NEW METHODS FOR MONITORING LASER WELDING PROCESS IN THE MANUFACTURE OF SOLAR ABSORBERS

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Abstract: Laser welding is a modern method of fusion welding. Due to high welding speeds is necessary to use the machinery welding. This leads to the need for the detection and eventually the elimination of weld defects. Penetration laser welding is not accessible to direct observation and therefore can be monitored only indirectly. A new of possibility is the study of plasma radiation forming over the keyhole using autocorrelation analysis. The intensity of plasma radiation approaching deterministic noise, therefore, commonly used FFT analysis does not produce satisfying results. The autocorrelation function finds repetitive sequences in the signal, which are related to the oscillation of the weld pool. Changes and irregularities in the frequency of these oscillations indicate weld defects and overall stability of the welding process. A series of welding experiments were studied. After the experiments, the autocorrelation functions were evaluated. Changes in frequency during the weld were related to the geometric characteristics of the weld.

KEYWORDS

laser welding, process monitoring, autocorrelation function

1. INTRODUCTION

The laser welding process is a complex combination of multiple interacting physical processes. The final weld is affected by a process parameters settings, such as welding power, welding speed, focus position, welding position and weld type [Kaplan 1994]. But also thermo-physical properties of welded material are involved. Setting the optimal process parameters given above is thus difficult and so far there is no methodology for their optimal adjustment to achieve quality weld in terms both geometry (depth of penetration, weld slenderness, etc.) and the occurrence of various weld defects [Kannatey-Asibu 2009]. It is necessary to perform a series of test welds with subsequent evaluation, which is a long and expensive process.

The welding process itself is accompanied by laser induced plasma plume above the welding spot whose temperature is over 10 000 K is a source of intense optical radiation. This fact makes difficult and almost impossible direct observation of the welding process and its continuous monitoring (depth of penetration, and so on). [Nakamura 2000], [Mrna 2014]. Hitherto is possible to get only indirect and incomplete information about progressing processes from the radiation of plasma plum (intensity comparison with the model weld: good-bad weld). Nevertheless, in nowadays quality control systems a documentation of each weld is required.

2. PHYSICS OF THE PENETRATION LASER WELDING

Plasma formation inside the key hole is not a stationary process. [Farson 1999], [Zou 2016]. Due to the complex dependence of radiation absorption on the plasma temperature and the positive feedback within the key hole occurs an avalanche-like increase in plasma temperature. Thus the plasma rapidly heats up and expands from a key hole in the form of the observable plume – plasma “burst” [Mrna 2014]. Therefore, the radiation forms sharp peaks. In solid-state lasers with a wavelength of around 1 micron is the absorption of radiation about 100 times lower compared to the CO2 laser with a wavelength of 10 microns. [Kawahito 2008], [Wang 2012]. Despite this difference leads conditions in the closed keyhole to the same behavior described above. In the case of conduction welding, the intensity signal is flat without characteristic bursts. More authors showed that the time sequence of the individual plasma "burst" has predominantly character of deterministic chaos [Szymanski 2001]. This is because the temperature increase of plasma depends strongly on the initial conditions, especially the temperature. Moreover, it is necessary to consider the fact that the key hole walls are constituted by a liquid metal which has its own dynamics and a key hole is moving. Several authors have been theoretically predicted that liquid metal weld pool surrounding the key hole can oscillate at multiple frequency modes. However, the model assumes a cylindrical shape vibrating metal and neglects other important factors [Klein 1994], [Matsunawa 1998]. But it can be assumed that weld pool always oscillates at least at some fundamental frequency. Oscillation affects the timing of the bursts through the keyhole volume changes. As mentioned in the previous paragraphs, the radiation is pulsing plasma plume.

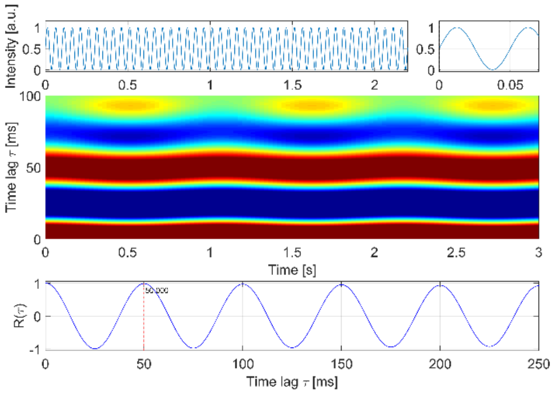


Fig.1a Autocorrelation function of periodic sinus function 20 Hz as waterfall diagram and as average 2D plot

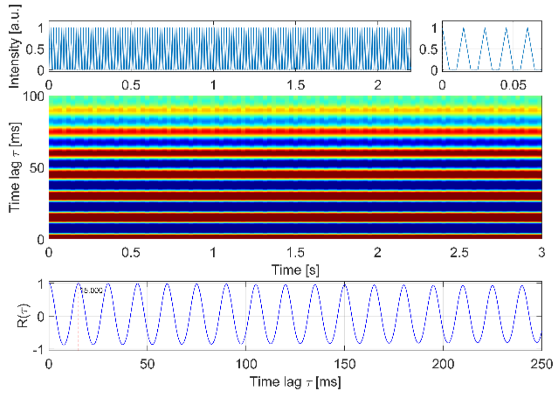


Fig.1b Autocorrelation function of periodic triangular function 66 Hz as waterfall diagram and as average plot

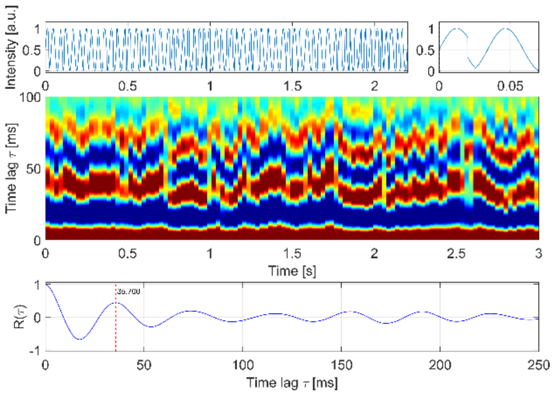


Fig.1c Autocorrelation function of periodic sinus function with random phase discontinuity as waterfall diagram and as average plot

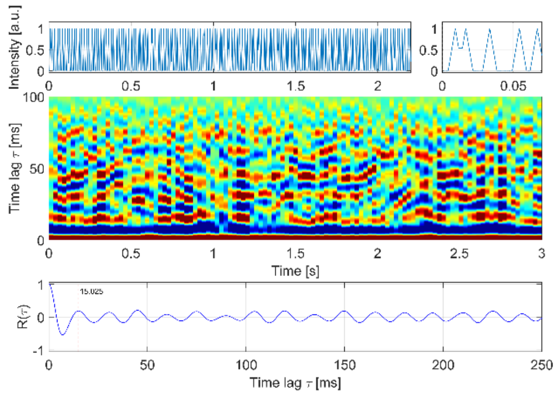


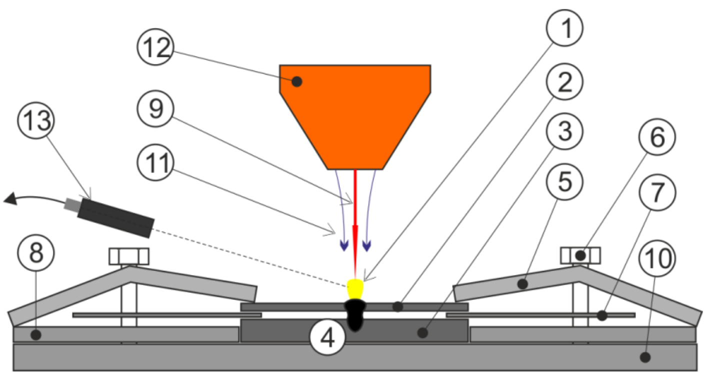
Fig.1d Autocorrelation function of periodic triangular function 66 Hz with jitter 10 ms as waterfall diagram and as average plot

The FFT (Fast Fourier Transformation) commonly used for frequency analysis this type of signals is not appropriate, because the signal has the character of many frequency components with similar intensity, so the result shows the noise character. Better results give so-called STFT (Short Time Fourier Transformation) analysis in the form of a waterfall diagram in which may be some characteristic oscillations in the form of a color contrasting strips observed.

As best choice for analyzing radiation in this situation appears the autocorrelation analysis which looks for a repetitive sequence in the signal. Furthermore, as in the case STFT an autocorrelation function viewed using the waterfall diagram, which gives a better idea of its development over time. In the figures are shown some typical cases (Fig. 1) [Mrna 2015].

3. EXPERIMENTAL SET-UP

In the experiments were used a fiber laser IPG YLS 2000 and welding head Precitec YW30. For recording the radiation of plasma plume was used wideband Si diode sealed in a tube with gray filter (to suppress saturation of intense radiation of



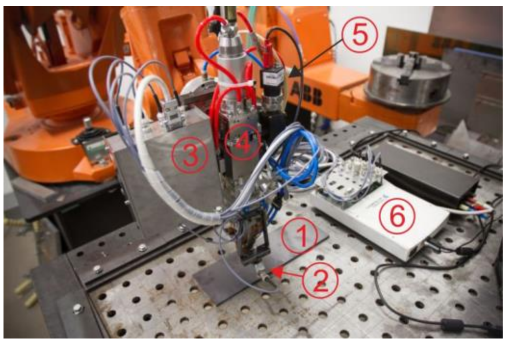


Fig. 2a Experimental setup for overlap weld: 1 – plasma plume, 2 – upper sheet, 3 – lower sheet, 4 – seam, 5 – clamp, 6 – clamping screw, 7- distance sheet, 8 – frame, 9 – laser beam, 10 - basic plate, 11 – shielding gas, 12 – coaxial nozzle, 13 – photodetector.

Fig. 2b Experimental setup: 1 – welded sample, 2- photodetector, 3 – amplifier, 4 – laser head YW30, 5 – coaxial camera, 6 – DAQ plasma plume) and a protect glass.

The construction of the tube narrows the viewing angle of the photodiode to the 3 degrees. For recording the intensity of the radiation was used LabView controlled data acquisition from NI and signal processing was performed in Matlab (see Fig.2a, b).

4. EXPERIMENTS

They were performed with two types of plates:

- Carbon structural steel S235JR
- Stainless austenitic steel X5CrNi 18-10

These materials are typical representatives of their classes with a wide spectrum of applications in the engineering industry. Following experiments were performed gradually verifying the behavior of autocorrelation functions for different welding conditions.

4.1 Dependence period of bursts on the depth of the weld

The first set of experiments was carried out the so-called. "Bead on plate" which was developed to weld solid material for different settings of process parameters. Using the autocorrelation function was found fundamental period – which means repeating plasma bursts - thus, the basic oscillation period keyhole. Afterwards, the depth of penetration was metallographically found out. Evaluation is on Fig.3

It is clear that the relationship between the penetration depth and the period bursts is linear for both materials. This is a very important result that allows us to monitor the depth of penetration (after calibration) during partial penetration welding – see Fig.4

4.2 The difference in period between bursts partial and full penetration

In the next step was conducted an experiment in which the same welding parameters were applied on materials of different thickness, so that in case the thickness of 6 mm (as above) was a partial penetration, and for thickness of 3 mm was full penetration with the root of weld visible along its length. Another experiment shows a different situation – see fig5. [Krasnoperov 2004]. For stainless steel resulted in the full penetration, but when viewed through the keyhole coaxial camera during welding, it is apparent that the melt from below due to the higher viscosity always closes the keyhole. Then the same conditions for the weld pool oscillations holds. Period bursts for both sheet thickness are practically the same. In the case of carbon steel, the keyhole is closed only for the lowest power of 1 kW. At higher power leads to its opening from below, which has a significant effect on the shape of the autocorrelation function and especially for a period of bursts, which is a 2.7 higher value. The explanation is in a different vertical distribution of liquid metal in the weld pool.

4.3 The differences in the autocorrelation function depending on the gap between the sheets at overlap joints

The next set of experiments was directed at identifying the autocorrelation function changes depending on the artificial gaps in a lap weld. This weld is important in the manufacture of plate solar collectors, where two sheets of material X5CrNi 18-10 are welded together. Any gap between the sheets, of course, leads to the creation burned seam and thus leakage. The metal sheets were 0.5 mm thick. Moreover, between the sheets was artificially created wedge gap ranging 0 - 0.5 mm. The experimental result is shown in Fig. 6

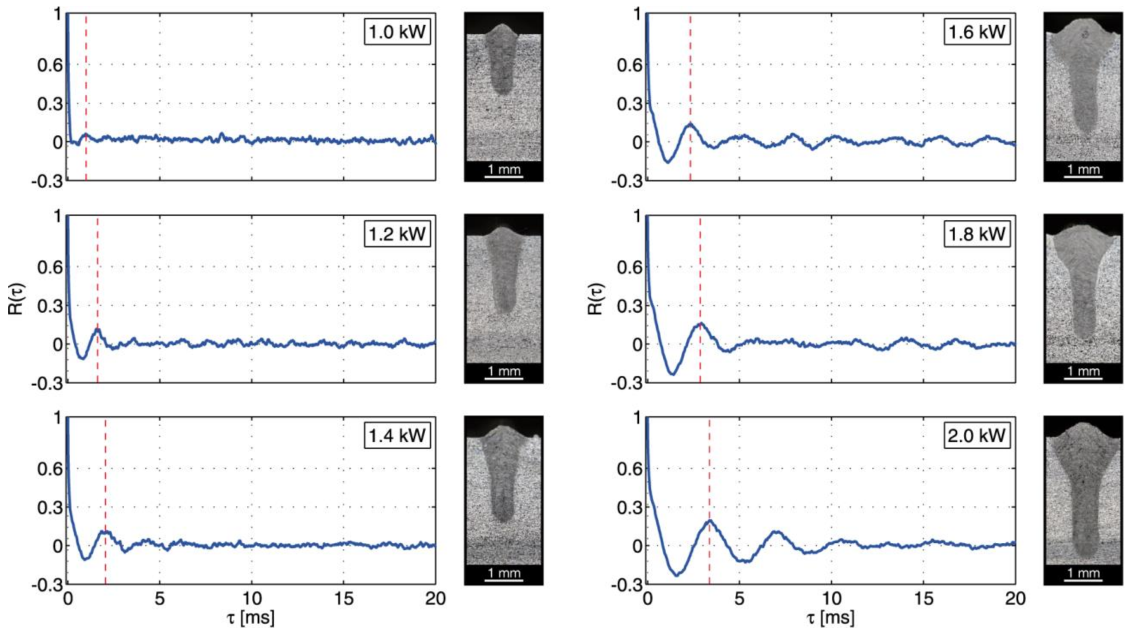


Fig. 3 Autocorrelation functions with the marked period (basic keyhole oscillation period) and corresponding macro of seams

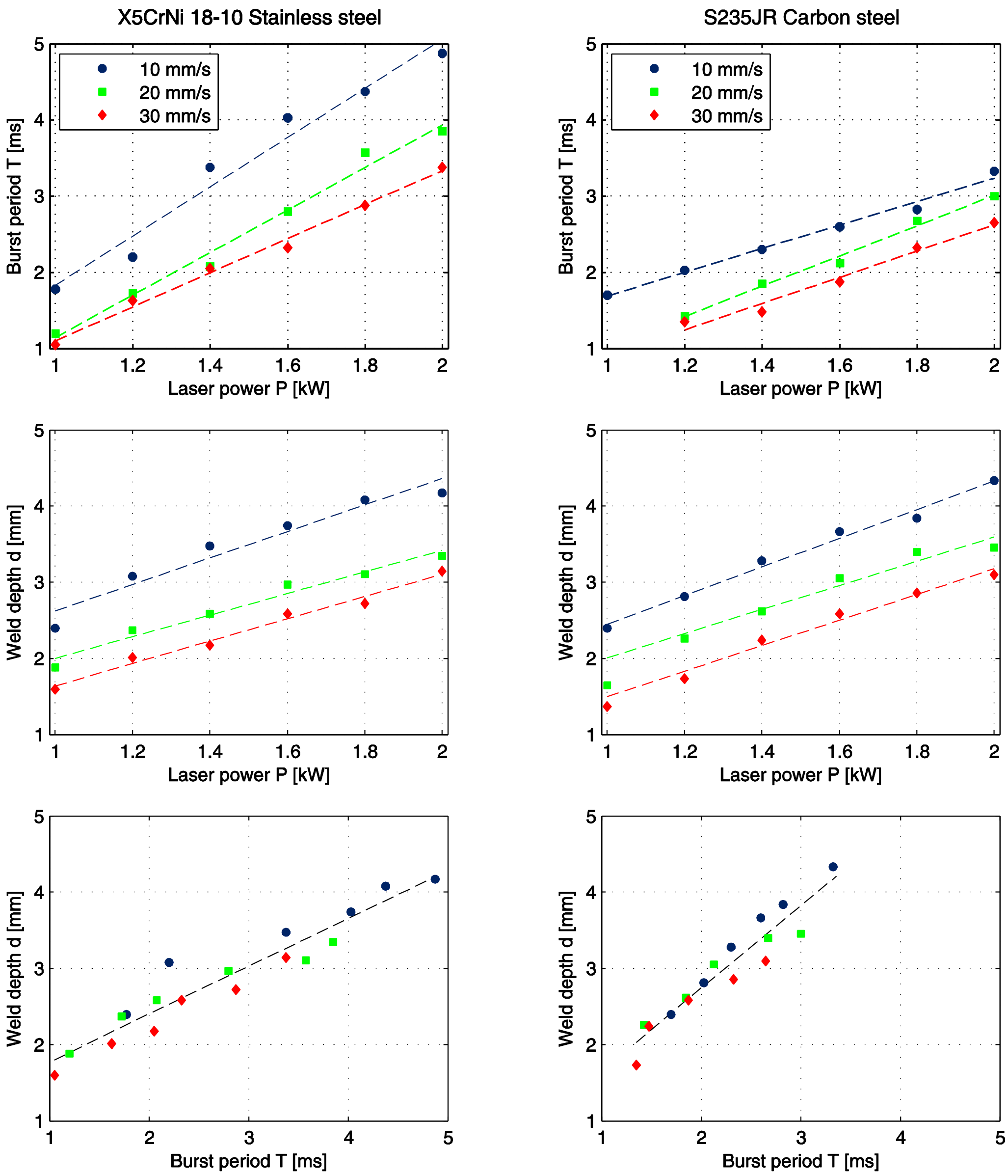


Fig. 4 Evaluation dependencies between the burst period, welding performance and depth of penetration for the two materials.

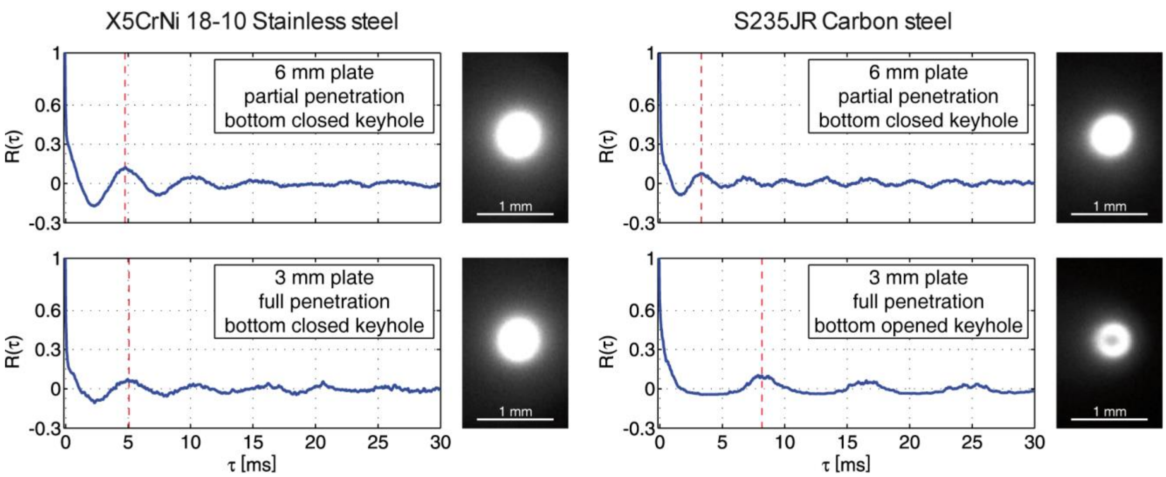


Fig. 5a Autocorrelation function and picture from coaxial camera for partial and full penetration for stainless and carbon steel

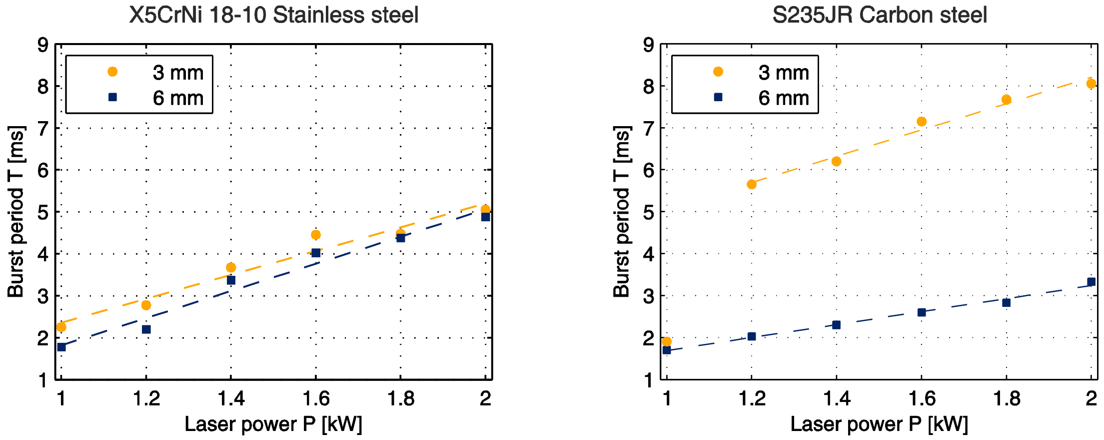


Fig. 5b Illustrations difference burst period for full penetration with a closed and an open keyhole for stainless and carbon steel

The figure shows that the result is very complex. First, the entire length of the weld in terms of full penetration - the root along the entire length of the weld. It is evident that at the gap size greater than 0.2 mm occurs burned seams. From the comparing the intensity of the radiation of plasma plume we can say that the first 10 mm were welded in conduction welding mode (low intensity, no bursts). In the next ten millimeters starts penetration mode, but the keyhole is a bottom closed (high intensity bursts), in the next 20 mm goes full penetration of keyhole bottom opened (low intensity bursts). Then it occurs to alternate between these modes. Comparing the weld appearance with the intensity and waterfall graph of the autocorrelation function is clear, however, is not well correlated with the occurrence of holes. It is also evident that the fundamental period keyhole relatively heavily fluctuating. Waterfall graph shows oscillation phase discontinuity and the jitter, by simulation according Fig. 1c and 1d.

For better orientation, the recording was divided into

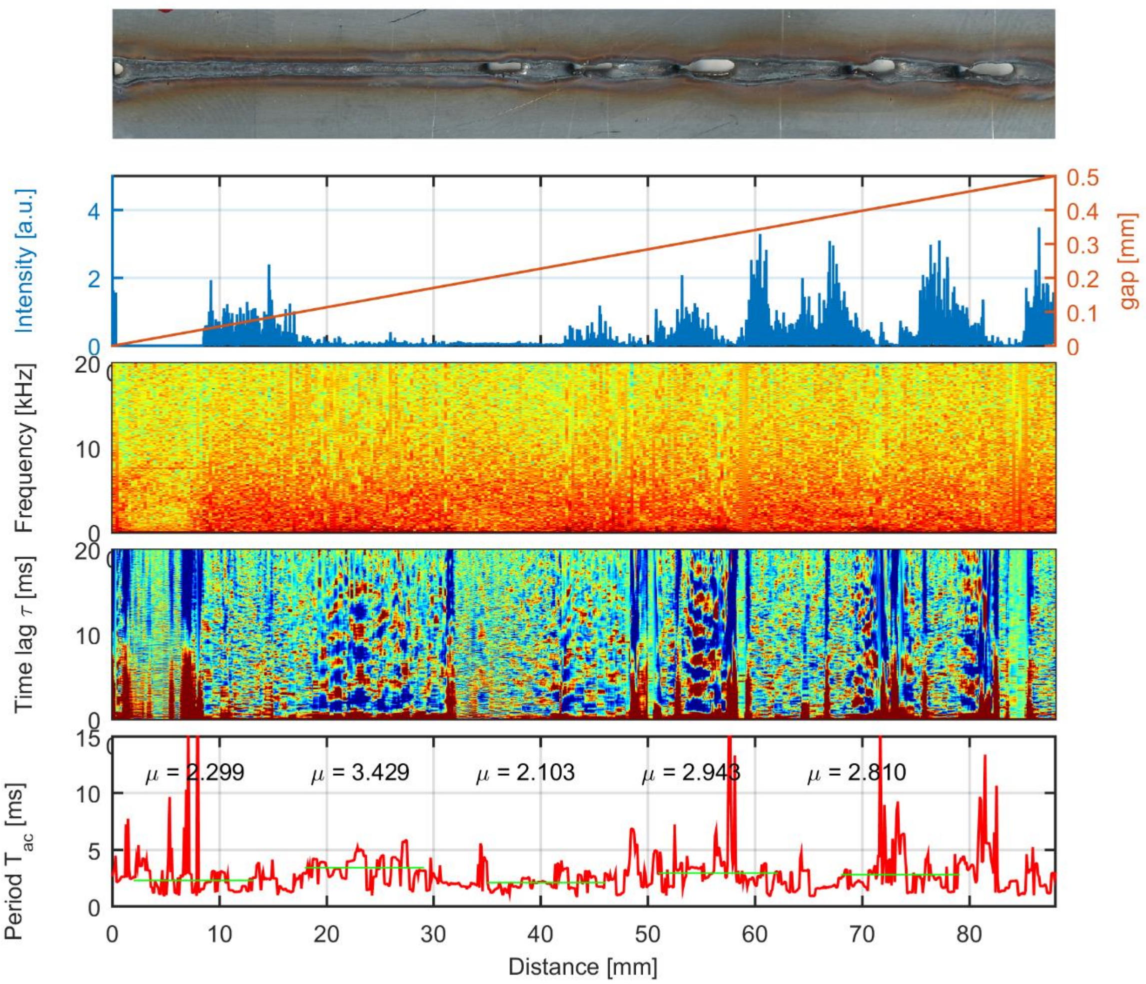


Fig. 6 Complex evaluation of overlap weld two sheet 0,5 mm thick, X5CrNi 18-10 with artificial gap 0 – 0,5 mm. From bottom: front view on weld, record of radiation of plasma plume from PD (with the size of gap), waterfall diagram STFT, waterfall diagram of autocorrelation function, evaluation of burst period along the seam.

five parts (by increasing the gap), and from

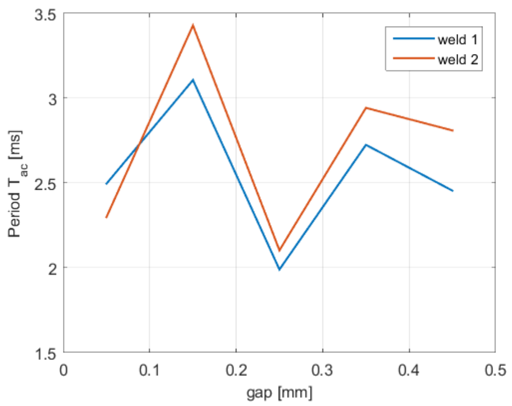


Fig. 7 Plotted period of burst for two weld with the same arrangement

these sections were calculated to average periods. These periods were plotted for both welds in the graph below - see fig.7.

It is clear that both welds have the same regularities due to the similar course of the oscillation period. From the facts described can be inferred that the mentioned phenomena relate more to the leading edge of the keyhole, wherein the principal interaction of the laser beam with a metal is, rather than the trailing edge. Understanding the whole complexity of the phenomena will require further study.

5. CONCLUSIONS

To monitoring of the laser welding process by means of plasma diagnostics was devoted a major effort worldwide in the last twenty years, but nevertheless the results are small. Until diagnostics using autocorrelation function gives the possibility to measure the depth of penetration by determining the fundamental period of plasma oscillations. It is also possible to use this method to distinguish some important modes during welding (full – partial penetration). It is important to note that this method is instrumentally very simple – we need just spot photodetector and evaluation electronics. Compared to other methods which, for example, using cameras with parallel processing of visual information using neural network or OCT is a significant contribution to the further improvement of methods for reliable detection of weld defects and other schemes will require further experimental work.

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