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A. Poueyo, L. Sabatier, G. Deshors, R. Fabbro, A. de Frutos, et al.. EXPERIMENTAL STUDY OF THE LASER INDUCED PLASMA IN WELDING CONDITIONS WITH CONTINUOUS HIGH POWER CO2 LASERS. Journal de Physique IV Proceedings, 1991, 01 (C7), pp.C7-183-C7-186. 10.1051/jp4:1991748 . jpa-00250990

HAL Id: jpa-00250990

<https://hal.science/jpa-00250990>

Submitted on 1 Jan 1991

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EXPERIMENTAL STUDY OF THE LASER INDUCED PLASMA IN WELDING CONDITIONS WITH CONTINUOUS HIGH POWER CO₂ LASERS

A. POUETO, L. SABATIER, G. DESHORS, R. FABBRO, A.M. de FRUTOS*, D. BERMEJO** and J.M. ORZA**

*Laboratoire d'Applications des Lasers de Puissance (Unité mixte E.T.C.A./C.N.R.S.),
16 bis avenue Prieur de la Côte d'Or, F-94114 Arcueil cedex, France*

**Universidad de Valladolid, Dpto. de Física Aplicada III, Spain*

***Instituto de la Estructura de la Materia, C.S.I.C. Madrid, Spain*

Abstract - It is well known that the metallic plasmas observed in laser welding play an important role in energy transfer during laser materials processing. They are critical to understanding energy transport to the workpiece. This paper reports an experimental investigation characterizing the plasma using visible emission spectroscopy. These experiments provided the electron density and temperature distributions ($\sim 10^{17} \text{ cm}^{-3}$ and 6000-7000 °K). The experimental data are then used to determine laser attenuation and refraction as the beam propagates through the plasma column. These results are compared with direct absorption measurements where an integrating sphere has been used, and with a numerical simulation. It was observed that the absorption coefficient is closely correlated to the spatial and temporal behaviour of the plasma and the effect of refraction is of primary importance for laser processing when using other gases than helium at high laser intensity.

1. INTRODUCTION

A wider use of laser welding in an industrial point of view requires an understanding of the interaction between laser and matter which ought to absorb an ever increasing proportion of energy.

For low laser intensities, it is commonly known that laser coupling is increased whenever a plasma is present in the interaction area. On the other hand, for high laser intensities, the plasma may shield the workpiece if no appropriate assisting gas such as helium is used. In order to understand and improve the procedure, we determined the microscopic parameters of a plasma created by two different lasers whose output power ranged from 1 to 15 kW and whose beam was focalized onto pure iron targets. The first one delivered an output intensity of about 1 MW/cm² and the other one delivered an intensity close to 5 MW/cm². Spectroscopic studies of plasma emission in the visible wavelength range were carried out for the derivation of both electronic temperature and density, and of the scale length as well. The knowledge of these parameters allowed us to get an estimation of the mechanisms of coupling. Using a simple technique where the reflected light is collected by an integrating sphere, we measured this coupling precisely and got its temporal resolution in the same time.

Moreover, we considered the refraction of the laser due to the plasma column. We can notice that the nature of the shielding gas is of a great importance at high intensities: indeed, the laser-supported-combustion waves are completely different and the refraction effect is enhanced using argon for example.

2. EXPERIMENTAL SET-UP AND PROCEDURES

A general view of the experimental set-up for the measurement of the total reflectivity during the interaction and for the spectroscopic measurements is presented in ref 1. The visible-range photodiode followed the space-integrated emission of the plasma plume, and a length of only 1 to 2 mm above the target surface was monitored.

In order to determine the plasma parameters, we used the spectroscopic arrangement described in reference 2. Concerning the derivation of the temperature, we used the 442.73 nm and 442.25 nm lines from the Fe(I) plasma spectrum. From both absolute emissivities of the lines of interest, we could get a straightforward determination of the plasma temperature. The derivation of the electronic density was based on the Stark broadening effect. We chose the 538.337 nm line, just as in ref.3, because in literature 4-5-6, its Stark coefficient was given with a much better accuracy than for any other one. Furthermore, this line under study turned out to be relatively isolated in the spectrum⁷. Moreover, before anything, some experimental conditions were checked out: thermodynamic equilibrium, selfabsorption for the line of interest, and measurement of the instrumental function³.

For the absorption measurements, we used an integrating sphere. The diagnostic was based on the signal recorded by the visible range photodiode which visualised the plasma emission, and by the signal of the CO₂ reflected radiation. This

solution allows to follow the coupling with a characteristic time limited by the transit time of the photons within the sphere, which is typically of the order of a few nanoseconds. These experiments were carried out with different laser intensities and the nature of the shielding gas was changed as well.

3. EXPERIMENTAL RESULTS

3.1. Spectroscopic results.

The experiments were performed in pulsed conditions for the sake of simplicity: a 200 ms pulse was released when the 25 kW laser was used and a 10 ms one with the 1 kW laser. However, some experiments were carried out with a target moving at 20 mm/s, this situation corresponding quite satisfactorily with a realistic treatment. The results agree with each other: this confirms the validity of the static plasma study. The spatial variation of the plasma parameters along the laser axis are displayed in figures 1 and 2.

We did not perform Abel's deconvolution on these experimental results, but numerical simulations were conducted in the aim of getting a more precise estimation of the effect of integration along the diameter of the plasma column.

Several realistic Ne and Te radial profiles were tested. A numerical integration of the emissivity of the line under study along the observation axis gives a mean half width of the theoretical Ne profile and the corresponding electronic density derived this way can be compared with the theoretical density on the axis. For the different tested electronic density profiles, it appeared that this overall axial density is about half of the maximum density along the profile. In a similar way but considering the intensity ratio of the lines of interest, the electronic temperatures integrated and theoretical were found to be quite close.

All the experiments at 5 MW/cm^2 used helium as shielding gas at a blowing rate of 5 l/min. On the other hand, at lower intensities, different gases were considered. Obviously, under such experimental conditions, the nature of this shielding gas does not have a significant influence on both temperature and density. Besides, it was impossible to use another gas than helium at high power intensities. A shielding plasma which became detached from the workpiece could be observed and the visible photodiode which was visualizing a volume of about 1 mm^3 on the target surface recorded an intensity peak only in the beginning and at the end of the laser impulsions, whenever argon or nitrogen was used.

These results led to an estimate of the absorption within the plasma column. The Inverse Bremsstrahlung absorption coefficient is given by the following equation:

$$K(\text{cm}^{-1}) = 3.10^{-35} \frac{\text{Ne}^2 (\text{cm}^{-3})}{\text{Te}^{3/2} (\text{eV})}$$

Fig 1: Temperature profile along the laser beam axis at 1 and 5 MW/cm^2

Fig 2: Electronic density profile along the laser beam axis at 1 and 5 MW/cm^2

Using the results from figures 1 and 2, the integral of K along the incoming light path leads to a 50% transmission for a 15 kW incident power and 92% in the case of 1 kW. This indicates that the plasma is rather transparent for the laser beam, whenever helium is used as shielding gas. Direct reflectivity measurements agree with this, as we shall see it in the following paragraph.

3.2. Reflectivity results.

With the help of the set-up we used in this experiment, correlations between photodiode and reflectivity recordings, with a 1 kW focalized energy, could be detected. Figure 3 displays these correlations: any local maximum in the photodiode recording corresponds to a local minimum in reflectivity. From this observation, by measuring the reflectivity without plasma (R_v) and in the presence of plasma (R_p), when no key-hole is present, we can evaluate the plasma transmission¹, which is given by:

$T = \left(\frac{R_p}{R_v} \right)^{1/2}$. We obtained a transmission coefficient of about 75% in our experimental conditions (fig.3)

Fig 3: Time dependance of target reflectivity and of the visible luminosity of the plasma Incident laser intensities : $1,3 \cdot 10^6 \text{ W/cm}^2$

4. DISCUSSION

Another crucial point of interest in this study is the estimate of the effects of refraction by the plasma column.

The knowledge of the electronic density allows us to estimate the refraction index gradient. From this result, we can then have an idea of the importance of the defocalisation of the laser beam at the target surface. The refractive index gradient is approximated by: $\nabla n = \frac{1}{2 N_c} \nabla N_e$, where N_c is the critical density, which is equal to 10^{19} cm^{-3} for the CO_2 laser wavelength.

The deflection angle of the laser beam propagating along the plasma column is then given by:

$\theta = \frac{\nabla n}{n} L = \frac{L}{2 N_c} \nabla n = \frac{N_e}{2 N_c} \frac{L}{R}$ where L is the length of propagation corresponding to the length of the plasma and R is the characteristic gradient length of the refraction index which typically is the radius of the plasma column.

In a first step, we shall consider the case of helium as shielding gas, which leads to a plasma localized upon the target. Using typical values of these parameters ($L=20 \text{ mm}$, $R=5 \text{ mm}$, $N_e=5 \cdot 10^{16} \text{ cm}^{-3}$), we obtained $\theta \approx 0.01 \text{ rad}$. The initial focal radius was about $250 \mu\text{m}$, and therefore, a 80% increase in the focal radius was expected due to the refraction effect. This corresponds to a 70% decrease in the mean intensity on the target surface.

In a second step, it is quite interesting to consider the reflectivity results during the welding process with argon and nitrogen as shielding gases (the incident intensity being set up at 5 MW/cm^2).

Fig. 4 : Effect of the shielding gases. Curve (1) corresponds to a 200 ms laser pulse (a.u). The intensity on the target surface is about 5 MW/cm^2 . Curve (2) is a target reflectivity record. Curve (3) is a photodiode signal (a.u). It can be seen that the plasma is only present on the target surface in the beginning and at the end of the laser pulse.

In these conditions, the absorption measurements (fig.4) show that only 50% of the incident laser light is absorbed. Moreover, the corresponding photodiode signal (fig.4) shows that the plasma is no longer existing at the workpiece surface. In fact, the plasma is localized at several centimeters above the target surface. Furthermore, in these conditions, we observed that the surface was slightly altered by the laser radiation, with no keyhole formation. As only half of the incoming laser energy is absorbed by the intense plasma which gets detached from the surface, this means that an important fraction of the laser beam is refracted while propagating across the plasma, and is consequently strongly defocused at the target surface. Eventually, these results indicate that this detached plasma mainly induces a strong effect of defocusing of the laser light at the target surface, and not a strong shielding effect as it is usually admitted.

Some numerical simulations were carried out to show the influence of the plasma on the laser propagation. The laser beam is divided into 100 beams which propagate through the plasma plume. The other parameters are the focal length, the focalisation, the plasma density profile, the plasma location. The absorption of the incoming light was not considered in the calculation of the intensity distribution on the target surface. The results obtained are presented in figure 5. It becomes obvious that the plasma strongly modifies the laser intensity distribution while propagating along the plasma column.

Fig 5: Effects of refraction: intensity distribution on the surface target. For a similar electronic density profile, the decrease of the intensity on the target in the focal volume is enhanced when Argon is used as shielding gas. The photograph show the two different plasmas obtained using Helium or Argon.

5.CONCLUSION

A spectroscopic study has been carried out in the aim of derivating the plasma parameters in laser welding conditions. From these results, the transmission of the plasma column was calculated. Direct reflectivity measurements were also performed. When helium was used as shielding gas, it appeared that the plasma does not play a significant role in the absorption of the laser radiation, even at high intensities, as it is usually thought. Nevertheless, the effects of refraction seem to play an important role in all cases and can probably explain the high level of the observed plasma fluctuations.

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