Spectral diagnostics of a vapor-plasma plume produced during welding titanium with a high-power ytterbium fiber laser

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Abstract. This work is devoted to the research of welding plume during high power ytterbium fiber laser welding of a titanium alloy in the Ar shielding gas environment. High speed video observation of a vapor-plasma plume for visualization of processes occurring at laser welding was carried out. The coefficient of the inverse Bremsstrahlung absorption of laser radiation is calculated for a plasma welding plume by results of spectrometer researches. The conclusion deals with the impact of plasma on a high-power fiber laser radiation.

1. Introduction
Ytterbium fiber laser production technology develops high- and ultra high-power laser radiation at a wavelength of 1.07 µm with high beam quality. Therefore the fiber lasers are of considerable interest as an energy source in deep penetration metal welding processes, when the heat input power density is the major parameter setting the weld depth/width ratio and the process velocity. In welding with traditionally used 10.6 µm wavelength CO₂ laser radiation this parameter was limited by the plasma shielding effect, i.e. by the absorption and refraction of the laser radiation in the welding plasma plume. As the wavelength of ytterbium fiber laser radiation is about 10 times shorter, the plasma absorption, being inversely proportional to λ², should be negligibly small. However, the diffraction effects, which worsen the power stability and the beam focusing quality, can limit the technical advantages of the fiber laser [1].

2. Experimental setup
Welding experiments were carried out in a robot welding cell (fig. 1) based on 10 kW ytterbium fiber laser (1). Radiation was delivered by a transport fiber (2) (200 µm core dia.) to the optical processing head (3) and focused using a lens having a focus distance of 200 mm. The diameter of the focused beam on the metal surface (4) was 0.35 mm. A robotic arm (5), holding the welding optical head (3), provided the independent discrete horizontal shift of the high power fiber laser beam focus area in two mutually perpendicular directions with the accuracy 0.1 mm. The positioning stage supplied also a possibility of the movement of the specimen near the chosen focus position with a xed speed as well as the vertical shift of the specimen, when the distance between the metal surface (4) and the focusing lens is kept constant with the accuracy...
0.1 mm. To determine the parameters of the welding plasma spectrometer ASP-150TF (6) was used with a fiber-optical input with the possibility of tuning the spectral range and spectral resolution of the spectrometer 0.09 nm. Measurements were carried out at a distance of 5 mm with aperture (7) above the sample surface (4) of titanium 6 mm thick. We used a high speed camera (8) for visualization processes during laser welding.

3. Results of high-speed video observation
The weld plume was observed with a high-speed video camera at frame rate 17000 fps. It was shown that besides the weld plasma there was a stream of small particles of condensed vapor, which almost agreed geometrically with the laser beam caustic and accelerated up to 10 m/s (fig. 2a). When we were using cross-jet the plume, this stream of particles was seen too. Cross-jet is not effective, because vapor reflect at robot, wall and another part of welded details back to caustic (fig. 2b). It is necessary to use additional cross-jet, venting for reducing the amount of steam in the caustic.

The stream of metal vapor particles spreads along caustic of laser radiation also during welding with the angle 15° to normal (fig. 2c). We state, that after vaporization particles of
metal fly to caustic laser and heat on side of laser radiation. It explains sloped direction of stream particles upper welding plume. There is a strong stream of metal particles in caustic beam, but in the case of steel \[2\](fig. 2d), there was burning of vapor. It is explained due to different thermal properties of these metals. There are no vapors and metal particles in caustic laser beam during welding of steel and using cross-jet is more effective in this case, in contrast with welding of titanium.

4. Result of spectrometric research
To study the welding plume using the spectral pyrometry method \[3\] a grating spectrometer with a fiber-optic input and a silicon CCD array was used to record the spectrum in the range of 200-1160 nm. The lineup includes 2048 pixels. The spectral resolution of the spectrometer is 1.4 nm.

Experimental spectral intensity \(I(\lambda, T)\) of thermal radiation (fig. 3a), i.e. power radiated by a unit surface in unit spectral range is:

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

where \(C_1 = 37418 \text{ W} \cdot \mu\text{m}^4/\text{cm}^2\), \(C_2 = 14388 \mu\text{m} \cdot K\), \(\varepsilon\) - emission coefficient, wavelength expressed in micrometers, the intensity in \(\text{W/cm}^2 \cdot \mu\text{m}\). For the Wines region \((C_2/\lambda T \gg 1)\) the previous expression after the transformation takes the form

\[
\ln \left( \lambda^5 I \right) - \ln (\varepsilon C_1) = -\frac{C_2}{\lambda T}
\]  

If \(\varepsilon = \text{const}\), a section of the spectrum in this regions linear in the coordinate plane \((X,Y)\), where \(X = \ln(\lambda^5 I)\) and \(Y = C_2/\lambda\), and the slope depends on the temperature of the plume (fig. 3b). The dependence \(\varepsilon(\lambda)\) appears only logarithmically. If \(\varepsilon\) changes in the selected range permanently or only slightly, its influence is manifested in a parallel shift straight along the \(X\) axis, but the slope and the desired temperature remain unchanged. Detailed description of the technique for measuring the temperature of the flame is represented in the works \[3, 2\].

![Figure 3](image_url)

**Figure 3.** Panoramic emission spectrum of the plasma plume using shielding gas argon (a); spectra of plasma plume rebuilt in the new coordinates (b).

Based on the spectroscopic data to calculate the degree of ionization (fig. 4b) using Saha equation taking into account single ionization at a gas pressure of 1 atm:
\[ \frac{\alpha^2}{1 - \alpha} = \left( \frac{2\pi m}{h} \right)^{3/2} \frac{(kT)^{5/2}}{p} \exp \left( -\frac{eV_i}{kT} \right) \]  \hspace{1cm} (3)

where, $\alpha$ is ionization degree, $m$ is mass of electron, $V_i$ is ionized voltage, $e$ is electronic charge, and $p$ is gas pressure.

Electron density (fig. 4c) was calculated for these temperatures, using the equation of state of ideal gas, according to the equation

\[ n_e = \frac{\alpha p}{kT} \]  \hspace{1cm} (4)

From the above given parameters of the welding plasma state the inverse Bremsstrahlung coefficient (fig. 4d) can be calculated for the ytterbium fiber laser wavelength [4, 5] (1.07 µm) by equation

\[ k_{ib} \approx \frac{\nu_c n_e e^2}{cm_e \omega} \approx 3.3 \cdot 10^{-41} \frac{n_e^2}{T^{3/2}} \]  \hspace{1cm} (5)

where $\nu_c$ is the collision frequency, $c$ - speed of light, $\omega$ - laser radiation frequency.

**Figure 4.** Temperature dependence on power density (a), ionization degree dependence (b), electron density dependence (c), coefficient of inverse Bremsstrahlung absorption dependence (d).
From the obtained absorption coefficient value it can be concluded that the welding plasma during the deep penetration metal welding with high power and high brightness solid-state lasers has practically no influence on the laser radiation and on the weld quality, even with a laser power density of up to 50 kW/mm$^2$. Temperature of boiling titanium (3560 K) [6] is achieved when power density is $\sim 20$ kW/mm$^2$. It leads to sharp increasing of ionization degree, electron density and coefficient of inverse Bremsstrahlung absorption. In case of welding steel listed parameters except the last one have values of the same order, but coefficient of the inverse Bremsstrahlung is less at two orders.

5. Conclusion
The features of the vapor-plasma plume formed by welding titanium alloy VT-23 with a high power fiber laser were determined. On frame of high-speed video it is shown that 3 cm high welding plume is formed on the metal surface, and it varies periodically in the welding direction. Stream of the fine particle size fractions of a millimetre is observed in the caustic of the laser beam, moving down at a speed of 15 m/s. System of cross-jet in the direction of welding cannot effectively deal with the negative impact of the metal vapor radiation. Boiling titanium is achieved when the laser power density is higher than 40 kW/mm$^2$, which leads to a sharp increase in the density of free electrons in the plasma, the degree of ionization and an inverse Bremsstrahlung absorption. Plasma plume is in a weekly ionized state (degree of ionization $\alpha \leq 2 \cdot 10^{-2}$) and negligible absorbs radiation (coefficient of inverse Bremsstrahlung $k_{ib} \leq 4 \cdot 10^{-2}$ m$^{-1}$). The total absorption by plasma is less than 1%.

Acknowledgments
This work was supported by the RFBR (project number 14-02-00369-a) and the Ministry of Education and Science of the Russian Federation (unique identifier PNIER RFMEFI58214X0004).

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