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Measurement of the influence of the vapor plume on laser beam characteristics during laser beam welding

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Abstract

During deep penetration laser welding a plume of hot metal vapor and particles is ejected by the keyhole. This vapor plume interacts with the incident laser beam by the means of scattering, absorption and phase front deformation. Within this work we present a measurement setup for diagnostics of the interaction characteristics. The setup combines a high-speed video with the measurement of the emitted spectrum of the vapor plume. This allows the location and differentiation between different zones of interaction between the laser beam and the plume. This knowledge will assist in the avoidance of weld defects which are induced by the vapor plume.

Keywords: Laser welding; vapor plume; beam characteristics

1. Introduction

Deep penetration laser welding is a well-established process in industry. During the formation of the welding keyhole a small percentage of the material is evaporated. Part of this vapor is emitted from the keyhole opening in the workpiece, whereupon it can interact with the incident laser beam. When welding with a high power CO_2 Laser, the metal vapor is heated until a plasma is formed, as shown by Miyamoto et al., 1997. For solid-state laser welding, the gaseous metal vapor only marginally absorbs the processing laser, forming a weakly ionized plume as shown by Miyamoto et al., 1997. In general, the vapor above the keyhole and surrounding the beam caustic of the processing beam cools down rapidly and forms a cloud of small

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particles. The size of the particles, as well as the particle density within the cloud, have been investigated by Shcheglov et al., 2011. The vapor plume and particle cloud interact with the incident laser beam by the means of scattering and absorption, see Michalowski et al., 2007. Another issue arises from refractive index gradients, which might be induced by both hot metal vapor as well as air which is heated by the condensing vapor. These refractive index gradients cause deformations of the phase front and thus lead to a change in the laser intensity distribution at the workpiece. This is especially important for beam shaping technologies, which are based on interference patterns. These technologies need a particularly stable phase front propagation in order to get the desired intensity profile at the workpiece.

To properly resolve the issues that arise from the vapor plume - laser beam interaction, a better understanding of the properties of the vapor plume is needed. Most of the previous research has focused on the properties of the general vapor plume and particle cloud. For example, Greses et al., 2004, Michalowski et al., 2007 and Shcheglov et al., 2011, measured the particle size and resulting attenuation of the laser beam. Uspenskiy et al., 2013, used an additional coaxial probe laser beam to qualitatively show scattering in the particle cloud, and additionally measured the temperature of the plume.

In order to investigate the plume-beam interaction, the approach presented here uses the thermal emission and scattering properties of the hot vapor and particle cloud. This is important, since the incident laser beam, within its caustic, influences the properties of the plume and particle cloud and thus the interaction mechanisms. In a first step, the thermal emission of the plume was investigated by high-speed imaging with different optical filters. Secondly, a spectrometer was used for analyzing the wavelength-dependent emission. This gave qualitative information about the general behavior, temperature and composition of the vapor plume.

2. Experimental setup

The experimental setup is shown in Fig. 1. Sheets of stainless steel (1.4301) 4 mm thick, were welded with a TruDisk 16002 with a wavelength λ = 1030 nm. A fiber diameter of 600 µm was used. Using focal lengths f_{coll} = 200 mm for the collimation and f_{focus} = 400 mm for the focal lens, the focus diameter was 1.07 µm. The beam waist was positioned on the surface of the sample. With a laser power of 5.5 kW and a feed rate of 2 m/min full penetration welding was achieved. The processing beam was inclined 5° in the feed direction.

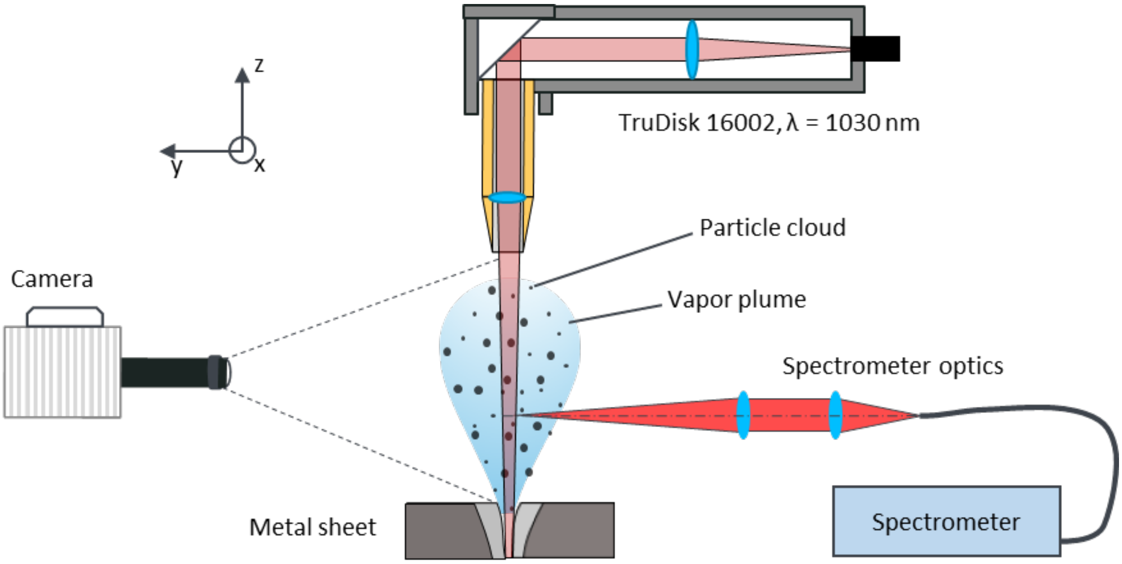

Fig. 1. Schematic measurement setup for the thermal emission of the vapor plume and scattering from the particle cloud during deep penetration welding of stainless steel.

As sketched in Fig. 1, a high-speed camera was placed horizontally to the metal sheet, which allowed the recording of the whole plume. The camera was an OS8 from IDT with the framerate set to 8000 Hz. The records were carried out without a filter, with a shortpass filter $\lambda_{pass} < 950$ nm and a bandpass filter at 1030/10 nm in front of the camera. In addition, a fiber coupled spectrometer OceanOptics 4000 was used with a collimation lens and focal lens with focal lengths of 50 mm and 300 mm, respectively. Together with the fiber diameter of 200 µm this results in a measurement spot diameter of 1200 µm. As sketched in Fig. 1, the measurement spot of the spectrometer coincided with the axis of the processing beam, in perpendicular alignment, at different heights above the work piece.

3. Results

The high-speed imaging setup enabled a good temporal resolution combined with a large field of view to capture the thermal emission and scattering of the vapor-beam interaction. For the analysis of the high-speed videos, an average image of 4000 images was created, which corresponds to a time period of 0.5 s, after the welding process achieved steady state condition. Fig. 2 shows the average image for the respective filter settings, Fig. 2a without a filter, Fig 2b with a shortpass filter $\lambda_{pass} < 950$ nm and Fig. 2c a bandpass filter at 1030/10 nm. Considering the spectral range of the camera sensor, which is roughly 200 - 1100 nm, and the narrow spectral gap between the shortpass and the bandpass filter used in Fig. 2b and Fig. 2c, it can be assumed that the average image in Fig. 2a is approximately equal to Fig. 2b plus Fig. 2c.

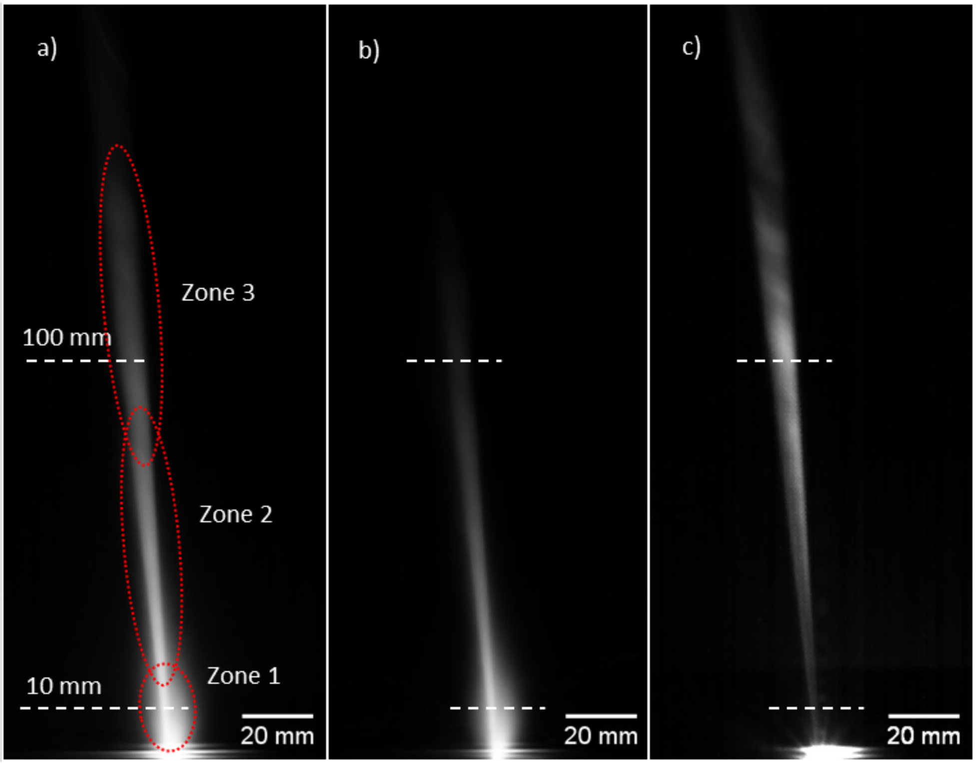

Fig. 2. Average images of the vapor plume during full penetration welding of stainless steel after different filter settings for a time period of 0.5 s. a) without filter, b) with a shortpass filter λ_{pass} = 950 nm and c) with bandpass filter at 1030/10 nm. P = 5.5 kW, v = 2 m/min.

During the process, the keyhole ejects vapor in a strongly variable manner. In the average image this can be seen by the increased grey values within zone 1 in Fig. 2a and Fig. 2b. In and above this area the caustic of the incident laser beam can be identified in the average image. In Fig 2a the brightness within the area of the caustic decreases with increasing distance to the surface of the sample. Using the shortpass filter $\lambda_{pass} < 950$ nm, it can be assumed that the light emitted from the vapor and particle cloud in Fig. 2b comes from thermal emission and not from the scattered laser light with a wavelength of $\lambda = 1030$ nm. This thermal emission is mainly concentrated within the zones 1 and 2. In contrast, Fig. 2c shows the beam caustic by capturing only scattered laser light at the wavelength of $\lambda = 1030$ nm. This is ensured by the narrow bandwidth of $\Delta\lambda = 10$ nm of the applied bandpass filter. The analyzation of Fig. 2c states, that scattered laser light seems to have a maximum around 100 mm above the surface and is the dominant source of optical emission in zone 3.

Fig. 3 shows the emission of the vapor plume, captured by the spectrometer at a height of 10 mm and 100 mm above the sheet surface. The spectrum measured 10 mm above the keyhole shows a strong emission in the visible wavelength range, see Fig. 3a. There are also strong line emissions between 500 nm - 550 nm which indicate a high temperature of the vapor or particles. 100 mm above the keyhole the spectrum shows a lower emission in the visible range of 380 nm – 780 nm, see Fig. 3b. Contrary to the spectrometer measurement closer to the keyhole, see Fig 3a, this spectrum features a significant peak at 1030 nm. This indicates stronger scattering of the incident laser beam in zone 3, compared to zone 1, which proves the findings resulting from Fig. 2c.

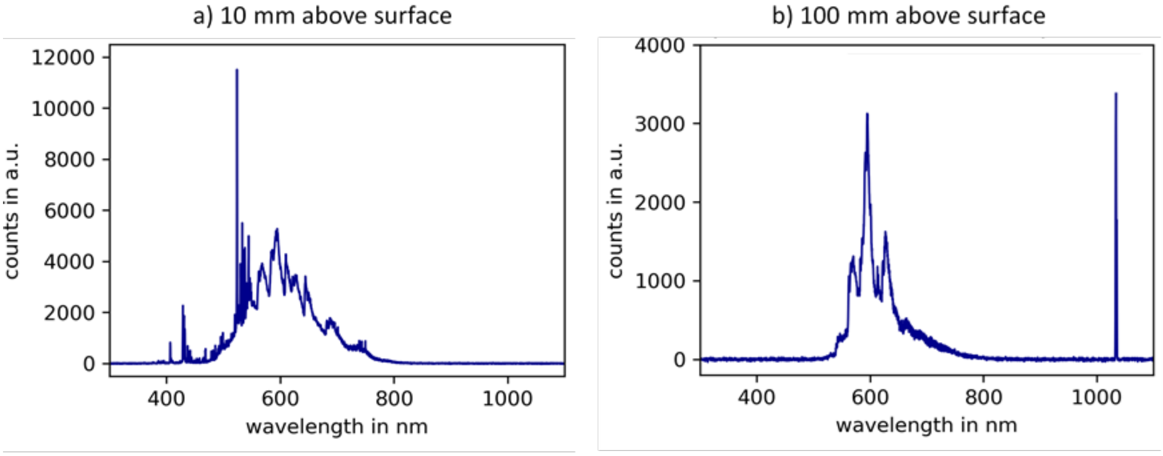

Fig. 3. Recorded raw spectra from the vapor plume a) 10 mm and b) 100 mm above the keyhole.

4. Discussion

The measurements indicate a change in the properties and behavior of the vapor plume and particle cloud within the caustic of the incident laser beam. The vapor in zone 1, that is emitted directly from the keyhole, shows strong atomic line emission in the spectrometer measurement of Fig. 3a and a very high brightness in the high-speed images of Fig. 2a and Fig. 2b compared to the visible plume within the caustic in zone 2 and 3, as presented in Fig. 2a. Assuming a correlation between the intensity of the thermal emission in the visible spectrum and the temperature of the vapor plume and particle cloud, it can be taken that the vapor is colder with increasing distance from the keyhole, until the emission falls below the sensitivity of the measurement setup. Both, the average image in Fig. 2c and the spectrum in Fig. 3b clearly show scattered laser light at the formed particle cloud in zone 2 and 3.

One explanation for the low scattering close to the keyhole is the high laser intensity of the incident beam. The focused laser beam might prevent the gaseous vapor from the formation of particles, or reheat and evaporate particles that previously formed beneath the caustic. Further up, in the zone 3 of Fig. 2a, it is presumed that the laser intensity is low enough for particle formation, which agrees well with the observed scattering in both Fig. 2c and Fig. 3b.

5. Summary

In this work, the thermal emission and the scattered light of the incident laser beam were captured. The use of different optical filters allowed the distinction between scattered light and thermal emission. The average images of the high-speed camera showed zones with different optical emission behavior. This in turn indicates locally different mechanisms of interaction between the vapor plume, the particle cloud and the incident laser beam. Additionally, spectrometer measurements confirmed the source of the optical emission. The thermal emission and therefore the temperature of the vapor plume decreases, with increasing distance to the keyhole. In the meantime, particle formation leads to increased scattering of laser light reaching its maximum in this case at around 100 mm above the keyhole.

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