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Autocorrelation analysis of plasma plume oscillations in deep penetration laser welding

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Abstract

The light emissions of plasma plume in deep penetration laser welding are typically characterized by irregular short-time pulses. Their timing is closely related to the dynamics of the keyhole formed within the workpiece and the surrounding weld pool. The nature of pulses limits the use of Fourier analysis because in most cases the frequency spectrum corresponds only to a colored noise. In this paper we present a study of the plasma plume oscillations using an autocorrelation function. We show that the autocorrelation function is an efficient tool to detect period of oscillations which are typically in the order of milliseconds. Finally, we compare the characteristics of autocorrelation function and the geometry of resulting welds carried out on a 2 kW Yb:YAG laser welding machine for the steel workpiece and various welding parameters settings.

Keywords: laser welding; plasma plume oscillations; autocorrelation analysis

1. Introduction

The deep penetration laser welding of metals is accompanied by the emergence of the keyhole filled with the laser induced plasma. It flows out of the keyhole and forms a bright plasma plume above the keyhole opening. The experimental observations show that the light emissions generated by the plasma plume have pulsed character indicating continuous oscillations of its size.

In recent years, the light emissions accompanying laser welding process have been studied with regard to possible applications in welding process diagnostics. Nakamura et al. (2000) have studied the intensity oscillations through the frequency analysis and have shown that the power spectrum has a noise character.

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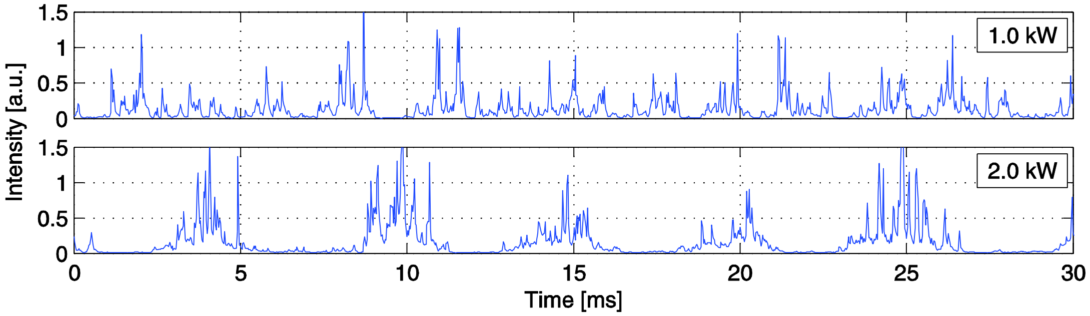

Fig. 1. Plasma bursts observed as the short-time pulses of the light emissions. Welding conditions: 6 mm stainless steel, argon shielding gas, laser power 1.0 and 2.0 kW, welding speed 10 mm/s.

Szymanski et al. (2001) have revealed that the time-varying intensity of acoustic and light emissions corresponds to the deterministic chaos. Kawahito et al. (2008) have used spectroscopy to show that the plume consisting of weakly ionized plasma is repeatedly generated from a keyhole in the form of short bursts with the period in the order of microseconds. Wang et al. (2012) have used a high-speed imaging to conclude that the plasma bursts are caused rather by the keyhole oscillations than the plasma absorption. Mrna et al. (2014) have found a relation between the weld geometry and the period of the plasma bursts detected through the short-time frequency analysis.

In this paper we present a study of the plasma plume oscillations through an autocorrelation function. We demonstrate that it is an efficient tool to detect the period of the plasma bursts ranging in the order of milliseconds. We compare the autocorrelation function characteristics and the geometry of the welds carried out on a 2 kW Yb:YAG laser welding machine for the steel workpiece and various welding parameters settings usually used in industry.

2. Theory

2.1. Plasma plume dynamics

The typical waveforms of the light emissions coming from the plasma plume that consist of the short-time pulses corresponding to the plasma bursts are shown in Fig. 1. To explain this experimental observation we consider the following theoretical concept of the plasma plume dynamics and burst generation that involves two main physical phenomena – the plasma absorption and the keyhole/weld pool oscillations.

We come out of the fact that the incident laser beam absorption by the plasma in the keyhole is characterized by an absorption coefficient that depends on the electron temperature and the pressure. The absorption causes the increase of the electron temperature and pressure which implies a further increase of the absorption itself. This gives rise to the snowball effect. When the temperature and pressure exceed a critical limit, the plasma expands out of the keyhole and forms a plasma plume above it. Then the temperature and pressure inside the keyhole decrease and the process starts again.

The generation of the plasma bursts is also affected by the keyhole dynamics – the compression of the plasma due to the keyhole oscillations accelerates the increase of the temperature and pressure. Klein et al. (1994) have shown that the keyhole oscillations can be described by the various radial, azimuthal and axial modes. However, the damping due to the viscosity significantly reduces the life time of the oscillations that are also affected by the welding parameters settings. If the welding conditions are far from to the optimum, the keyhole oscillations are damped and irregular, so the burst generation seems to be random. On the

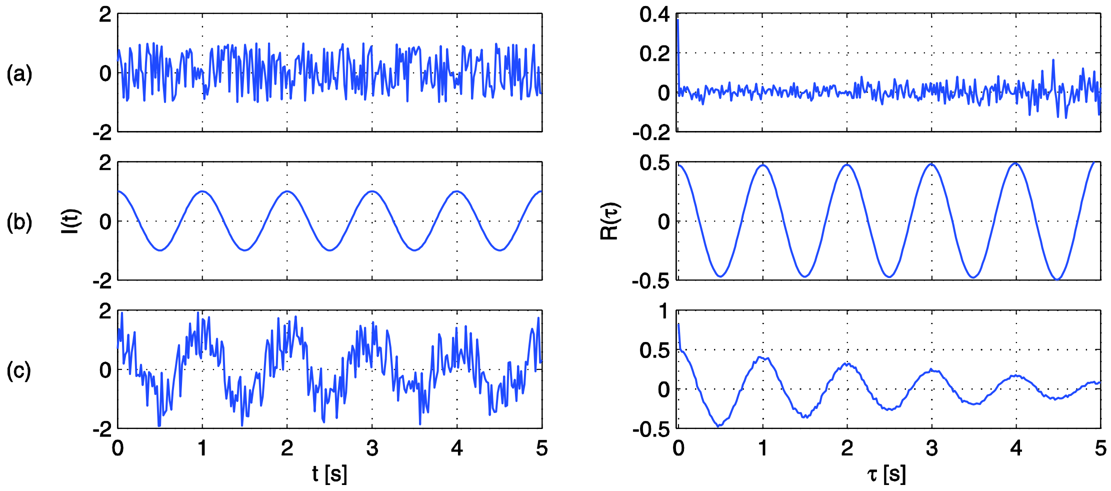

Fig. 2. Autocorrelation function $R(\tau)$ for the signal $I(t)$ representing (a) a Gaussian noise; (b) a periodic signal; (c) a noisy periodic signal.

contrary, if the welding conditions are optimal, the keyhole oscillations are nearly stationary and the burst formation is temporally coherent. Then the period of the plasma bursts corresponds to the period of the keyhole oscillations.

In our previous papers by Mrna et al. (2013, 2014) we have studied the light emissions of the plasma plume through the frequency analysis. However, the complex time series of the plasma bursts limit the use of the Fourier transform suitable rather for the periodic signals. Therefore, in this paper we study the light emissions through the autocorrelation function that is generally more appropriate for the analysis of the non-periodic signals on a short-time scale.

2.2. Autocorrelation function

The discrete autocorrelation function $R(\tau)$ with the time lag τ for a real discrete signal $I(t)$ is defined as

$$R(\tau) = \sum_{\tau} I(t) I(t-\tau). \tag{1}$$

In Fig. 2 we show the comparison of the signal $I(t)$ and the corresponding autocorrelation $R(\tau)$ for three different signal types. If the signal $I(t)$ represents a Gaussian noise, the autocorrelation $R(\tau)$ has a sharp maximum for $\tau = 0$. For a periodic signal $I(t)$ we obtain an autocorrelation $R(\tau)$ that oscillates with the same period and constant amplitude. Finally, for a noisy periodic signal $I(t)$ we get the function $R(\tau)$ with a maximum at $\tau = 0$ and an exponentially decreasing envelope (this phenomenon is referred to as a phase diffusion). Note that the last example is relatively similar to the signals and autocorrelations that we meet in our experiments.

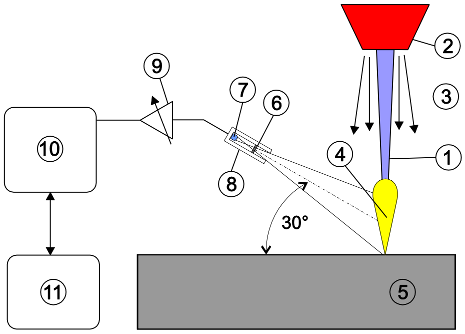

Fig. 3. Experimental setup: 1 – laser beam, 2 – coaxial nozzle, 3 – shielding gas, 4 – plasma plume, 5 – workpiece, 6 – neutral density absorptive (grey) filter, 7 – photodetector, 8 – photodetector mounting tube, 9 – amplifier with adjustable gain, 10 – data acquisition device, 11 – PC with control software.

3. Experimentation

3.1. Experimental setup and evaluation

The experiments were carried out on a 2kW Yb:YAG fiber laser welding system operating at the wavelength 1.07 μm. The experimental setup is shown in Fig. 3. The intensity of the light emissions produced during the bead-on-plate welding was continuously detected by a photodetector operating in the wavelength range 190-1100 nm, sampled by a data acquisition device at the frequency 40 kHz and stored in a PC for further data processing.

We carried out two sets of welds with the welding parameters chosen within the ranges usually used in industry. The common parameters for both sets were the following: the 3 and 6 mm carbon and stainless steel as a workpiece material, argon as a shielding gas with the volumetric flow rate of 18 liters per minute and the welding speed 10, 20 and 30 mm/s. The first set was characterized by the weld length 83 mm and the constant laser focus position z_f = +1 mm (positive values are below the workpiece surface). The laser power was changed stepwise from 1.0 to 2.0 kW with the step of 0.2 kW during each weld. The second set was characterized by the weld length 42 mm and the constant laser power 1.0 or 2.0 kW. Each weld was carried out with different focus position z_f taking the values from -3 to +5 mm with the step of 1 mm.

The evaluation of the welds was based on mutual comparison of several process characteristics. First was the signal $I(t)$ sampled by the photodetector. Second was the autocorrelation $R(\tau)$ calculated separately for the section of the signal $I(t)$ corresponding to each step of the laser power or the focus position z_f. The function $R(\tau)$ was normalized such that $R(0) = 1$. The time lag corresponding to the first maximum of the autocorrelation $R(\tau)$ was identified as the time period of the plasma bursts T. Finally, the weld depth d was measured from the scanned image of the weld section obtained by metallographic processing.

3.2. Results

The experimental results can be divided into two parts. First, we compare the autocorrelations $R(\tau)$ corresponding to the welds obtained for various welding parameters settings. Second, we describe the relations between the laser power, the period of plasma bursts and the weld depth.

In Fig. 4 we show the autocorrelation functions $R(\tau)$ corresponding to the welds carried out for the 6 mm stainless steel, the welding speed 10 mm/s and the laser power changed stepwise from 1.0 to 2.0 kW. The

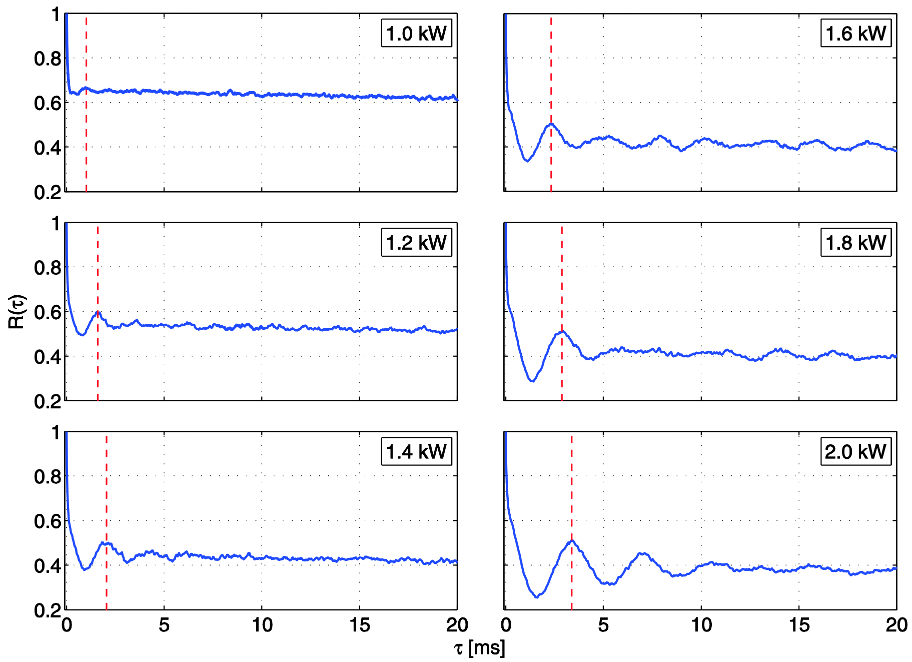

Fig. 4. Autocorrelation functions $R(\tau)$ for the weld carried out for the stepwise changed laser power. Welding conditions: 6 mm stainless steel, argon shielding gas, laser power from 1.0 to 2.0 kW, welding speed 30 mm/s, focus position z_f = +1 mm. The red dashed line indicates the position of the first maximum.

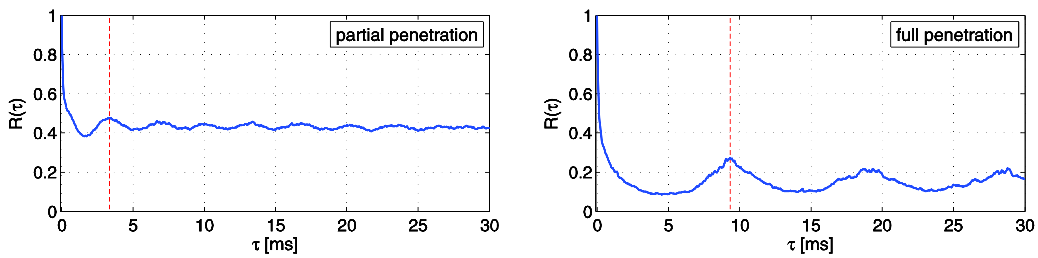

Fig. 5. Autocorrelations $R(\tau)$ for the partial and full penetration welds. Welding conditions: 6 and 3 mm carbon steel, argon shielding gas, laser power 2.0 kW, welding speed 10 mm/s, focus position z_f = +1 mm.

period of the plasma bursts corresponding to the position of the first maximum apparently increases with increasing laser power. This can be justified by two facts. First, it takes longer time to reach a critical temperature in the keyhole that has a larger volume due to a higher laser beam power. Second, the weld pool has a larger volume due to a higher laser power and, therefore, the system oscillates more slowly.

Next, in Fig. 5 we show the autocorrelation functions $R(\tau)$ for the partial and full penetration welds. The period of the plasma bursts is much higher in the case of the full penetration. The reason is that the keyhole in the full penetration mode typically has higher radius which implies higher period of the keyhole oscillations and the corresponding plasma bursts.

In Fig. 6 we show the autocorrelation functions $R(\tau)$ for the welds carried out for a variable focus position z_f. Although the period of bursts remains almost constant, the phase diffusion is significantly different. If the focus position is far from optimum, the exponential decrease of the envelope is very fast.

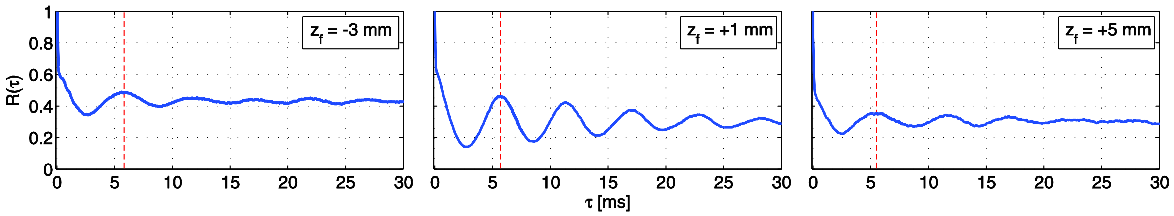

Fig. 6. Autocorrelations $R(\tau)$ for the welds carried out with the various focus position z_f. Welding conditions: 6 mm stainless steel, argon shielding gas, laser power 2.0 kW, welding speed 10 mm/s.

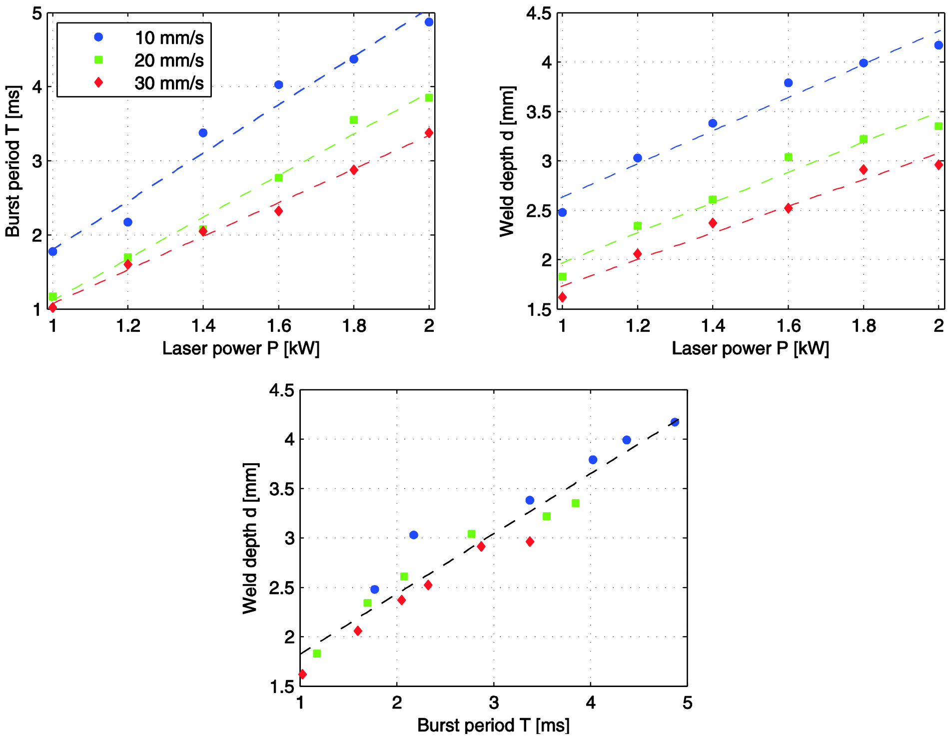

Fig. 7. Relations between the laser power P, the burst period T and the weld depth d. Welding conditions: 6 mm stainless steel, argon shielding gas, laser power 1.0-2.0 kW, welding speed 10, 20 and 30 mm/s, focus position z_f = +1 mm. The dashed lines represent the linear fit of the measured data.

This reveals that the generation of the plasma bursts is relatively irregular. On the contrary, if the focus position is close to optimum, the exponential decrease of the envelope is slow. This indicates regular generation of the plasma bursts and nearly stationary oscillations of the keyhole and the weld pool.

The plasma bursts have been observed for all welding parameters settings in the case of stainless steel but only for the welds carried out with high laser power in the case of carbon steel. Therefore, in Fig. 7 we show the relations between the laser power P, the period of plasma bursts T and the weld depth d only for the stainless steel. The first two plots show that the burst period and the weld depth depend approximately linearly on the laser power for each welding speed. For a constant laser power, the burst period as well as the weld depth decrease with increasing welding speed. The third graph shows that the weld depth and the burst period exhibit a linear dependence irrespectively to the welding speed.

4. Discussion

The autocorrelation analysis has proven as an efficient tool for studying the light emissions generated by the plasma plume. The method is able to detect the period of the plasma bursts typically ranging in the order of milliseconds. In the case of stainless steel, the experimental data revealed the linear relation between the burst period and the weld depth that is independent of the welding speed. This represents an important result since we have found a direct connection between the weld geometry and the physical quantity characterizing the welding process that can be inferred from the observable light emissions. The form of the autocorrelation function also indicates the suitability of the welding parameters settings (e.g. the focus position of the laser beam) and the character of the welding mode (i.e. the partial or full penetration).

On the contrary, the use of the autocorrelation analysis has limitations that should be mentioned. Its applicability for the welding process diagnostics is so far limited to the cases where the plasma bursts are observed. The form of the autocorrelation $R(\tau)$ depends on the length of the corresponding signal $I(t)$. So, if the signal $I(t)$ was too short, the autocorrelation $R(\tau)$ will lose its relevance. This fact implies the need to investigate the lower limit of the signal length sufficient to detect the period of the plasma bursts. To answer this open issue we intend to study the waterfall plots of the autocorrelation function that are analogous to the spectrograms used in the short-time frequency analysis.

5. Conclusion

We have presented an experimental study of the plasma plume dynamics in the deep penetration laser welding of steel. We have studied the light emissions generated by the plasma plume through the autocorrelation analysis. We have shown that the autocorrelation function is an efficient tool to detect the period of the plasma bursts and to indicate the suitability of the welding parameters settings. As an outcome of the experiments, we have described a direct relation between the burst period and the weld depth that is valid for the stainless steel. This is an important result that represents motivation for further study of the plasma bursts with regard to possible applications in welding process diagnostics.

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