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Study of laser wobbling welding process through the radiation of plasma plume

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Abstract

During laser welding with wobbling to the vector of the welding speed adds trivial movement of the beam in the shape of a circle or other shapes. Therefore, the laser beam moves with much higher current speeds than during normal welding. The melting of material on the leading edge of the keyhole occurs periodically. This fact is reflected in the character of the radiation of plasma plume over the keyhole. Experiments were conducted in which it was obtained spectrum of plasma plume radiation by using autocorrelation function for different parameters of circular wobbling (circle diameter, frequency) and for different materials. In the spectra are found the higher harmonic frequency of wobbling. The results were also compared with the radiation of the plasma plume during pulsed laser welding where the laser beam also periodically melts the leading edge.

Keywords: laser welding; wobbling; process monitoring

1. Introduction

The wobbling technique begins to play an important role in laser welding because it allows to programmatically change the width and other characteristics of the weld, see Hao et al., 2015 or Fritsche et al., 2016, and allows to make large welds even with a small spot size, Vanska and Salminen, 2012. In this technology, a periodic repetition of the primitive curve is added to the welding velocity vector. Nowadays, a number of primitive curves have been experimentally tested, such as a line (perpendicular to a welding velocity vector), circle, eight or infinity. Keyhole accompanied by weakly ionized plasma emissions in the form of plasma bursts also arises in this mode. The keyhole retention and stability conditions are more

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complex in this mode because the keyhole passes through the weld pool already created and the material melts only when it moves towards the face of the weld pool.

For the experiments described below, a circle was chosen as the primitive curve, which appears to be the most appropriate wobbling representative. Unlike the line motion, there are no turning points in which a deeper penetration occurs, Yamazaki et al., 2016. The position of the laser beam using secondary circular motion is given by equation (1). Because of the addition of the velocity vector of both movements, the instantaneous velocity of the keyhole (2) periodically varies with the interval given by the basic welding speed. The mean value corresponds to the circular velocity.

$$\boldsymbol{p} = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} vt + r_w \cos(2\pi f_w t + \varphi_0) \\ r_w \sin(2\pi f_w t + \varphi_0) \end{pmatrix} \tag{1}$$

$$v_{act} = \left| \frac{d\boldsymbol{p}}{dt} \right| = \sqrt{v^2 + 4\pi^2 f_w^2 r_w^2 - 4\pi f_w r_w v \sin(2\pi f_w t + \varphi_0)} \tag{2}$$

Figure 1 is a simulation of keyhole trajectory and periodic change of instantaneous speed for the specified parameters. From the speed values, it is clear that the speed of the keyhole movement is an order of magnitude higher than in conventional welding.

Since Wobbling welding is a periodic process a comparison with pulse welding is offered. Significant frequency components excited by the periodic movement of the laser beam or its modulation can be expected for such signals.

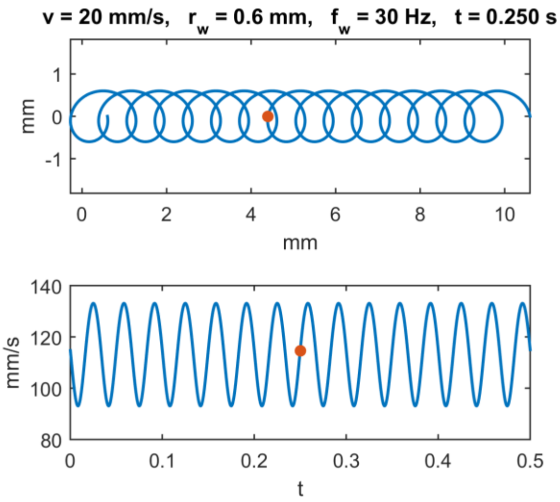

Fig. 1. Simulation of the keyhole trajectory and the speed of its movement

2. Methods and experimental results

2.1. Experimental setup

The experiments were carried out with 2 kW fiber laser IPG YLS-2000 and scan head ARGES Fiber RHINO 31. The scan head is primarily intended for scanner welding, nevertheless, can be also used for welding in wobbling mode. For our purposes the head was not used in the scanning mode, only securing the secondary movement of the laser beam. We have also installed a holder for the plasma radiation photodetector and the side gas nozzle onto the head as shown in fig. 2. Supply of shielding gas was necessary to keep same conditions as with conventional laser welding.

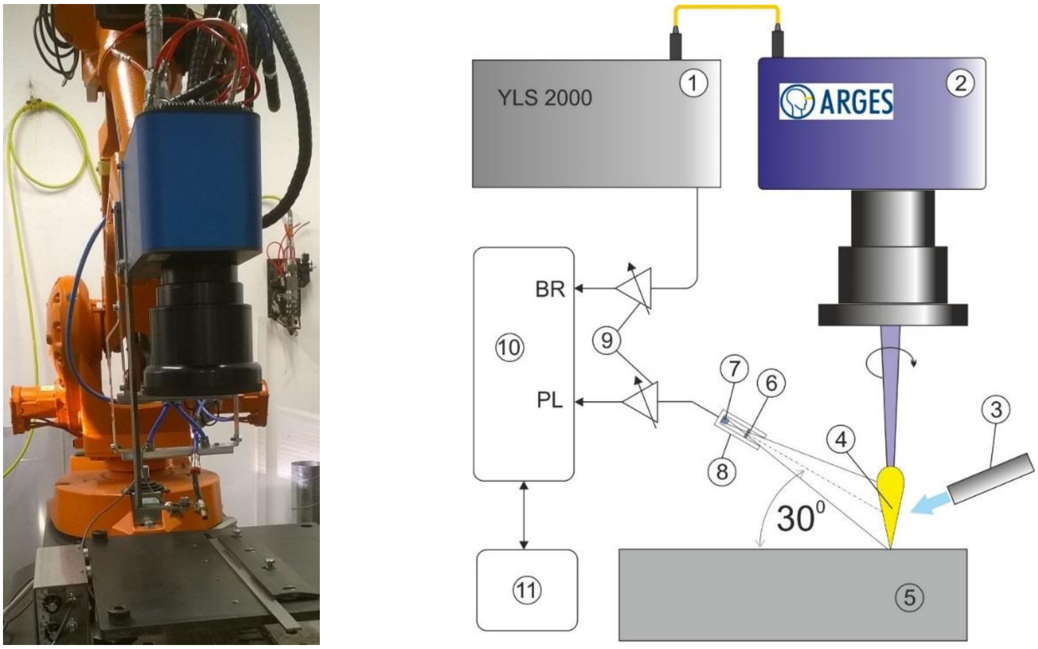

Fig. 2. (a) Experimental setup; (b) Experiment schema: 1 laser, 2 scan head, 3 gas nozzle, 4 plasma plume, 5 material, 6 gray filter, 7 photodetector, 8 photodetector housing, 9 amplifiers, 10 DAQ, 11 PC

In addition to the plasma intensity (PL), a signal proportional to the laser back-reflection (BR) was recorded. The back-reflection signal can provide us additional keyhole state information, Stritt et al 2011. The signals were acquired for each weld using a DAQ at the sampling frequency of 40 kHz and the goal was to examine their frequency characteristics and interrelationships using the Fourier transform (FT) and the autocorrelation function. We used two methods because of the nature of the plasma intensity signal - sharp short peaks with a random behavior. This signal is inappropriate to process using FT, and the autocorrelation function appears to be a better tool. If the oscillation frequency is not recognizable in the Fourier spectrum, the autocorrelation function usually reveals it. For a better insight into the welding process, both the FT and autocorrelation functions were used in their waterfall forms. The analysis of the used methods is in Mrňa and Horník, 2016 or Mrňa et al., 2017.

The similar experiments were made using the laser in pulse configuration and conventional welding head Precitec YW30. In addition, a signal which controls the power of the laser was recorded.

2.2. Pulse welding

To achieve better understanding and easier orientation we have made a set of linear welds in pulse mode first. The laser power was controlled by an external analog signal from the signal generator. Two waveforms were selected, sinusoidal and rectangular with a power range 0 - 1.5 kW. An example of recording and evaluation is in figure 3.

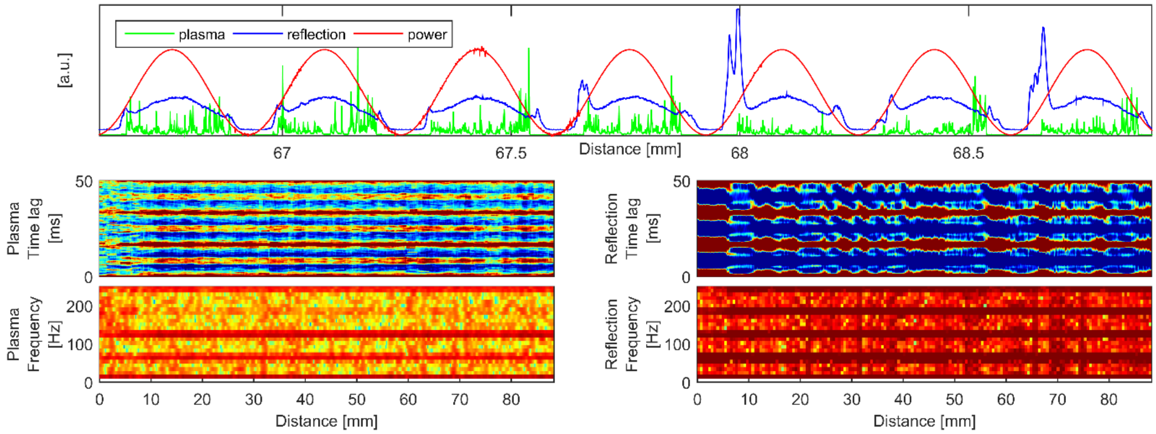

Fig. 3. Stainless steel, P_{max} = 1.5 kW, v = 20 mm/s, sinus modulation 60 Hz

There is a peak at the beginning and end of the BR signal period, which corresponds to the creation and extinction of a keyhole. More energy is reflected back due to the shape of molten metal in conduction mode than escapes from keyhole in the penetration welding mode.

We supposed that deeper keyhole absorbs more energy and BR will be even lower. However, it is interesting that the BR signal traces the laser power over the period. From this, we can deduce that the increasing power has a greater effect on the back-reflection than the deepening keyhole. The situation is more complex with the plasma plume radiation signal. Plasma burst clusters are synchronous with the BR signal. However, at the end of these sections, the plasma bursts are higher - more intense, which correspond to a reduction of the keyhole. The shrinking keyhole throws away more plasma. Also, thanks to this effect, the autocorrelation function has a complicated course.

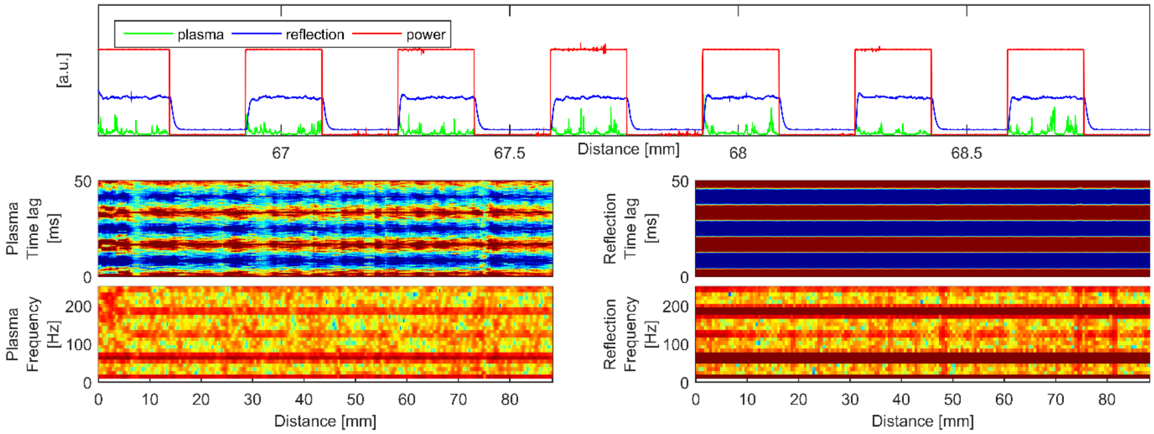

Fig. 4. Stainless steel, P_{max} = 1.5 kW, v = 20 mm/s, square modulation 60 Hz

In the case of the rectangular shape of laser power, the situation is simpler with respect to the course of the BR signal, which is more or less rectangular. Corresponding autocorrelation function and the Fourier spectrum is typical for the rectangular signal. There are again clusters of the plasma burst synchronous with the laser power waveform. Both signals and their autocorrelation functions are different than in the first case. It is obvious that the different laser power shapes interact differently with welded material.

2.3. Wobbling welding

Two materials carbon steel S235JR and stainless steel X5CrNi18-10 were used for experiments. The reason is the different material behavior due to the different thermal conductivity and the different viscosity of the weld pool. In experiments were always constant the wobbling radius r_w = 0.6 mm, the welding power P = 1.5 kW and the velocity v = 20 mm/s. Three wobbling frequencies of 30, 60 and 90 Hz were chosen. We see in fig. 5, that both signals have no trend and inner structure is different. Autocorrelation function and periodogram give us more accurate information about periodicity, while their waterfall forms show frequency variations in time. It is evident that frequency, respectively period, of both signals is identical with wobbling frequency. It is more clear in the back-reflection signal.

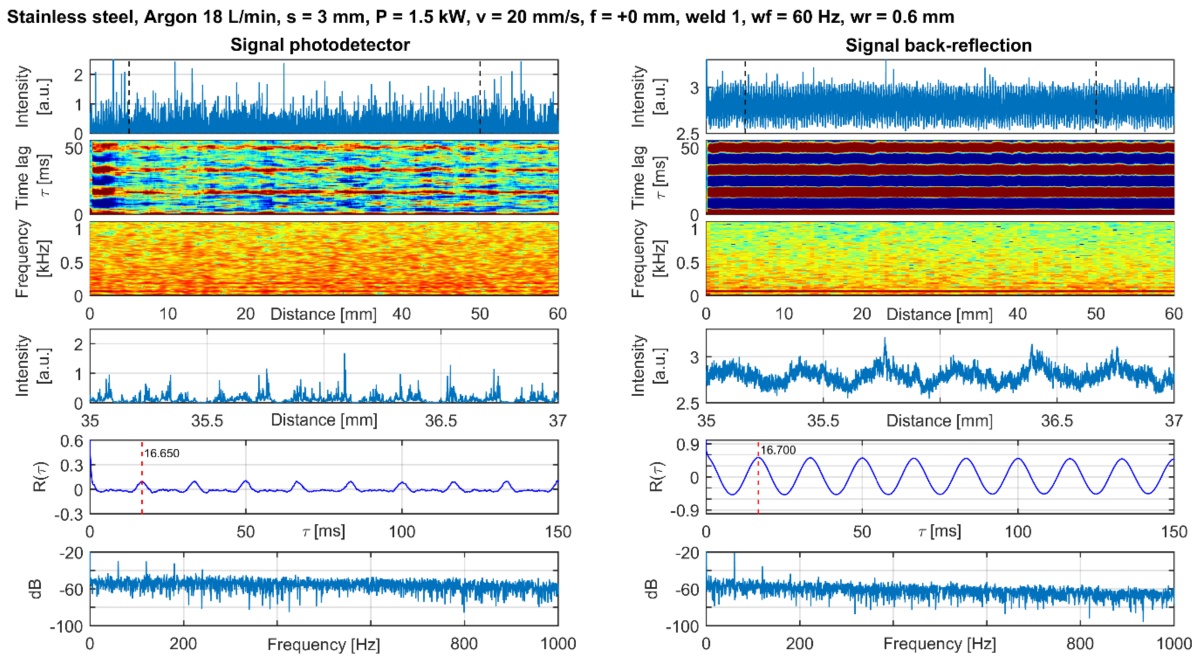

Fig. 5. Experiment evaluation

3. Discussion of results

It is necessary to consider what changes during the welding process:

- Change of instantaneous velocity - results from linear and circular velocity vector addition
- Change in the keyhole position - keyhole is not stable in the middle or in front of the weld pool as in a conventional laser welding, but constantly changes its position. It is therefore assumed that they create a different flow of metal inside the weld pool.
- Changing thermal conductivity of the surroundings - is the difference when the beam moves through the weld pool on the back of the semicircle and when melting the material on the front of the semicircle

These facts result in a change in the depth and overall geometry of a keyhole. This is reflected in the BR signal - with a deeper keyhole, the magnitude of the BR is reduced, and it will also be reflected in the character of the plasma bursts. On high-speed camera images is evident that plasma bursts are not always perpendicular to the surface of the weld pool. Their tilt suggests that at that in this moment the keyhole is strongly sloped, figure 6.

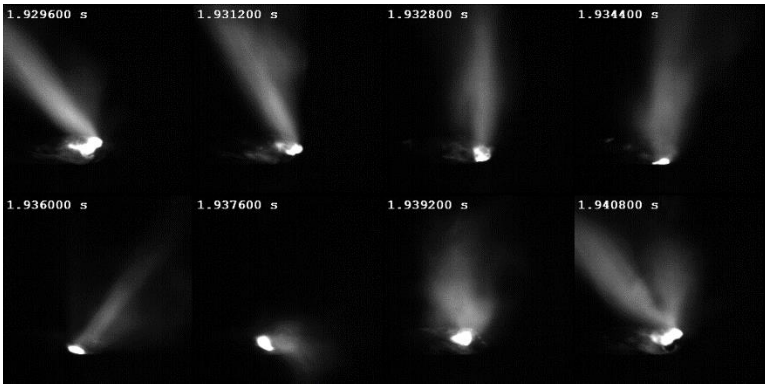

Fig. 6. Plasma plume during wobbling welding carbon steel

3.1. Plasma bursts and back-reflection comparison

The comparison in figure 7 shows that with increasing wobbling frequency and thus increasing the instantaneous velocity of the laser beam in weld pool, the amplitude of waves in BR signal is also increasing.

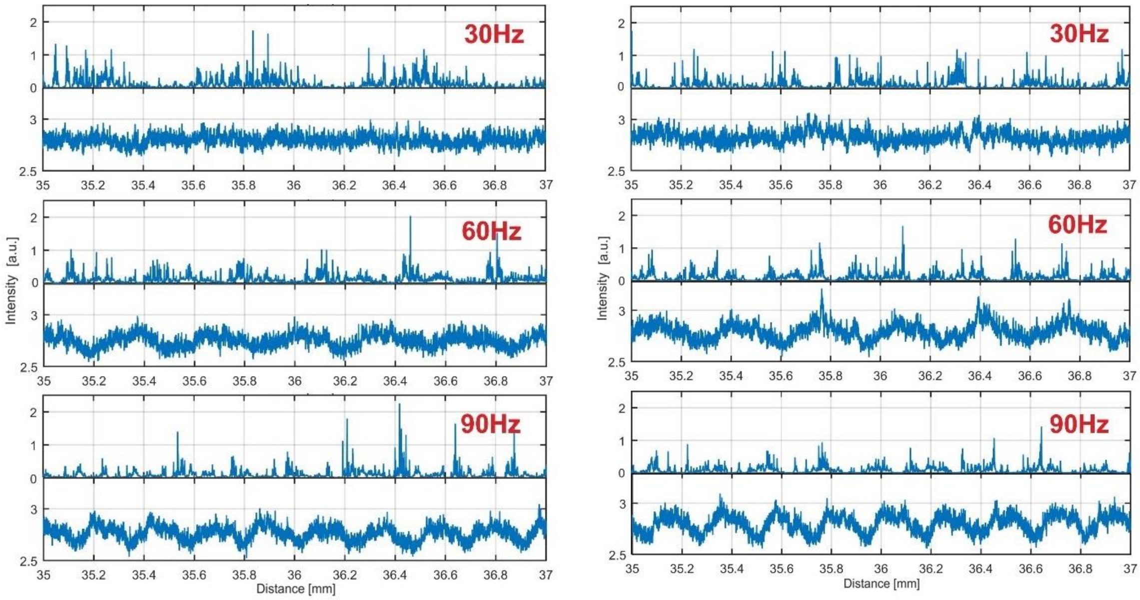

Fig. 7. Plasma intensity (top) and back-reflection intensity (bottom) for Carbon steel (left) and Stainless steel (right)

Moreover, both the plasma bursts and back-reflection are synchronized. Plasma bursts clusters are located in minima of BR signal. This can be explained by the greater depth of the keyhole which lowers the BR and hence creates an environment supporting the burst.

3.2. Autocorrelation functions comparison

Although plasma intensity and back-reflection signals give us some useful information about welding process, we can obtain additional information about periodicity, while maintaining information about shape. Look at the appearance of autocorrelation functions of both signals for each parameter setup. The comparison is shown in figure 8. It is clear that while the signal from BR can be considered periodic and sinus in all cases, thus autocorrelation function is similar to cosine. On the other hand, the plasma intensity signal does not copy the sine wave, thus the autocorrelation function has a different shape. This is, of course, due to the basic character of the signal in the form of a set of sharp peaks, however, it can be stated that for carbon steel at frequencies 60 and 90 Hz, autocorrelation functions show regular local maxima indicating also components of higher harmonic frequencies. From this, we conclude that the keyhole does not change only its depth but also shows changes in the diameter (radial oscillation) which cause further synchronization of the plasma bursts. This effect does not occur in stainless steel where the viscosity of the melt is higher and therefore the radial oscillation is suppressed.

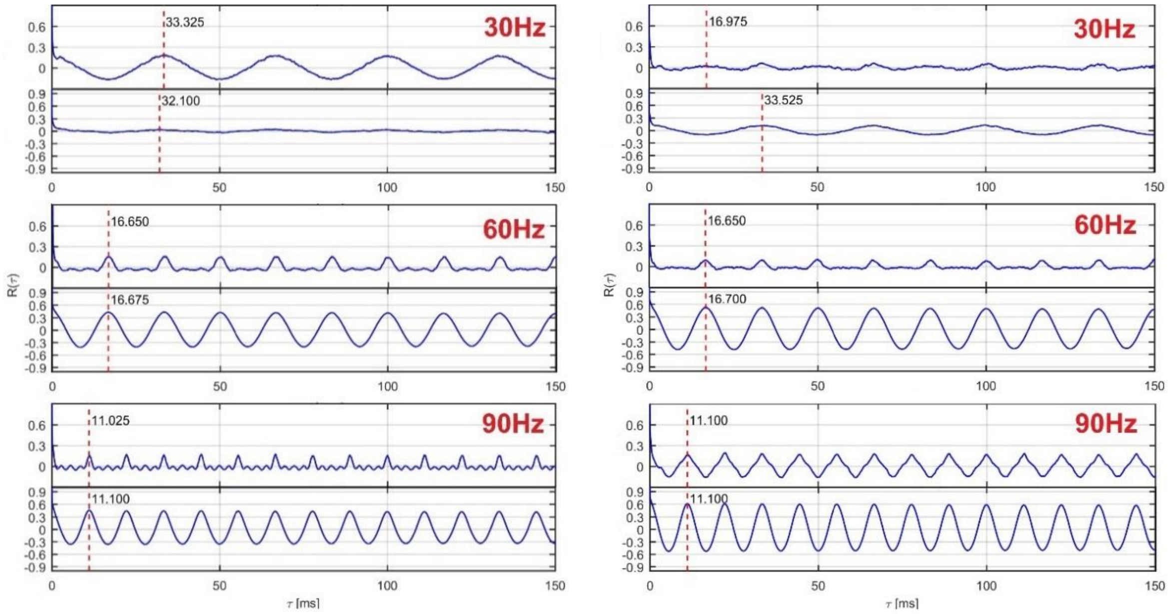

Fig. 8. Autocorrelation function from plasma intensity (top) and back-reflection intensity (bottom) for Carbon steel (left) and Stainless steel (right)

There is a comparison between autocorrelation function of pulse and wobbling welding in fig. 9. Autocorrelation functions of both welding technology at 90 Hz are similar so welding process is somehow similar in meaning of back-reflection. With increasing frequency similarity is also increasing. However, signals differ in the meaning of plasma behavior. There are no harmonic frequencies during wobbling welding.

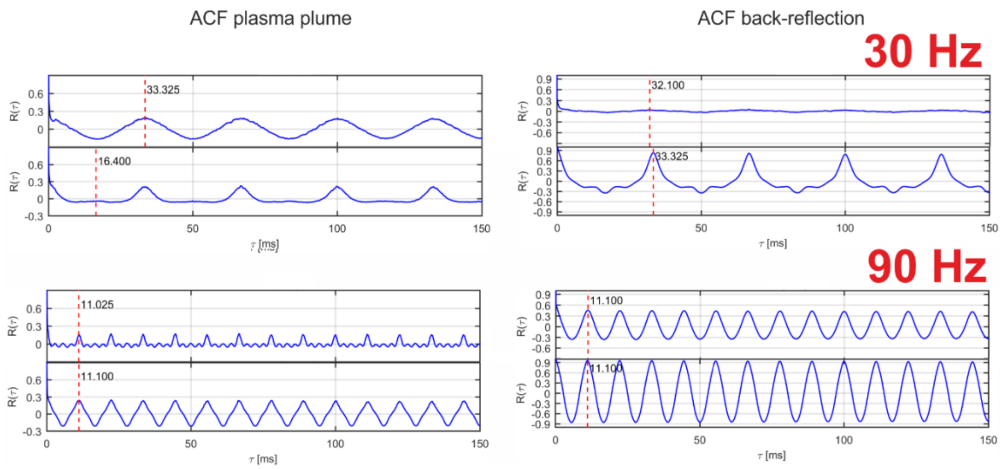

Fig. 9. Autocorrelation function of pulse (top) and wobbling (bottom) welding of carbon steel

4. Conclusion

Plasma plume radiation diagnosis accompanied by a back-reflection signal appears to be a useful source of information on the laser welding process. By using two independent signals, intensity of plasma plume radiation and back-reflection, the insight into the process is more complex. Experiments show that during the welding process there is a periodic change of depth and keyhole geometry, which is reflected both in the plasma plume radiation and in the BR signal. With an increasing wobbling frequency, this fluctuation increases.

Welding by wobbling technique is a very useful tool to extend the possibilities of laser welding. On the other hand, it can be assumed that this form of welding can induce oscillation in the weld pool, which can lead to welding defects.

Acknowledgements

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