the plume. Darkness around the laser spot on the titanium surface observed due to deposition of the nanoparticles increases with decrease in size and expansion rate of the plume which indicates that reabsorption of the laser pulse is the main cause of dark colouration of the surface. The bright appearance of a part of the plume produced by one laser at which another laser whose spectral profile cover many Ti I transitions is passed confirms the reabsorption process. Clean appearance of the surface around the laser spot along with enhancement of the plume size and expansion rate is observed for lasers with customized spectral profiles which do not overlap with any Ti I transitions. Modulation of the temporal profile can moderately improve the plume expansion rate and reduce the darkness around the laser spot provided that the laser spectral profile does not overlap with many Ti I transitions, particularly, with those whose energy of lower levels is less than 3 eV.

1. Introduction

Titanium and its alloys have widely been used in aviation, automotive, aerospace, biomedical, shipbuilding, petrochemical, nuclear and power generation industries due to their high strength, low density, high fracture toughness, fatigue strength and resistance to crack propagation, superior biocompatibility, high temperature mechanical properties, and excellent corrosion resistance [1–3]. With the advancement of different applications of titanium and its alloys in various industries, several welding techniques such as tungsten inert gas (TIG) welding, laser welding, laser-hybrid welding, electron beam welding and friction welding have been developed [2]. Among the aforementioned techniques, laser welding has been paid significant attention due to its high energy concentration, ease of realizing automation and rapid processing, high precision, high weld quality with narrowest fusion and heat affected zones, high efficiency and excellent flexibility [1,4]. In laser welding process of metals, a high power laser beam is focused onto the metal pieces for joining which results in melting, evaporation and resolidification. Many different kinds of lasers such as CO2, Nd:YAG, diode, disk, and fiber lasers have been employed as heat source to realize the high quality weld of titanium and its alloys [1–5,6]. Currently, fiber laser welding has gained popularity as a promising joining technology for different metal pieces due to high power of the laser with low beam divergence, flexible laser beam delivery, low maintenance cost, high efficiency, and compact size [6,7]. Auwal et al. [1] have comparatively discussed the results on laser welding of titanium alloys obtained using different laser systems, and reported that the laser processing parameters have great influence on joint microstructure and properties. Thus, different process parameters have been optimized in order to achieve better weld quality. The effect of laser power and welding speed on weld quality has been extensively studied [8–11]. Cao et al. [8] have welded annealed Ti–6Al–4V alloy sheets using an Nd:YAG laser and investigated the effects of welding speed on surface morphology and shape, welding defects, microstructure, hardness and tensile properties. They also observed appearance of silver colour at the weld surface for all the joints that is close to the natural colour of the base metals, and attributed it to good shielding of laser interaction zone by argon gas. Li et al. [12] have reported the effects of oxygen contamination in the argon shielding gas on the weld surface colour and microstructures during laser welding of commercially pure titanium thin sheets. They found that the increase of oxygen content in the argon shielding gas leads to change in colour of the weld surface from silver to straw/dark straw, purple and blue depending on the oxygen content. Ahn et al. [11] have used fiber laser for welding of Ti–6Al–4V thin sheets and investigated to determine the effect of welding parame-

* Corresponding author.
E-mail address: antaryami.mohanta@empa.ch (A. Mohanta).

https://doi.org/10.1016/j.optlaseng.2020.106173
Received 27 February 2020; Received in revised form 12 April 2020; Accepted 4 May 2020
Available online 5 June 2020
0143-8166/© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license. (http://creativecommons.org/licenses/by/4.0/)
ters including laser power, welding speed and beam focal position on the weld microstructure, bead profile and weld quality. They have shown that the weld top and bottom width increase with both increase and decrease in beam focal position, and also with increasing laser power and decrease in welding speed. In addition, at very high welding speeds, they have observed spatter at the bottom surface. Kaplan et al. [13] have detected small particles of the resolidified melt at the surface of the workpiece along the weld bead due to spatter generation during the laser welding process. Akman et al. [10] have investigated the influence of the laser output parameters such as pulse energy and duration on the weld quality of Ti-6Al-4V alloys. They have observed crater formation on the surface of the materials at higher laser peak power and therefore increased the pulse duration at a fixed laser peak power to increase the penetration depth in order to avoid craters. Although the influence of different process conditions such as laser peak power, pulse duration, welding speed, shielding of interaction zone, laser beam focal position, oxygen contamination in argon shielding gas, etc. on the weld quality has been studied, the effect of temporal and spectral laser profiles has not been investigated in detail. In this study, we have comparatively investigated the effect of interaction of four different lasers having different spectral and temporal profiles on the surface quality of titanium with in-situ characterization of ejected plume by high-speed imaging (HSI) and optical emission spectroscopy (OES).

2. Experimental details

The lasers used in this study for their interactions with a titanium plate (grade 1) are listed in Table 1 along with their centre wavelengths and manufacturers, which are named as Nd:YAG, IPG1064, IPG1070 and IPG1083. The temporal profiles of the lasers were determined by a fast photodetector (THORLABS) and a digitizing oscilloscope (Teledyne LeCroy). The spectral profiles of the lasers were measured by using a spectrometer (Ocean Optics). The peak powers of the lasers were kept sufficiently high to match the requirements of the laser welding process conditions. The laser beams were focused using a Precitec YW30 welding head onto the titanium plate which is placed normal to the laser beam and is kept inside a simulation chamber containing 38 view ports at atmospheric pressure in argon environment. The focal diameters of different laser beams were determined to be between 620 and 635 μm by using a charge-coupled device (CCD) camera beam profiler (Spitronic, OPHIR Photonics). All the lasers have top-hat beam shape. The peak powers of the lasers were varied whereas pulse duration of each laser was kept constant at 1.5 ms. The ejected plume in the form of plasma/hot vapour due to the interaction of laser with titanium plate was investigated by HSI and OES through the view ports of the simulation chamber. A schematic diagram of the HSI and OES experimental apparatus is depicted in Fig. 1. HSI experiment was conducted by using a Videal Motion Pro Y4 high-speed camera with a Carl Zeiss MakroPlanar 2/100 ZF.2 lens. The high-speed images were acquired at angle of 90° with respect to the axis of the laser beam with 800 ns exposure time and f/8 aperture at a frame rate of 25 kHz. Colour image of the ejected plume was recorded using a fast imaging camera A4S3 mono (Videal AG) mounted with a Zeiss 100 photographic objective. OES experiment was carried out by using collection optics, fiber optic patch cable and a high-resolution spectrometer [Andor Technology (Shamrock Spectrograph and Newton CCD)]. The integration time for acquiring the optical emission spectra was varied up to the end of the laser pulse i.e. 1.5 ms. Optical images of the surface of titanium plate shot by the lasers were acquired by using an Axioplan (Zeiss) optical microscope equipped with a ProgResC14 plus camera (Jenoptik). Scanning electron microscopy (SEM, Hitachi S-4800) and Energy Dispersive X-ray Spectroscopy (EDS) were used to analyse the surface morphology of the titanium plate after the laser shot. Titanium grade 23 was considered for analysis of the penetration depth profile, and the cross-sections after the laser shot were prepared by cutting, polishing and etching. The etching was performed by using the Keller’s reagent: 95 mL of distilled water, 2.5 mL of nitric acid (HNO₃), 1.5 mL of hydrochloric acid (HCl) and 1.0 mL of hydrofluoric acid (HF). Subsequently, the cross-sectional images were obtained by using the aforementioned optical microscope.

3. Results

Fig. 2 shows the optical microscope images of the laser spot on titanium plate produced by different lasers (Nd:YAG, IPG1064, IPG1070 and IPG1083) with laser peak power of 1 kW. The surface around the laser spot produced by Nd:YAG laser appears clean as shown in Fig. 2(a). For IPG1064, IPG1070 and IPG1083 lasers, dark colour around the laser spot is observed as shown in Fig. 2(b)–(d) which is less for IPG1064, intermediate for IPG1083 and intense for IPG1070. The increase in darkness of the colour around the laser spot is not monotonic with increase in laser wavelength. The spot colouration can also not be attributed to the effect of oxidation as reported by Li et al. [12] since experiment was conducted in argon environment and clean surface is observed for one laser i.e. Nd:YAG laser. The dark colour around the laser spot shown in Fig. 2(b)–(d) is uniformly distributed which indicates that the colouration could not be due to spatter generation where small particles of the resolidified melt are randomly sticked to the surface [13]. Moreover, the laser peak power and pulse duration of both Nd:YAG and IPG1064 lasers are almost same which precludes the concept of spatter generation for dark colouration [10]. The surface having dark colouration around the laser spot was further investigated by SEM and EDS. EDS analysis and SEM images shown in Fig. 3 reveal that dark colour around the laser spot is caused by the deposition of titanium nanoparticles whose size ranges from 5 to 260 nm with an average size of about 70 nm. The shape of larger size particles indicates agglomeration due to coalescence of smaller size nanoparticles. In order to understand the process of deposition of particles around the laser spot, high-speed camera acquired time-resolved images of the plume that is produced due to interaction of the lasers with titanium plate are investigated.

3.1. Plume dynamics

The temporal evolution of the high-speed images of the plume emissions produced by Nd:YAG, IPG1064, IPG1070 and IPG1083 lasers having peak power of 1 kW from titanium plate up to the end of the laser pulse is shown in Fig. 4(a)–(d). Although the high-speed images were acquired at fixed frame rate of 25 kHz, we have shown few images at larger and nonperiodic time interval as representative of all the images. Careful inspection of Fig. 4 reveals that plume emission starts appearing at earlier time and expands at faster rate for Nd:YAG than other IPG lasers.
Fig. 1. Schematic representation of the HSI and OES experimental apparatus for monitoring the plume produced by the lasers.

Fig. 2. Optical microscope images of the laser spot on titanium plate for (a) Nd: YAG, (b) IPG1064, (c) IPG1070, and (d) IPG1083 laser.

Fig. 3. SEM images of (a) the spot on titanium plate produced by IPG1064 laser, (b) and (c) coloured surface around the laser spot, and (d) pristine area of the titanium plate.
The plume emission for Nd:YAG laser shown in Fig. 4(a) commences at about 0.05 ms and disappears above 1.3 ms before the end of the laser pulse (pulse duration = 1.5 ms). It is also obvious from Fig. 4(a) that plume is effectively produced up to 0.8 ms which expands and screens the laser pulse at and above 1 ms preventing further plume generation. By contrast, plume emission starts appearing at later time of about 1 ms and lasts up to the end of the laser pulse i.e. 1.5 ms in case of IPG lasers as shown in Fig. 4(b)–(d). Among the IPG lasers, the plume expansion is more for IPG1064, intermediate for IPG1083 and less for IPG1070. Comparison of Figs. 2 and 4 betokens that the decreasing rate of plume expansion could be related to increasing darkness of the colour around the laser spot. In other words, appearance of dark colour around the laser spot shown in Fig. 2 could be associated with the dynamics of the plume produced by different lasers. In order to understand the plume dynamics further, a colour image of the plume produced by the IPG1064 laser is recorded at 1.5 ms which is shown in Fig. 5. The plume structure is similar to the mantle plume caused by heat conduction and consequent entrainment of the surrounding fluid [14,15]. Different features of the plume are marked by 1–6 in Fig. 5 corresponding to the source region, hot plume axis, source material of original plume head, cooled source material, heated and entrained surroundings, and plume head containing hot source material, respectively, following the nomenclature used for the mantle plume [14,15]. Since the IPG1064 laser pulse starts ejecting the material from the titanium plate at about 1 ms, which continues up to the end of the pulse i.e. 1.5 ms, the hot source material is continuously supplied to the top of the plume head through the hot plume axis. The plume head becomes larger than the width of the hot plume axis close to the source region since the plume cannot displace the ambient rapidly and ascend. The expanding plume exhibits spherical shape at the plume head which could be due to the maximum deceleration of the ejected source material in the direction of hot plume axis compared to the expansion in radial directions, as the density of the ambient Ar gas is adequately high at atmospheric pressure [16,17]. Such deceleration of the expanding plume is resulted due to the collision with species of the ambient which in turn leads to rapid cooling of the species of plume. At atmospheric pressure, chemical reactions upon sufficient cooling has been known to result in formation of nanoparticles in vapour phase [18–21]. Thus, nanoparticles can form at the outer periphery of the plume due to condensation. Consequently, a thin layer of ambient adjacent to the plume head is heated up. When its temper-

Fig. 4. Temporal evolution of the high-speed images of the plume emissions produced by Nd:YAG, IPG1064, IPG1070 and IPG1083 lasers having laser peak power of 1 kW and pulse duration of 1.5 ms from titanium plate.

Fig. 5. A colour image of the plume produced by IPG1064 laser recorded at 1.5 ms. Different plume features are marked by 1–6: 1: source region, 2: hot plume axis, 3: source material of original plume head, 4: cooled source material, 5: heated and entrained surroundings, 6: plume head containing hot source material.
wrapped together. In Fig. 4(a), spherical vortex flows far away from the surface of the titanium plate with the expanding plume avoiding deposition of particles which results in clean surface as shown in Fig. 2(a). In Fig. 4(b), lighter particles flow away from the surface along with the spherical vortex whereas heavier particles cannot follow the spherical vortex recirculation path and are deposited back onto the surface which results in mild dark colouration around the laser spot (Fig. 2(b)). On the other hand, the spherical vortex formation is not clearly evident in Fig. 4(c) and (d) in case of IPG1070 and IPG1083 lasers, respectively, which indicates different plume dynamics. Moreover, since the plume size is different for different lasers in spite of having almost same laser intensity, analysis of penetration depth profile to understand the impact of different lasers on titanium plate is imperative.

3.2. Penetration depth

IPG1064 and IPG1070 lasers were considered as representative of all the lasers to make comparative investigation of the penetration depth profiles of the laser spot on titanium plate. Fig. 6 shows the cross-sectional optical microscope images of the laser spot at laser peak power of about 1 kW for both IPG1064 and IPG1070 lasers. The penetration depths are found to be about same i.e. 120 and 122 μm, respectively, for IPG1064 and IPG1070 lasers as shown in Fig. 6. The aspect ratio (depth/width) of the penetration profile is also almost same which indicates that the difference of 6 nm in wavelengths of the IPG1064 and IPG1070 lasers does not affect the penetration profile. Since the width is much larger than the depth, the laser interaction with titanium plate in this study corresponds to the conduction mode welding. In order to have further evidence, variation of penetration depth with laser peak powers for both IPG1064 and IPG1070 lasers shown in Fig. 6 are analysed. Penetration depth is found to increase in both cases which is in agreement with the fact that the thickness (ΔXc) of the material evaporated per pulse in accordance with the heat balance equation is linearly proportional to (E0−Eθ) where E0 and Eθ are the incident and threshold laser energy, respectively [22,23]. The saturation behaviour observed above 1.4 kW could be due to increase in screening of the laser pulse by the energetic evaporated species. Moreover, the penetration depth evolves at the same rate with increase in laser peak power for both IPG1064 and IPG1070 lasers. In other words, penetration depth is nearly same at each laser power which is in agreement with about same absorption coefficient of titanium at 1064 and 1070 nm [24,25]. Insignificant difference in penetration depth and absorption coefficient for both IPG1064 and IPG1070 lasers indicates that the amount of vaporized material in both cases is approximately same although the plume size is different. Temporal profiles of all the lasers are therefore investigated to understand the cause of different size and dynamics of the plume observed in Fig. 4.

3.3. Effect of temporal profile of the lasers

Fig. 8 shows the temporal profiles of the lasers which are obtained by coupling the laser beams separately with the photodiode and recording the corresponding electronic signal with the oscilloscope. The temporal profile of the Nd:YAG laser exhibits modulation with a peak-to-peak amplitude of about 300 mV and a frequency of about 20 kHz. Similarly, IPG1064 laser has the temporal profile which shows modulation with a peak-to-peak amplitude of about 80 mV and a frequency of about 175 kHz. On the other hand, IPG1070 and IPG1083 lasers have modulated temporal profile with very small peak-to-peak amplitude and very large frequency. Different modulating behaviour of the temporal profiles of the lasers could be associated with the different plume dynamics observed in Fig. 4. Modulation of temporal profile with larger peak-to-peak amplitude (300 mV) and smaller frequency (20 kHz) for Nd:YAG laser could be correlated to larger plume size, earlier appearance and faster expansion of the plume [Fig. 4(a)] which eventually prevents the redeposition of the particles on the surface. For IPG1064 laser, comparative smaller peak-to-peak amplitude (80 mV) and larger frequency (175 kHz) of modulation of the temporal profile could result in smaller plume size and expansion in Fig. 4(b) compared to that in Fig. 4(a). Similarly, negligibly small peak-to-peak amplitude and infinitely large frequency of modulation of temporal profiles of IPG1070 and IPG1083 lasers could result in smaller plume size and expansion, and increasing darkness around the laser spot compared to the case of IPG1064. In order to understand the effect of modulating behaviour of temporal profile of lasers on plume dynamics and the darkness around the laser spot, the temporal profiles of IPG1070 and IPG1083 lasers are manually modulated with different peak-to-peak amplitudes, frequencies and shapes. Among many different shapes having various peak-to-peak amplitudes
and frequencies, one shape of temporal profile of the IPG1083 laser with modulation up to 0.75 ms of the laser power having peak-to-peak amplitude of 635 mV and frequency of 9 kHz shown in Fig. 9 is finalized based on its effectiveness in removing the darkness around the laser spot. The peak-to-peak amplitude (635 mV) of manual modulation of the temporal profile of IPG1083 laser is more than that (300 mV) of Nd: YAG laser. Moreover, the frequency (9 kHz) of manual modulation of temporal profile of IPG1083 laser is less than that (20 kHz) of Nd: YAG laser. This indicates that higher peak-to-peak amplitude and lower frequency of modulation of temporal profile of the lasers could be considered effective in preventing the deposition of nanoparticles onto the surface. The preconfigured designed shape for the temporal profile is represented by a thin red line and the effective temporal profile measured using the photodiode and oscilloscope is shown by a black curve in Fig. 9. In such modulated configuration of the temporal profile of the IPG1083 laser, the darkness around the laser spot [Fig. 10(a)] is found to be drastically reduced as compared to Fig. 10(c), which shows the optical microscope image of the spot produced by the IPG1083 laser with unmodulated temporal profile. In other words, the deposition of nanoparticles formed in vapour phase onto the titanium surface is nullified if the temporal profile of the IPG1083 laser is modulated in accordance with the shape shown in Fig. 9. This indicates that the initial part of the laser pulse has significant influence on the plume dynamics and the dark appearance of the surface around the laser spot. Fig. 10(b) shows the temporal evolution of the plume produced by the IPG1083 laser with modulated temporal profile shown in Fig. 9. The plume size and expansion are comparatively more in Fig. 10(b) than that in Fig. 10(d), which shows the temporal evolution of the high-speed images of the plume produced by IPG1083 laser without modulation of its temporal profile. However, the plume size and expansion in Fig. 10(b) are less than that of Fig. 4(a) for which the surface around the laser spot on titanium plate is clean. On the other hand, the darkness around the laser spot remains intense similar to Fig. 2(c) for IPG1070 laser even after manual modulation of its temporal profile with different peak-to-peak amplitudes, frequencies and shapes. In other words, the manual modulation of temporal profile is ineffective for IPG1070 in contrast to that for IPG1083. Further investigation was carried out by characterizing the spectral profiles of the lasers and studying their influence on the plume dynamics and the darkness around the laser spot.
3.4. Influence of laser spectral profiles

Since the fiber lasers have widely been used for laser manufacturing [6,7], we have considered only IPG lasers for further analysis. In addition, dark colouration around the laser spot is observed only for IPG lasers. The spectral profiles of the IPG1064, IPG1070 and IPG1083 are shown in Fig. 11 which are represented by the solid curves (left Y-axis). The symbols (■) and (○) represent the energy of the lower levels (right Y-axis) for the neutral atomic (Ti I) and singly ionized (Ti II) titanium transitions, respectively, at corresponding transition wavelengths. The red symbol (■) marked by (↓) represent the lower level energy of Ti I at 1064.64 nm. The information about the Ti I and Ti II transitions are taken from the NIST [26]. The full width at half-maximum (FWHM) of the spectral profile of the IPG1064 is about 0.43 ± 0.01 nm whereas that of IPG1070 and IPG1083 lasers are 3.75 ± 0.02 and 1.35 ± 0.02 nm, respectively, which cover different Ti I transition wavelengths listed in Table 2. The Ti II transition wavelengths also partially overlap with the spectral profile of the IPG1070 laser and are listed in Table 3. It should be noted that the transition wavelength corresponds to the energy difference between the higher and lower energy levels of Ti I or Ti II where the transition occurs. It is obvious from Fig. 4 that the plume is produced during the laser pulse. Since the spectral profiles of IPG1070

Fig. 11. Spectral profiles of the IPG1064, IPG1070 and IPG1083 lasers represented by the solid curves. The symbols (■) and (○) represent the lower level energy of Ti I and Ti II electronic transitions, respectively, at corresponding transition wavelengths [26]. The red symbol (■) marked by (↓) represent the lower level energy of Ti I at 1064.64 nm.

Table 2
List of transition wavelengths for Ti I with their corresponding lower level energy in the spectral regions of the IPG1070 and IPG1083 lasers.

| Laser    | Transition wavelength (nm) | Lower level energy for Ti I (eV) |
|----------|-----------------------------|---------------------------------|
| IPG1070  | 1067.70                     | 0.836                           |
|          | 1068.91                     | 2.175                           |
|          | 1068.94                     | 3.727                           |
|          | 1069.10                     | 1.502                           |
|          | 1072.64                     | 0.813                           |
|          | 1073.09                     | 3.718                           |
|          | 1073.29                     | 0.826                           |
|          | 1073.98                     | 4.178                           |
|          | 1074.16                     | 3.708                           |
| IPG1083  | 1081.70                     | 3.727                           |
|          | 1081.72                     | 3.708                           |
|          | 1082.03                     | 3.334                           |
|          | 1082.79                     | 0.836                           |
|          | 1083.34                     | 3.718                           |

Fig. 12. High-speed image of the plume emission at 0.946 ms produced by Nd:YAG laser from the titanium plate where IPG1070 laser is passed through the plume.

Fig. 13. Optical emission spectrum of the plume produced by the IPG1083 laser at integration time of 1.5 ms in the spectral region between 475 and 535 nm.
and IPG1083 lasers overlap with different Ti I and/or Ti II transition wavelengths, the neutral and/or ionized titanium atoms present in the plume could reabsorb the laser pulse and become hot. Reabsorption of the laser pulse by the plume species can lead to reduction in plume expansion and increase in plume brightness as depicted in Fig. 4(c) and (d). The nearby Ti I transition at 1064.64 nm having lower level energy of 3.708 eV [Fig. 11] could plausibly interact with the IPG1064 laser to produce mild brightness in the lower part of plume below the vortex as shown in Fig. 4(b). In order to verify the reabsorption process of the laser pulse by the plume species, a separate experiment was conducted where the Nd:YAG laser was focused onto the titanium plate to create the plume and IPG1070 laser was passed through the plume. Fig. 12 shows the corresponding high-speed image of the plume emission recorded at 0.946 ms. The portion of the plume at which IPG1070 laser is passed appears bright. This indicates that the constituents of the plume absorb the IPG1070 laser. The plume emission characteristics are further investigated by optical emission spectroscopy to understand the bright appearance of the plume for IPG1070 and IPG1083 lasers.

### 3.5. Optical emission spectroscopy

Optical emission spectroscopy experiment was carried out by coupling the plume of about 0.5 mm diameter close to the surface of the titanium plate with the high-resolution spectrometer. Optical emission spectra of the plumes emissions produced by the IPG1064, IPG1070 and IPG1083 lasers were recorded at different integration times. Fig. 13 shows the optical emission spectrum of the plume produced by the IPG1083 laser at integration time of 1.5 ms in the spectral region between 475 and 535 nm as representative of all the lasers and integration times. The spectra are mostly dominated by the emission due to Ti I transitions. The Ti I transitions occurring at 484.1 nm [3d(^2)F4s4p(^1P^0) → 3d^2s^2 a ^1D_2], 485.6 nm [3d(^2)H4p z ^3P^0 → 3d^2s^2 a ^1H_2], 488.5 nm [3d(^2)G4p y ^3H_2 → 3d(^2)G4s a ^3G_3], 491.4 nm [3d(^2)G4p y ^3H_2 → 3d(^2)G4s a ^3G_3], 506.5 nm [3d(^2)F4s4p (^3P^0) → 3d^2s^2 a ^1F_2], 517.3 nm [3d(^2)F4s4p (^3P^0) z ^3P^0 → 3d^2s^2 a ^3F_2], and 519.3 nm [3d(^2)F4s4p (^1P^0) z ^3P^0 → 3d^2s^2 a ^3F_2] are considered to determine the plume temperature \( T \) under the assumption of the local thermodynamic equilibrium (LTE) by using the Boltzmann plot method:

\[
\ln \left( \frac{I_k \lambda_{ki}}{g_k A_{ki}} \right) = -\frac{E_k}{k_B T} + C
\]

where \( C \) is a constant, \( I_k \) is the intensity of the emission line at wavelength \( \lambda_{ki} \), \( g_k A_{ki} \) is the product of the statistical weight of the upper level \( k \) and the transition probability, \( E_k \) is the energy of the upper level \( k \) and \( k_B \) is the Boltzmann constant. The slope \( \left( -\frac{1}{k_B T} \right) \) of the plot between \( E_k \) and \( \ln \left( \frac{I_k \lambda_{ki}}{g_k A_{ki}} \right) \) obtained using the spectral response corrected aforementioned Ti I emission lines gives the value of \( T \). The values of different parameters used in Eq. (1) are taken from NIST [26], Fig. 14 shows the Boltzmann plot for IPG1083 laser at integration time of 1.5 ms in which the solid line is the linear fit to the data points with \( R^2 > 0.99 \) that gives \( T \) of 5600 ± 200 K. Similarly, \( T \) is found to be 5000 ± 250 and 9100 ± 500 K for IPG1064 and IPG1070 at integration time of 1.5 ms. Fig. 15 shows the plume temperature at different integration times for the lasers IPG1064, IPG1070 and IPG1083. The plume temperature is found to increase as the integration time increases and exhibits saturation above sufficiently high integration time. Such increasing behavior of the plume temperature indicates that initial part of the laser pulse produces the plume and the remaining part of the laser pulse is absorbed by the plume that raises the temperature. Moreover, the plume temperature...
4. Discussion

Plume dynamics during laser processing of titanium is strongly influenced by the temporal and spectral profiles of the lasers that affects the weld surface colouration. Modulation in the temporal profile of the lasers is expected to accelerate the plume expansion. Peak-to-peak amplitude and frequency of modulation in the temporal profile affect the efficiency in driving the spherical vortex away from the surface of the titanium plate. Although the spherical vortex is not obvious in the high-speed images of the plume emissions for IPG1070 and IPG1083, it remains closer to the surface in comparison to that for Nd:YAG and IPG1064 laser since plume expansion rate and size are smaller. Since the penetration depths of the laser spot on the titanium plate are about same for all the lasers, the amount of evaporated materials is same indicating higher density of titanium species in the smaller size plume. Higher density of titanium species in a smaller plume can lead to increase in nanoparticles formation in vapor phase because of increasing supersaturation. Thus, increasing darkness around the laser spot follows the order of decreasing plume size, increasing nanoparticles formation and reposition; highest for IPG1070 laser, intermediate for IPG1083, and less for IPG1064. The temporal profile of IPG1083 laser is manually modulated to obtain the effect on plume dynamics and weld surface colouration similar to that of Nd:YAG laser. The manual modulation of the temporal profile of the IPG1083 laser with optimized peak-to-peak amplitude and frequency has significantly reduced the darkness around the laser spot. On the other hand, the darkness around the laser spot on the surface of the titanium plate remained intense for the IPG1070 laser even after manual modulation of the temporal profile with different shapes, peak-to-peak amplitudes and frequencies. The ineffectiveness of the manual modulation of the temporal profile of the IPG1070 laser in reducing the darkness around the laser spot persuaded further investigation on the laser characteristics and their effect on plume dynamics. The spectral analysis of the lasers reveals that the line profiles of the IPG1070 and IPG1083 coincide with the Ti I and/or Ti II transitions that leads to the reabsorption of laser pulse by species of the plume. The Ti I transitions with smaller energy value of lower level can dominate the reabsorption process as electrons that absorb the photons from the lasers are more populated in the lower energy levels. The energy of the lower level of Ti I transitions at 1069.1 nm \([3d^2(^4F)4s4p(^2P)z^2G_y] \rightarrow 3d^2 4s^2 a^1G_{1s}\) and 1073.29 nm \([3d^2(^4F)4s4p(^2P)z^2G_y] \rightarrow 3d^2 (^4F)4s 3^2F_{5/2}\) are 1.502 and 0.826 eV, respectively. Recall that these transitions overlap with the spectral profile of the IPG1070 laser which produces intense darkness around the laser spot. It should further be noted that oscillator strength is a dimensionless quantity that can be a measure of the probability of absorption of electromagnetic radiation in transitions between the lower and higher energy levels of an atomic system. The oscillator strengths for Ti I transitions at 1069.1 nm and 1073.29 nm are \(6.67 \times 10^{-05}\) and \(1.9 \times 10^{-04}\), respectively. The higher value of the oscillator strength for the Ti I transition at 1073.29 nm is consistent with the smaller energy value of the lower level in comparison to that for the Ti I transition at 1069.1 nm. The IPG1070 laser energy reabsorbed by the Ti I species in the plume between the lower and higher energy levels corresponding to the Ti I transitions at 1069.1 nm.
The interaction of lasers having different temporal and spectral profiles with titanium is investigated at atmospheric pressure in Ar ambient by HSI and OES in order to understand the effect on the weld surface quality during laser welding process. Plume dynamics is significantly affected due to the reabsorption of the laser pulse by the plume constituents. Neutral titanium atoms are the major species in the plume that reabsorb the laser pulse whose spectral profile overlaps with the respective transition energy of Ti I. Reabsorption of the laser pulse by singly ionized titanium atoms is negligible which could be due to the higher energy value of the lower level. Plume brightness and temperature increase with increase in rate of reabsorption process. Reabsorption of the laser pulse by the species of the plume results in reduction in plume expansion rate and size, which leads to increase in formation and deposition of pure Ti nanoparticles on the weld surface of titanium and consequently to dark colouration around the laser spot. Such dark colouration in the weld surface can be avoided by customizing the laser spectral profile, which does not overlap with the Ti I transition energy. Modulation in
the temporal profile has negligible effect on the plume dynamics and reduction in dark colouration around the laser spot if the laser spectral profile overlaps with many Ti I transitions having lower level energy less than 3 eV. This study can be helpful to customize the lasers for welding of different metal pieces with appropriate spectral profiles which do not fall in the region of neutral atomic transition energies. Absence of reabsorption of the laser pulse by the neutral atomic species in the plume during laser welding process can lead to the clean weld surface which eventually can save cost and time of the post-treatment to improve the weld surface quality.

CRediT authorship contribution statement

Antaryami Mohanta: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. Matthias Leistner: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - review & editing. Marc Leparoux: Conceptualization, Supervision, Writing - review & editing, Project administration, Funding acquisition.

Acknowledgements

Authors would like to thank the Commission for Technology and Innovation (CTI), Switzerland for the SIPQuat project (No. 16110.2 PFNM-NM) and Dr. Sébastien Favre, Medtronic Europe Sarl, Switzerland for valuable suggestions and financial support.

References

[1] Awual ST, Ramesh S, Yusuf F, Manland SM. A review on laser beam welding of titanium alloys. Int J Adv Manuf Technol 2018;97:1071–98. https://doi.org/10.1007/s00170-018-2030-x.
[2] Gao X-L, Zhang J-L, Liu J, Zhang J-X. A comparative study of pulsed Nd:YAG laser welding and TIG welding of thin Ti6Al4V titanium alloy plate. Mater Sci Eng A 2013:559:14-21. http://dx.doi.org/10.1016/j.msea.2012.06.016.
[3] Yunlian Q, Ju D, Quan H, Liying Z. Electron beam welding, laser beam welding and gas tungsten arc welding of titanium sheet. Mater Sci Eng A 2000;280:177-81. https://doi.org/10.1016/S0921-5093(99)00662-0.
[4] Li C, Li B, Wu Z-F, Qi X-Y, Ye B, Wang A-H. Stitch welding of Ti-6Al-4V titanium alloy by fiber laser. Trans. Nonferrous Met. Soc. China 2017;27:91-101. https://doi.org/10.1016/S1003-6326(17)60010-4.
[5] Fomin F, Froend M, Ventsile V, Alvarez P, Bauer S, Kasheva N. Metallurgical aspects of joining commercially pure titanium to Ti-6Al-4V alloy in a T-joint configuration by laser beam welding. Int J Adv Manuf Technol 2018;97:2019-31. https://doi.org/10.1007/s00170-018-1968-z.
[6] Quintino L, Costa A, Miranda R, Yapp D, Kumar V, Kong CJ. Welding with high power fiber lasers – a preliminary study. Mater Des 2007;28:1231–7. https://doi.org/10.1016/j.matdes.2006.01.009.
[7] Campanelli SL, Casalino G, Mortello M, Angelastro A, Ludovico AD. Microstructural characteristics and mechanical properties of Ti6Al4V alloy fiber laser welds. Procedia CIRP 2015;33:428–33. https://doi.org/10.1016/j.procir.2015.06.098.
[8] Gao X, Jahazi M. Effect of welding speed on butt joint quality of Ti-6Al-4V alloy welded using a high-power Nd:YAG laser. Opt Laser Eng 2009;47:1231–41. https://doi.org/10.1016/j.optlaseng.2009.05.010.
[9] Squillace A, Prisco U, Caliberto S, Antarita A. Effect of welding parameters on morphology and mechanical properties of Ti-6Al-4V laser beam welded butt joints. J Mater Process Technol 2012;212:427–36. https://doi.org/10.1016/j.jmatprotec.2011.10.005.
[10] Akman E, Demir A, Canel T, Sinmazcelik T. Laser welding of Ti6Al4V titanium alloys. J Mater Process Technol 2009;209:5705–13. https://doi.org/10.1016/j.jmatprotec.2008.06.026.
[11] Ahn J, Chen L, Davies CM, Dear JP. Parametric optimisation and microstructural analysis on high power Yb-fibre laser welding of Ti-6Al-4V. Opt Laser Eng 2016;86:156–71. http://dx.doi.org/10.1016/j.optlaseng.2016.06.002.
[12] Li X, Xie J, Zhou Y. Effect of oxygen contamination in the argon shielding gas in laser welding of commercially pure titanium thin sheet. J Mat Sci 2005;40:3437–43. https://doi.org/10.1007/s10853-005-0447-8.
[13] Kaplan AFH, Powell J, Spatter in laser welding. J Laser Appl 2011;23:032005-1–7. https://doi.org/10.2351/1.3597830.
[14] Campbell IH, Griffiths RW. Implications of mantle plume structure for the evolution of Eoood basalt. Earth Planet Sci Lett 1999;99:79–93. https://doi.org/10.1016/S0012-821X(99)00772-6.
[15] Campbell IH, Griffiths RW, Hill RI. Melting in an Archaean mantle plume: heads it’s basaltas, tails it’s komatiites. Nature 1989;339:697–9. https://doi.org/10.1038/339697a0.
[16] Sharma AK, Thareja RK. Plume dynamics of laser-produced aluminun plasma in ambient nitrogen. Appl Surf Sci 2005;243:68–75. https://doi.org/10.1016/j.apsusc.2004.09.093.
[17] Kushwaha A, Mohanta A, Thareja RK, C2 and CN dynamics and pulsed laser deposition of CN films. J Appl Phys 2009;105:044902-1-5. https://doi.org/10.1063/1.3078078.
[18] Mohanta A, Singh V, Thareja RK. Photoluminescence from ZnO nanoparticles in vapor phase. J Appl Phys 2008;104:054903-1–6. https://doi.org/10.1063/1.2957756.
[19] Mohanta A, Thareja RK. Rayleigh scattering from gaseous phase nanoparticles synthesized by pulsed laser ablation of ZnO. J Appl Phys 2009;106:124909-1-6. https://doi.org/10.1063/1.3273478.
[20] Thareja RK, Mohanta A. Gas suspended ZnO clusters and pulsed laser deposition of ZnO thin films. Phys Status Solidi C 2010;7:1413–16. https://doi.org/10.1002/pssc.200983357.
[21] Mohanta A, Kung P, Thareja RK. Exciton-exciton scattering in vapor phase ZnO nanoparticles. Appl Phys Lett 2015;106:013108-1-4. https://doi.org/10.1063/1.4905320.
[22] Mohanta A, Thareja RK. Plasma synthesis of nanomaterials. 21st Century Nanoscience – A Handbook 2019. 21–2-19

Singh RK, Narayan J. Pulsed-laser evaporation technique for deposition of thin films: physics and theoretical model. Phys Rev B 1990;41:8843–59. https://doi.org/10.1103/PhysRevB.41.8843.
[24] Johnson PB, Christy RW. Optical constants of the noble metals. Phys Rev B 1976;209:3707–30. https://doi.org/10.1103/PhysRevB.6.4370.
[25] Johnson PB, Christy RW. Optical constants of transition metals: Ti, V, Cr, Mn, Fe, Co, Ni, and Pd. Phys Rev B 1979;209:5056–70. https://doi.org/10.1103/PhysRevB.209.5056.
[26] National Institute of Standards and Technology (NIST) Atomic spectra data baseavailable from www.nist.gov. https://doi.org/10.18434/T4W30F.