Quantum Electronics **45** (3) 218–223 (2015)

INTERACTION OF LASER RADIATION WITH MATTER

PACS numbers: 42.55.Wd; 42.62.Cf; 52.50.Jm; 81.20.Vj
DOI: 10.1070/QE2015v045n03ABEH015577

Investigation of the vapour-plasma plume in the welding of titanium by high-power ytterbium fibre laser radiation

D.P. Bykovskiy, V.N. Petrovskiy, S.A. Uspenskiy

Abstract. **The vapour-plasma plume produced in the welding of 6-mm thick VT-23 titanium alloy plates by ytterbium fibre laser radiation of up to 10 kW power is studied in the protective Ar gas medium. High-speed video filming of the vapour-plasma plume is used to visualise the processes occurring during laser welding. The coefficient of inverse bremsstrahlung by the welding plasma plume is calculated from the data of the spectrometric study.**

Keywords: *laser welding, spectral diagnostics, welding plume.*

1. Introduction

In the past 5–10 years, technology of laser processing of thick metal sheets received a new impetus due to the development of basically new types of high-power laser radiation. A class of so-called high-power, high-brightness solid-state lasers has come into existence; presently, these include ytterbium fibre lasers and YAG : Yb^{3+} crystal lasers [1–4].

In particular, of major interest is the use of high-power fibre lasers for welding different refractory materials in machine building, aircraft and chemical industries. In connection with the permanent broadening of the area of technological applications of fibre lasers, there is a need to study the processes in the vapour-plasma cloud produced at the surface of the sample under irradiation, because they have a significant effect [5, 6] on material processing.

When the surface of a material is exposed to laser radiation with a power density higher than the critical power density, this material is heated at a rate which far exceeds the rate of heat removal due to heat conduction, convection and radiation. As this takes place, the metal is not only melted, but also superheated locally to temperatures higher than the boiling temperature. This results in an intensive metal evaporation and vapour expansion, giving rise to a reactive force, which curves the liquid melt surface. As a result, above the metal surface there appears a welding plume, which is responsible for nonuniform scattering, absorption and reflection of radiation. This affects the stability of the characteristics of laser radiation that heats the material and lowers the welding efficiency.

The lower part of the plume is a weakly ionised plasma; the upper part consists primarily of metal vapour [7]. In the interaction with high-power laser radiation, the metal vapour is heated by inverse bremsstrahlung, i.e. in the interaction of the electromagnetic wave with free electrons. There are different assumptions concerning the emergence of free electrons in the vapour cloud. These electrons may be knocked out of the metal by the photoeffect under laser irradiation or arise from thermal electron emission, with the result that the metal vapour produced at the surface is already partly ionised. Moreover, the free electrons may result from the multiphoton ionisation of impurity atoms with a lower ionisation potential. The effective energy loss of laser radiation in the course of welding is primarily due to its absorption in the surface plasma and the subsequent dissipation via thermal radiation and plasma expansion in the ambient space.

An investigation of the vapour-plasma plume produced in the welding of different steels by radiation of high-power fibre lasers is the concern of several papers, of Refs [8–10] in particular.

In this paper we investigated the state of the vapour-plasma plume emerging in different technological regimes of titanium welding by radiation of a high-power fibre laser. We determined the parameters of the welding plasma and its effect on the transmitted radiation.

2. Experimental facility

The welding plume was investigated on a facility (Fig. 1) with an LS-10 (λ = 1.07 μm) ytterbium fibre laser (*1*) of power up to 10 kW and a six-axis robot (*2*). Radiation was transported to the welding spot via an optical fibre (*3*) with a core 200 μm in diameter and was focused with an optical head (*4*) onto the metal surface (*5*). The focal distance of the optical system was equal to 300 mm. The waist diameter of the beam (*6*) was equal to 0.35 mm. The manipulator of the robot (*2*), which holds the optical welding head (*4*), transferred the focal point of the laser beam over the metal surface in two mutually perpendicular directions in the horizontal plane and transferred the optical head vertically with an accuracy of 0.1 mm. For weld samples (*2*), use was made of 6-mm thick VT-23 titanium alloy plates. In all our experiments, the fibre laser beam (*6*) as well as all the measuring equipment remained immobile; the welding was realised by moving the metal samples (*5*) on a linear translatable platform (not shown in the diagram). Due to the interaction of high-intensity laser radiation with the metal, a welding plume (*7*) was produced above the surface of the sample (*2*), which was the object of our investigation. Protective technological gases were delivered to the welding zone using a comb of four tubes arranged along the welding seam (*8*) above the molten pool behind the laser beam (*6*). A video camera (*9*) was mounted for the high-

D.P. Bykovskiy, V.N. Petrovskiy, S.A. Uspenskiy National Research Nuclear University 'MEPhI', Kashirskoe shosse 31, 115409 Moscow, Russia; e-mail: d.bykofsky@gmail.com

Received 3 June 2014; revised 25 August 2014
Kvantovaya Elektronika **45** (3) 218–223 (2015)
Translated by E.N. Ragozin

speed photography of welding. In spectrometric measurements, a narrow slit (*10*) was placed behind the welding plume; placed behind the slit was an optical fibre collimator. An optical fibre (*11*) coupled the collimator to a spectrometer (*12*), which operated in the 200–1160-nm range with a spectral resolution of 1.4 nm. With the exception of the laser, all the equipment was accommodated in a specialised enclosure intended for laser welding.

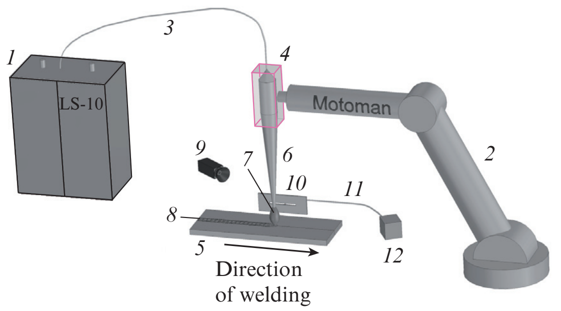

Figure 1. Schematic representation of the experimental facility (see notations in the text).

3. Experimental results and their discussion

3.1. High-speed video filming

High-speed video filming was carried out to visualise the processes occurring at the metal surface during welding. The measurements were made during welding with the delivery of a protection gas – argon. Figure 2 shows a frame recorded in the filming at a rate of 17000 frames s^{-1} with an exposure time of 20 μs. One can see that there forms a 3-cm high welding plume above the metal surface, which periodically tilts in the direction of welding (Fig. 2b).

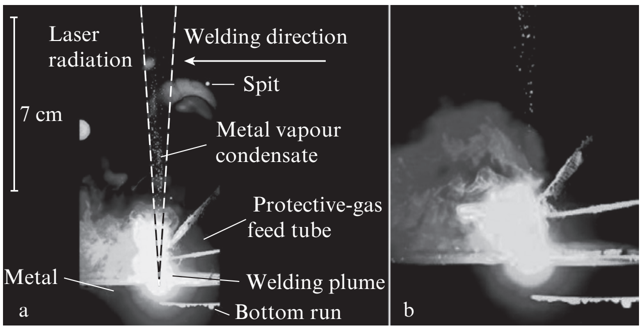

Figure 2. Frame of high-speed video filming of the welding plume for normal incidence of radiation on the metal (a) and magnified image of the welding plume (b).

Observed above the plume is a flux of particles, which move downwards with acceleration inside the caustic of the laser beam also exerting an adverse effect on radiation by scattering and absorbing it. To calculate the flux dynamics in the caustic of the laser beam we traced the motion of individual particles. From the known time interval between the frames and their spatial scale we calculated the acceleration and velocity of these particles. We observed a strong difference in the dynamics of particles in the radiation caustic. The positions of some particles were hardly changed, while other particles managed to travel all the way during this interval, their acceleration ranging up to 2500 m s^{-2} and their velocity up to 15 m s^{-1}.

Figure 3 shows the frames of high-speed video filming carried out when laser radiation was incident at an angle of 15° to the normal of the sample surface. One can see from Figs 3b–3d that the plume also propagates at an angle, primarily in the region of laser radiation. As in the case of normal incidence, we observed a stream of metal droplets travelling with acceleration along the laser beam (the arrow in Fig. 3a) rather than vertically. During welding, the metal is vaporised from the molten pool. On reaching the caustic, there occurs repeated vaporisation, primarily on the side of the laser beam. In this case, there emerges a reaction force directed along the laser radiation caustic. Therefore, the vapour cloud does not pass freely by the caustic; instead it changes the direction of its motion and moves towards the molten pool to exert a longer adverse effect on the welding procedure. In the accelerated motion of vapour in the caustic there occurs coagulation of its particles. Also observed is the transient dynamics of the flow of metal particles in the laser radiation caustic because of the varying amount of vapour that enters the domain of radiation propagation.

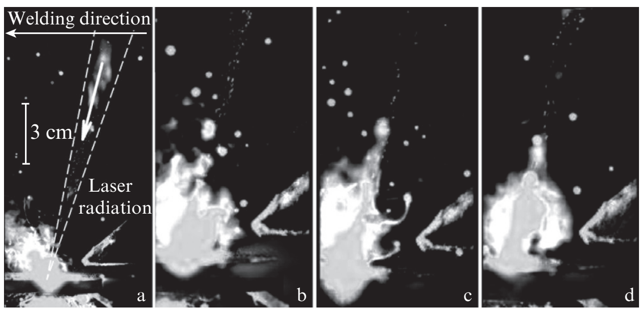

Figure 3. Frames of high-speed video filming of the welding plume when laser radiation was incident on the metal surface at an angle of 15°.

To weaken the effect of the welding plume on laser radiation in metal welding, use is made of blowing-off by gas, which is referred to as cross-plume blowing. High-speed video filming of titanium welding was carried out with the use of a cross plume of compressed air at a pressure of 12 atm (Fig. 4).

The welding plume does not propagate above the cross plume. However, a downward particle flux is also observed in this region; it is less intense than in the previous cases, but also exerts effect on laser radiation. The dynamics of this flux is transient because of the varying amount of metal vapour that enters the caustic of laser radiation. This is due to the fact that the metal vapour which rises from the fusion is carried away from the welding zone with a high velocity under the action of the cross plume. However, subsequently it reflects from obstacles – from the walls of the welding booth, the robot and other parts of the welding components (Fig. 1) located within a distance of 1.5 m – and returns to the region of laser radiation propagation, though above the blow-off region. In addition, the metal vapour rises above the plume due to thermogravitational convection. Then there occurs repeated vaporisation to give rise to the transient particle flux in the caustic, which exerts effect on radiation. Consequently, additional

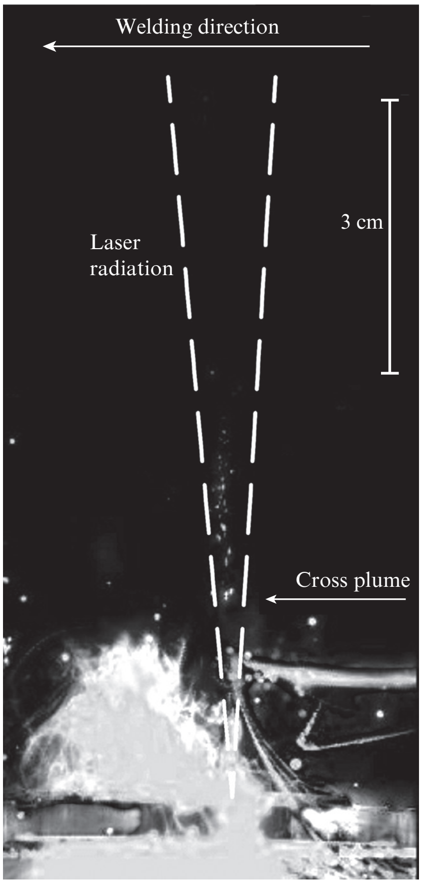

Figure 4. Frame of high-speed video filming of titanium welding using the blow-off of the welding plume with a cross plume of compressed air.

means should be employed in order to eliminate the repeated metal vapour–radiation interaction for improving the stability of laser welding, such as vapour extraction or the use of an additional system of cross plumes located above.

3.2. Spectral vapour-plasma plume diagnostics

The vapour-plasma plume was investigated for different intensities of laser radiation. Measurements were made at a constant height of 5 mm above the metal surface and a welding rate of 3 m min^{-1}.

From the theory of optical pyrometry technique [11] it follows that the spectral intensity $I(\lambda,T)$ of thermal radiation depends on the temperature and is described by the expression

$$I(\lambda,T) = \varepsilon C_1 \lambda^{-5}\left[\exp\left(\frac{C_2}{\lambda T}\right) - 1\right]^{-1}, \quad (1)$$

where C_1 = 37418 W μm^4 cm^{-2}; C_2 = 14388 μm K; ε is the emissivity coefficient; and the wavelength λ is expressed in micrometres and the spectral intensity I in W cm^{-2} μm^{-1}.

For Wien's domain $[C_2/(\lambda T) \gg 1]$, relation (1) after rearrangement assumes the form

$$\ln\frac{\lambda^5 I}{\varepsilon C_1} = -\frac{C_2}{\lambda T}. \quad (2)$$

For ε = const, the portion of the spectrum in this domain straightens in the XY coordinate plane, where $X = \ln[(\lambda^5 I \times (\varepsilon C_1)^{-1}]$ and $Y = C_2/\lambda$, the slope of the line being determined by the radiation temperature T. The $\varepsilon(\lambda)$ dependence manifests itself only logarithmically. When ε is constant or varies only slightly in the range selected, its influence adds up to a parallel translation of the curve along the X axis, but the slope of the curve and the sought-for temperature remain invariable. The technique of measuring the plume temperature is described in greater detail in Refs [11, 12]. Figure 5 shows the measured spectra and the spectra represented in new coordinates. The spectral peaks correspond to singly ionised titanium. Using the method described, above we calculated the vapour-plasma plume temperature for different intensities of laser radiation; a linear approximation of the spectra in the new coordinates was performed using the least squares technique. The welding plume temperature was found to depend linearly on the laser radiation intensity (Fig. 6). The highest temperature was equal to 5200 K.

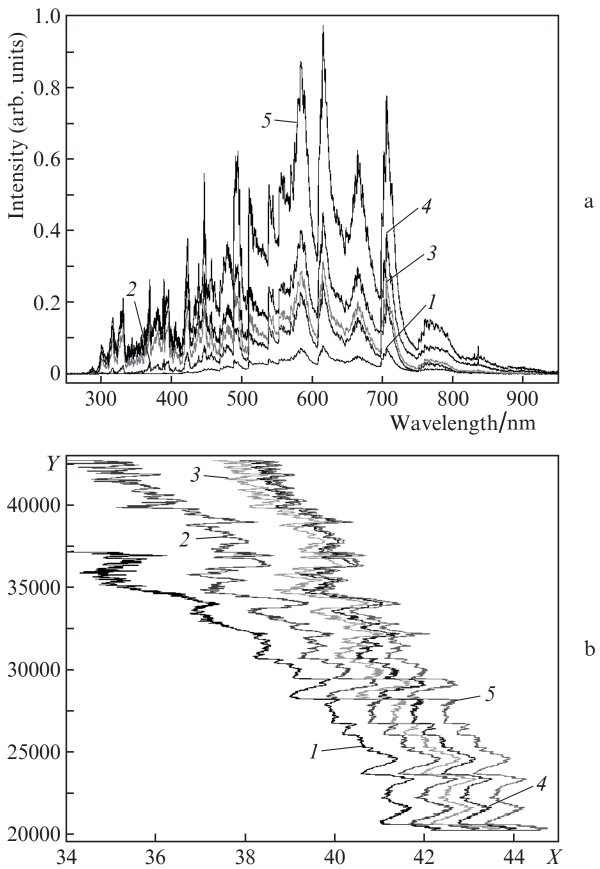

Figure 5. Emission spectra of the vapour-plasma plume measured for laser radiation intensities of (*1*) 10, (*2*) 31, (*3*) 52, (*4*) 73 and (*5*) 94 kW mm^{-2} (a) and represented in the new coordinates (b).

Proceeding from the resultant spectroscopic data, to calculate the degree of ionisation we take advantage of the well-known method which was tested in Refs [9, 12] and made use of the Saha equation

$$\frac{n_{m+1}n_e}{n_m} = 2\frac{u_{m+1}}{u_m}\left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2}\exp\left(-\frac{eV_m}{k_B T}\right), \quad (3)$$

where n_m, u_m and V_m are the density, statistical weight and ionisation potential of the mth ion, respectively; n_e is the elec-

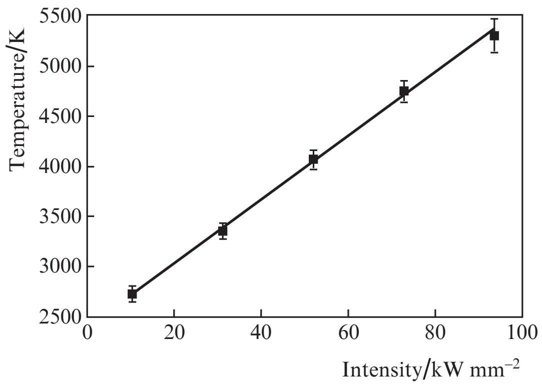

Figure 6. Dependence of the vapour-plasma plume temperature on the intensity of laser radiation.

tron density; e and m_e are the electron charge and mass; and k_B and h are the Boltzmann and Planck constants. Taking into account that there occurs only single ionisation (for titanium $V_1 = 6.82$ eV [13]) at the resultant temperatures and using the expression

$$\alpha = \sum \frac{N_m}{N} = \sum n_m \frac{V}{N}$$

for the degree of ionisation (V is the interaction volume) as well as the ideal gas equation, we rearrange the Saha equation to the following form:

$$\frac{\alpha^2}{1-\alpha} = \left(\frac{2\pi m_e}{h^2}\right)^{3/2} \frac{(k_B T)^{5/2}}{p} \exp\left(-\frac{eV_1}{k_B T}\right). \quad (4)$$

An appreciable reduction of the welding plume size with a lowering of the ambient pressure was observed in Ref. [14]. Relying on the previously confirmed data (see Refs [9, 12, 15]) and considering the fact that the plume does not broaden, the pressure p in formula (4) is assumed to be equal to the atmospheric one. The calculated dependence of the degree of ionisation on the intensity of laser radiation is plotted in Fig. 7. The highest degree of ionisation amounts to 0.015, and the welding plume is therefore a weakly ionised metal vapour.

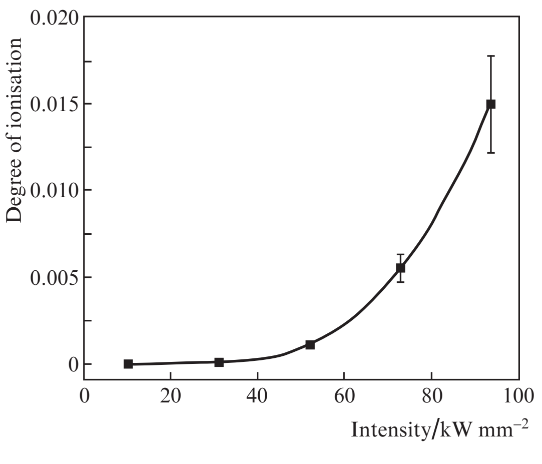

Figure 7. Degree of ionisation of the vapour-plasma plume as a function of the laser radiation intensity.

This is an important difference between this welding regime and the regime typical for CO_2 lasers, whereby there occurs an avalanche ionisation of the metal vapour and an optical breakdown occurs at a certain radiation intensity.

The free-electron density in the plasma (Fig. 8) may be determined from the equation of state of ideal gas:

$$n_e = \alpha n_0 = \alpha \frac{p}{k_B T}, \quad (5)$$

where n_0 is the density of Ti atoms (it is assumed that the plume consists of only titanium atoms near the metal surface).

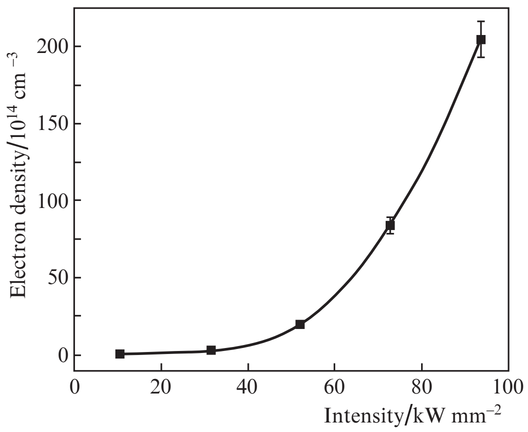

Figure 8. Free-electron density in the welding plume plasma as a function of the laser radiation intensity.

In the classical Lorentzian oscillator model, the coefficient of radiation absorption due to the inverse bremsstrahlung effect is represented in the form [14]

$$k_{ib} = \frac{2\sqrt{2}\pi}{\lambda} \times \left[\sqrt{\left(1 - \frac{\omega_p^2}{\omega^2 + \nu_c^2}\right)^2 + \left(\frac{\nu_c}{\omega}\frac{\omega_p^2}{\omega^2 + \nu_c^2}\right)^2} + \frac{\omega_p^2}{\omega^2 + \nu_c^2} - 1\right]^{1/2}, \quad (6)$$

where ω_p is the plasma frequency, $\omega_p^2 = n_e e^2/(\varepsilon_0 m_e)$; ν_c is the collision frequency, which contains the contributions from electron collisions with atoms (ν_{ea}) and ions (ν_{ei}):

$$\nu_c = \nu_{ea} + \nu_{ei}; \quad (7)$$

$$\nu_{ea} = \frac{8}{3\sqrt{\pi}} \sigma_c n_0 \sqrt{\frac{2k_B T}{m_e}}; \quad (8)$$

$$\nu_{ei} = \frac{e^4 \ln[12\pi n_e^{-1/2} e^{-3} (\varepsilon_0 k_B T)^{3/2}]}{3\varepsilon_0^2 \sqrt{m_e}} (2\pi k_B T)^{-3/2} (n_1 + n_2 + \ldots); \quad (9)$$

and $\sigma_c = \pi(r_1 + r_2)^2$ is the classical collision cross section for particles with radii r_1 and r_2. When $\omega \gg \omega_p$, which is fulfilled for a plasma produced in the processing of materials by solid-state laser radiation, formula (6) may be simplified by expanding it in a series in the small parameter $\omega_p^2/(\omega^2 + \nu_c^2) \ll 1$:

$$k_{ib} \approx \frac{\nu_c}{c} \frac{n_e e^2}{\varepsilon_0 m_e \omega^2} \sim \lambda^2 n_e^2 T^{-3/2}. \quad (10)$$

To numerically calculate the inverse bremsstrahlung coefficient for a wavelength of 1.07 μm, in practice advantage is taken of the simplified formula

$$k_{\mathrm{ib}} \approx 3.3 \times 10^{-41} n_{\mathrm{e}}^2 T^{-3/2}, \tag{11}$$

where n_{e} is taken in m^{-3} and T in Kelvins. The result of calculation is plotted in Fig. 9. The inverse bremsstrahlung coefficient amounts to 0.04 m^{-1}, i.e. for the specified intensities the absorption of laser radiation by the welding plume plasma is negligible at 5 mm above the metal surface.

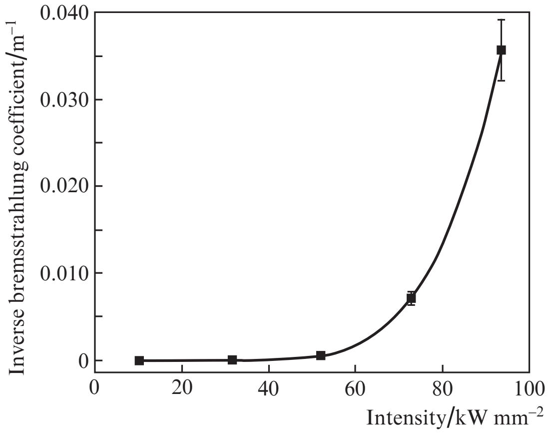

Figure 9. Dependence of the inverse bremsstrahlung coefficient for the vapour-plasma plume on the laser radiation intensity.

It is noteworthy that the titanium boiling temperature (3560 K) was attained for intensities of laser radiation above 40 kW mm^{-2}. This resulted in a steep rise in electron density, degree of ionisation and the inverse bremsstrahlung coefficient for laser radiation.

3.3. Dependence of the parameters of the welding plume on the height above the metal surface

We performed several measurements of the emission spectrum of the welding plume at different heights above the metal surface at the same intensity of 52 kW mm^{-2} with subsequent calculation of the temperatures. The dependence of the welding plume temperature on the height above the metal surface is plotted in Fig. 10. The wide spread in temperature values above 20 mm is due to the transient character of the flow of the metal vapour incoming to the caustic of laser radiation, which results in its nonuniform heating. We calculated the inverse bremsstrahlung coefficient from formula (11) and performed integration of the loss along the entire plume. The total absorption by the welding plume plasma is estimated at less than 1%, i.e. the plasma exerts no effect on laser radiation.

The majority of works on the investigation of laser welding with the use of solid-state fibre lasers are concerned with the welding of steel. In view of the investigations performed in Refs [12, 15, 16], it is possible to compare the results on the welding of steel and titanium by high-power fibre laser radiation. In steel welding, the upper part of the plume was a flame rather than the flow of vapour particles. This was because the steel vapour would instantly burn in the caustic of the laser

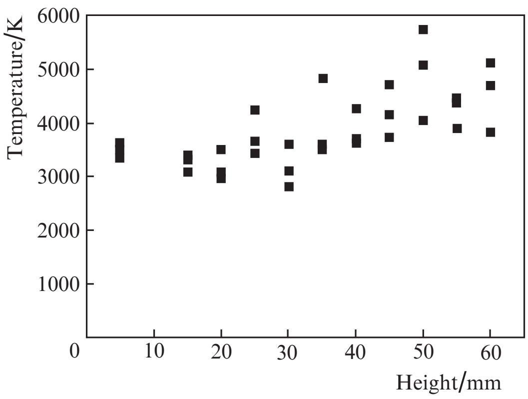

Figure 10. Height dependence of the welding plume temperature in the welding of titanium.

beam unlike the vapour of refractory titanium. The parameters (the degree of ionisation, the temperature, the inverse bremsstrahlung coefficient for laser radiation) of the welding plume plasmas in the welding of steel and titanium turned out to be equal by the order of magnitude. For steel, the effect of the flow of small in-plume particles on laser radiation was experimentally demonstrated, which gave rise to power modulation with an average amplitude of ~9% at frequencies of up to 2–3 kHz. This modulation may be responsible for an appreciable impairment of the stability of the weld seam. Similar research for titanium is yet to be carried out.

4. Conclusions

We have determined the properties of the vapour-plasma plume produced in the welding of VT-23 titanium alloy plates by high-power fibre laser radiation. The video made with a high speed camera shows that a 3-cm-high welding plume is formed above the metal surface, the plume periodically tilting in the direction of welding. Observed in the laser beam caustic is a flow of small particles having a size of a fraction of a millimetre, which travel downwards with acceleration, at a velocity of up to 10 m s^{-1}. The use of a cross plume in the direction of welding does not permit suppressing efficiently the adverse effect of metal vapour on radiation. The titanium boiling temperature is attained for a laser radiation intensity above 40 kW mm^{-2}, which results in a steep rise in electron plasma density, degree of ionisation and inverse bremsstrahlung coefficient. In titanium welding by high-power laser radiation, the plasma of the welding plume is in a weakly ionised state (the degree of ionisation, $\alpha < 2 \times 10^{-2}$) and the radiation absorption is negligible (the inverse bremsstrahlung coefficient, $k_{\mathrm{ib}} < 4 \times 10^{-2}$ m^{-1}): the total absorption is under 1%.

The results of our work may be used to make a system for real-time measurements of welding plume parameters for the purpose of improving the stability of laser radiation–metal interaction and raising the quality of welded joints.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 14-02-00369-a) and the Ministry of Education and Science of the Russian Federation (Unique Project Identifier: PNIER RFMEFI58214X0004).

References

1. Gapontsev V.P. *Proc. 12th Int. Laser Physics Workshop (LPHYS`03)* (Hamburg, 2003) Paper PS3.
2. Petrovskiy V.N., Prokopova N.M., Shcheglov P.Yu., et al. *Laser Phys. Lett*., **7**, 396 (2010).
3. Contag K., Karszewski M., Stewen C., Giesen A., Hugel H. *Kvantovaya Elektron*., **28**, 139 (1999) [*Quantum Electron*., **29**, 697 (1999)].
4. Speiser J. *J. Opt. Soc. Am. B*, **26**, 26 (2009).
5. Vedenov A.A., Gladush G.G. *Fizicheskie protsessy pri lazernoi obrabotke metallov* (Physical Processes in Laser Machining of Metals) (Moscow: Energoatomizdat, 1985).
6. Arutyunyan R.V., Baranov V.Yu., Bol'shov V.A., et al. *Vozdeistvie lazernogo izlucheniya na materialy* (Action of Laser Radiation on Materials) (Moscow: Nauka, 1989).
7. Eriksson I., Kaplan A. *Proc. 28th Int. Congress on Applications of Lasers & Electro-Optics* (Orlando, USA, 2009) p. 1419.
8. Kawahito Y., Matsumoto N., Mizutani V., Katayama S. *Sci. Technol. Weld. Joining*, **13**, 744 (2008).
9. Kawahito Y., Mizutani M., Katayama S. *Trans. JWRI*, **37**, 13 (2008).
10. Shcheglov P.Yu., Uspenskiy S.A., Gumenyuk A.V., et al. *Laser Phys. Lett*., **8**, 475 (2011).
11. Kop'ev V.A., Kossyi I.A., Magunov A.N., et al. *Prib. Tekh. Eksp*., (3), 1 (2006).
12. Petrovskii V.N., Uspenskii S.A., Shcheglov P.Yu., Gumenyuk A.V., Rethmeier M. *Yad. Fiz. Inzh*., **2**, 159 (2011).
13. Zefirov N.S. *Khimicheskaya entsiklopediya* (Chemical Encyclopedia) (Moscow: Izd. 'Bol'shaya Rossiiskaya Entsiklopediya', 1995) Vol. 4.
14. Katayama S., Yohei A., Mizutani M., Kawahito Y. *Phys. Procedia*, **12**, 75 (2011).
15. Shcheglov P.Yu. *Cand. Diss.* (Moscow: NRNU MEPhI, 2011).
16. Uspenskii S.A., Shcheglov P.Yu., Petrovskii V.N., Gumenyuk A.V., Rethmeier M. *Opt. Spektrosk*., **115** (1), 160 (2013).