Lasers in Manufacturing Conference 2023

Enhancement of weld depth analysis in laser welding by extension of the oct data scope

Ronald Pordzik[a,*], Timon Ahlers[a], Thorsten Mattulat[a]

[a]*Bremer Institut für angewandte Strahltechnik GmbH, Klagenfurter Straße 5, 28359 Bremen, Germany*

Abstract

Due to the challenging environment inside the keyhole during laser welding the evaluation of the penetration depth from measurements via Optical Coherence Tomography (OCT) demands for statistical filtering of the raw OCT-signal. Hereby, most commonly only the highest peak of the OCT-spectrogram is considered while maxima of higher orders and their intensities are neglected. However, due to the high keyhole dynamics the highest peak does not always correspond to the keyhole bottom, but it is possibly still represented in the OCT-spectrogram by higher order maxima. In this study the influence of maxima up to the 5^{th} order and their corresponding intensities on the temporal resolution of the statistical weld depth analysis are investigated based on the frequency distribution of data points. The results show that considering the extended set of information increases the significance of the features in the frequency distribution that are associated with the keyhole depth.

Keywords: keyhole welding; process monitoring; optical coherence tomography

1. Introduction

In deep penetration laser welding the laser power is absorbed inside a vapor capillary formed by the laser-induced evaporation pressure onto the molten surface of the substrate material, referred to as keyhole. Despite several advantages like high welding depths, high efficiency due to laser power absorption of up to 93 % (Kawahito et al., 2011) and a narrow heat affected zone, the keyhole is highly dynamic, resulting in strong fluctuations of its shape regarding the keyhole depth and the shape of the keyhole walls. Process defects like the formation of pores and blow-outs as a consequence of keyhole collapses and constrictions are commonly known to negatively affect the qualities of the resulting weld seams. Therefore,

* Corresponding author.

on-line process monitoring of laser welding processes is an indispensable tool to identify or even prevent the occurrence of such defects during the process, further reducing the demand for post-process test procedures to qualify the weld seams. For such purposes optical coherence tomography (OCT) has been proven a promising technology for on-line monitoring the keyhole depth (Bautze and Kogel-Hollacher, 2014). As the name implies OCT is originally a tomographic measurement technique that allows for measuring absolute distances inside the measuring field weighted by their respective prevalence resulting in a depth-resolved measurement in the range of the measuring spots extend.

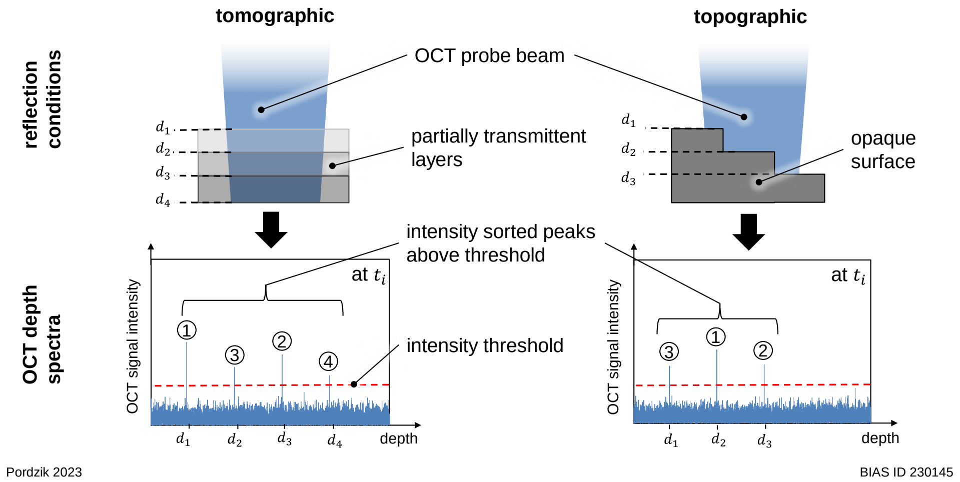


Fig. 1. Schematic of the different operation modes of OCT and the resulting depth spectrum

Different measuring distances in the OCT measurement can occur in two different ways (see fig. 1). If the sample is partially transparent for the OCT probe beam, the OCT can detect different depth layers of the sample assembling to a stack of partially reflective layers what accounts for the tomographic application of the measuring technique. This feature has been widely utilized for medical purposes e. g. for the non-invasive examination of living tissue (Huang et al., 1991). The second case treats the characterization of surfaces which are opaque for the OCT probe beam such as metallic surfaces in solid or liquid state as they are to be encountered during deep penetration laser welding of metals. In this case the OCT still yields the potential to detect different depths inside the measuring spot but rather originating from the opaque surface topography than from in-depth information of the sample structure. A single 1D OCT measurement cannot provide spatially resolved information in the measuring plane about the measured distances but only raise information about the prevalence of the measured distances inside the measuring spot indicated by the peak heights of the depth spectrum. Due to the capability of OCT to raise information about the surface structure of a target the technology has been applied in laser beam welding for example by Stadter et al., 2019 to track the welding joint for process control using the OCT probe beam in leading configuration as well as for evaluating the weld seam quality by positioning the probe beam behind the process zone. Other applications of OCT focus on direct observations of the process zone especially by probing the keyhole itself. In this case the OCT probe beam is coupled coaxially into the beam path of the processing laser. This way depth signal distributions from inside the keyhole can be derived as described by Bautze and Kogel-Hollacher, 2014. The scope of OCT-based keyhole analysis can be extended to access further properties like the three-dimensional keyhole mapping as demonstrated by Sokolov et al., 2020.

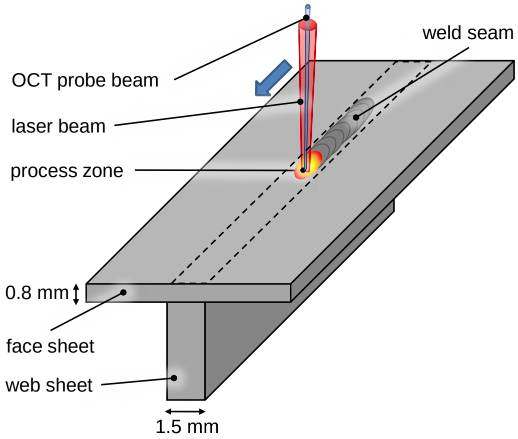
Schmoeller et al., 2022 implemented an OCT-based weld depth control using inline generated OCT data to maintain a constant weld depth throughout the process emphasizing the high potential of this technology regarding laser deep penetration processes. Focusing on the purpose of reliable weld depth extraction, strong dynamics of the keyhole process causing fluctuations of the keyhole walls in the range of up to 5 kHz, as described by Schou et al., 1994, disturb the OCT-based measurement of the keyhole bottom. Therefore, single OCT measurements do not reliably represent depths associated with the keyhole bottom but potentially other geometric features inside the keyhole. To overcome this issue, the recorded OCT data needs to be analyzed statistically to extract the keyhole depth from the data point cloud. Besides filtering methods like percentile filters that are calibrated experimentally from metallographic cross-sections, the histographic analysis of the OCT data by means of the last local peak (LLP) introduced by Mittelstädt et al., 2019 provides a method to extract the keyhole depth with a significantly reduced demand for experimental calibration of the filter. They found that the last significant local peak of the frequency distributions is in good agreement with the actual weld depth obtained from metallographic cross-sections. Further correlation between the characteristics in the frequency distribution and the keyhole dynamics has been demonstrated by Pordzik et al., 2022 who compared the frequency distributions of OCT data points between welds of aluminum under atmospheric pressure and reduced ambient pressure. The stabilizing effect of the reduced ambient pressure on the keyhole dynamics showed a major impact on the characteristics of the respective frequency distributions like strong accumulations of the data points at certain depths. Up to now the method of the last local peak in the frequency distribution of OCT data points has been only applied to the highest OCT depth peaks from the OCT depth spectra ignoring information about the keyhole shape and dynamics that higher order peaks possibly contain. Extending the OCT data scope for this analysis method by considering the OCT depth peaks up to the 5^{th} order along with their corresponding intensities the following research questions are to be explored in the course of this study:

- Do the higher order peak distributions yield different characteristics in their frequency distributions or are they complementary to the first order peak distributions?
- Does weighting the data counts in the frequency analysis by their intensity values increase the prominences of the distribution features, thus enhancing the reliability of the LLP-method?
- How does the combination of the different peak distances to a single data set affect the significance of the weld depth determination by means of the LLP-analysis?

2. Experimental setup and methods

2.1. Experimental setup

The OCT measurements were performed during the welding of hidden T-joints on a length of 80 mm. The face sheet had a thickness of 0.8 mm while the web sheet had a thickness of 1.5 mm. The weld experiments were conducted on metal sheets consisting of pure nickel pure nickel (NI99.5). In all configurations the weld seams were located right in the middle of the edge of the web sheet, thus the process zone containing the melt pool and the keyhole was surrounded by solid material at any given time. For the experiments a disk laser of the type TruDisk 12002 from the manufacturer TRUMPF operating at a wavelength of 1030 nm was used as a laser source in combination with a processing head of the type YW52 from the manufacturer PRECITEC. Using a fiber core diameter of 200 µm along with aspect ratio of 3:2 the nominal focus diameter resulted in 300 µm. The processing head was equipped with an OCT-measuring-module with a focal diameter of approximately 70 µm using a probe beam generated from a superluminiscent diode (SLD) with a central wavelength of 1550 nm, a spectral width of 35 nm (full width at half maximum) and a power of 40 mW. A schematic of the process configuration including the applied parameters is given in fig. 2. For the OCT-measurements the maximum sampling rate of 70 kHz was used and from the resulting Fourier spectra in spatial domain at each time step the highest 5 peaks above the intensity threshold were recorded sorted by their intensity in a descending order. The peak intensities in the Fourier spectra in the recording software IDM from PRECITEC range between 0 and 999. An intensity threshold for peak detection of 25 was applied so that alle peaks below that threshold were considered noise and neglected. The weldments were performed at three different process velocities 50 mm/s, 100 mm/s and 200 mm/s at a constant weld depth of ~1.6 mm, thus for each process velocity the laser power was adjusted to obtain the required weld depth.The laser beam was aligned perpendicular to the surface and argon was used as shielding gas throughout the experiments flowing at a rate of ~0.5 L/s. All experiments were repeated three times to validate the results statistically. The standard deviations being referred to in the results chapter relate to the deviations from these three experimental repetitions.



Process parameters	
laser power	1.25 … 4 kW
laser wavelength	1030 nm
process velocity	50 … 200 mm/s
weld depth	~1.6 mm
beam inclination	0°
focal position	0 mm
spot diameter	300 µm
weld length	80 mm
material	Ni 2.4068

OCT parameters	
central wavelength	(1550 ± 35) nm
SLD power	40 mW
sampling rate	70 kHz
spot diameter	~70 µm

Fig. 2. Experimental setup for the weld experiment including the applied process and OCT parameters

2.2. Methods

OCT is an optical measuring technique that is based on the principle of white light interferometry. In the case of one-dimensional frequency domain OCT (FD-OCT) as it is applied in this case, a certain continuous portion of the light spectrum is used as light source for an interferometric measurement of a surface with the surface acting as a reflector in an interferometric arm as depicted in fig. 3. Each wavelength of the OCT spectrum fulfills unique interference conditions depending on the distance of the reflecting surface to be measured. The OCT detects the interference pattern on a line-detector discretely resolved by the wavenumber of the corresponding wavelengths, thus the Fourier spectrum of the depth distribution in the measuring region is recorded effectively. Performing the inverse Fourier transform of the recorded spectrum to the spatial domain yields a Fourier transformation of the wavenumber-resolved interference pattern where prominent peaks indicate measuring distances at which strong reflections of the probe beam occur (see fig. 3).

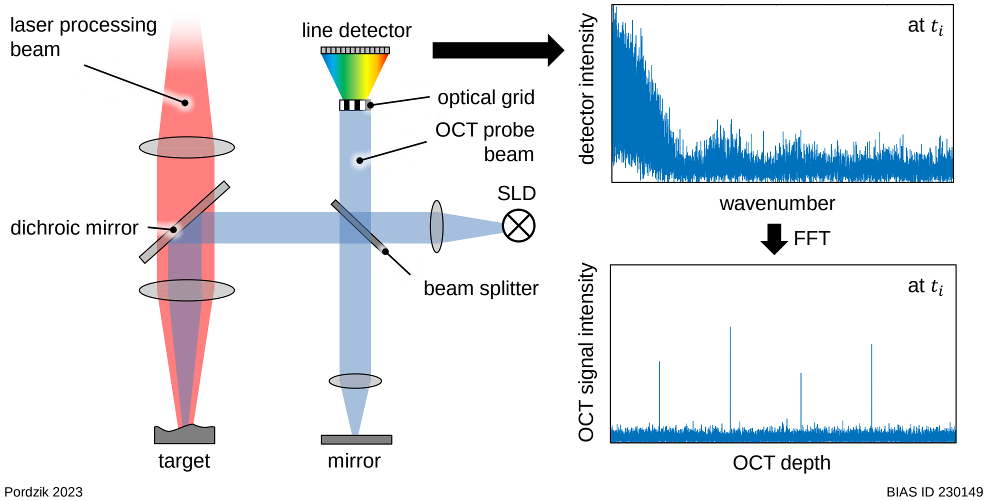


Fig. 3. Functioning principle of frequency domain OCT

The height of the peaks in the Fourier spectrum in spatial domain account for the reflection strength at a given distance, thus weighting the different distances of reflecting surfaces inside the OCT measuring spot by their intensities. As the reliability of detecting a surface at a certain distance increases with the peak prevalence in the Fourier spectrum in spatial domain the height of the peak, as being associated with the quality of the measurement, is also referred to as quality value.

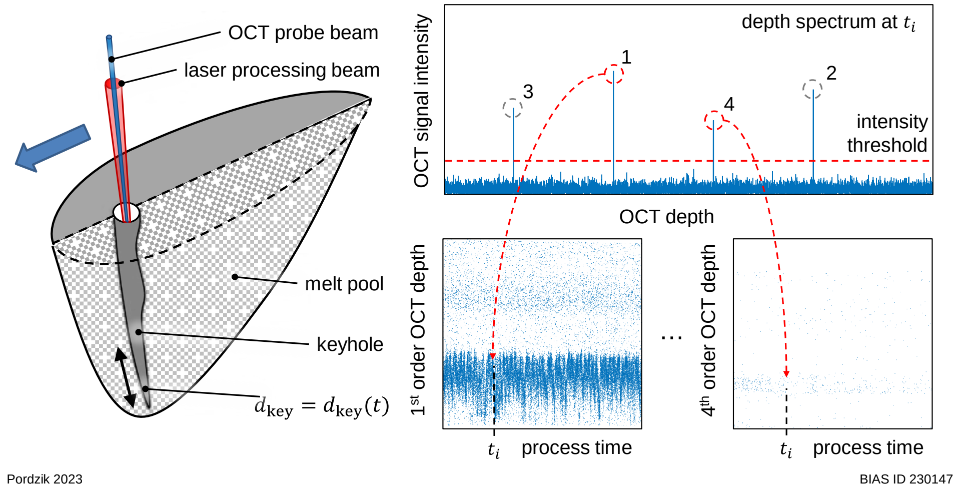


Fig. 4. Principle of the OCT data acquisition measuring the OCT depth spectrum at each time step and transferring the highest order peak positions to the time resolved OCT depth distribution (exemplarily for the 1st order peak)

Concerning the on-line weld depth monitoring of the keyhole process via OCT this means that fluctuations of the keyhole shape can obstruct the OCT probe beam adding other reflective geometric features from inside the keyhole to the OCT measurement than the keyhole bottom. As these obstructive features of the keyhole shape might not only contribute to the OCT spectrum but rather dominating it, the detectability of the keyhole bottom is potentially negatively affected when only the highest peak of the OCT spectrum in location space is considered for the weld depth evaluation. Therefore, it seems promising to consider higher order peaks of the OCT spectra so that the information about specific features like for example the keyhole bottom can still be found in those rather than being neglected completely. For the OCT measurements the highest five peaks at their corresponding distances in the Fourier spectrum in spatial domain were considered for the analysis including their respective intensity values. Fig. 4 shows how each Fourier spectrum in spatial domain contributes to the commonly known OCT depth distributions. The data was evaluated by means of the LLP-analysis introduced by Mittelstädt et al., 2019 using characteristics in the histographic distribution of the OCT data points to statistically extract the penetration depth from the noisy entirety of the OCT data points. According to their methodology the OCT data points are sorted into bins of a constant width that was chosen to be 100 µm in this investigation. The last local peak (LLP) in the histogram that exceeds a significance threshold is associated with the keyhole depth. The significance threshold itself is defined by an integer multiple of the standard deviation σ of the total frequency distribution above the average bin value and is used to exclude small fluctuations in the histographic distribution from the LLP-analysis. In this investigation the 2σ-environment above the mean bin value was chosen as the significance threshold. Two approaches of counting the data points for the histographic evaluation are investigated, the first by simply counting the number of data points belonging to a certain depth bin and the second by additionally weighting these counts with the intensity of the respective Fourier peak of the according data points, thus taking into account the significance of the detected geometric feature that is represented by the peak, as depicted in fig. 5. In the following the values obtained from the method counting the data points by number are referred to as frequencies while the intensity-weighted counts of data points are referred to as integrated intensities.

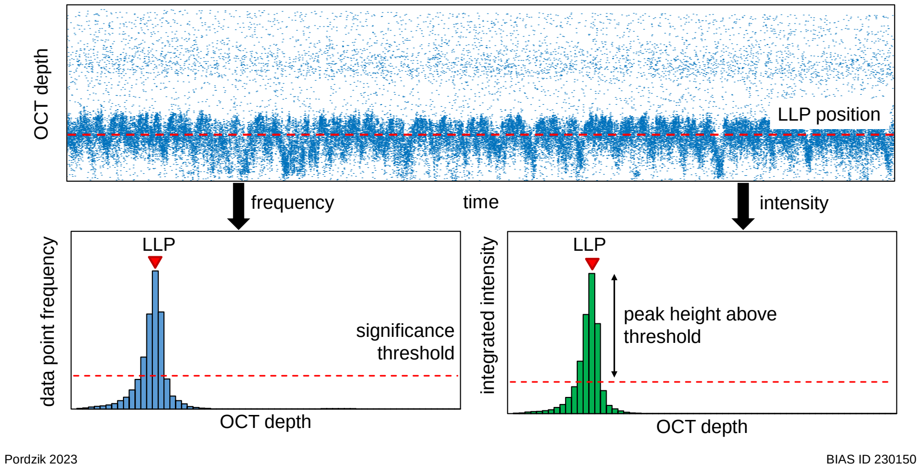


Fig. 5. Histographic LLP-analysis transferring the OCT depth distribution to a frequency distribution with the last local peak being associated with the keyhole bottom

The set of valid data points is analyzed regarding the distributions of the depth values sorted by the peak order individually as well as the distribution from all peaks combined, with respect to the counts per bin as well as the integrated intensity per bin. A data point is considered valid when its intensity surpasses the intensity threshold and when its depth value lies below the sample surface located at 0 µm, thus potentially originating from inside the keyhole. From all performed measurements the inner 90% of the measuring signal were selected for further analysis to exclude effects from the start and the end of the laser welding process that generally exhibit different behaviors. To enable the different analyses to be compared properly the histograms are normalized with regard to the overall sum of their bins. The significance of the LLP is measured in terms of its relative height above the significance threshold. The frequency distributions for LLP-analysis were calculated for the whole timespan of the welds, thus the extracted keyhole depth represents the mean value along the complete inner 90 % of the weld length and therefore no time-resolution or spatial resolution in the welding direction respectively of the weld depth is considered in this investigation.

3. Results

The OCT-measurements were analyzed regarding the properties of the depth distributions from the different peak orders. Furthermore, the two different counting methods for the histographic analyses as described in chapter 2.2 were tested on the data. The resulting distributions were analyzed with respect to the following three properties:

1. Ratio of valid counts
2. Measured depth at the LLP
3. Relative height of the LLP above the intensity threshold as a measure of the LLPs unambiguity.

The emphasis of the investigation lies on the welding of nickel at a process velocity of 200 mm/s, while the other investigated processes are considered for comparison and validation of the generalizability of the results. At first the ratio of valid counts, in the following being referred to as validity ratio, sorted by the different peak orders is analyzed. In this context data points that pass the pre-filtering conditions described in chapter 2.2 are considered as valid for further analysis. The validity ratio is defined as the quotient between the fraction of valid counted values and the total amount counted values in the evaluated data region, where counted values either refer to the frequency of data points or their integrated intensities depending on the counting method. Regarding the data point frequency, the validity ratio is related to the mean effective measuring frequency as it represents the effective percentage of OCT measurements considered for the LLP-analysis.

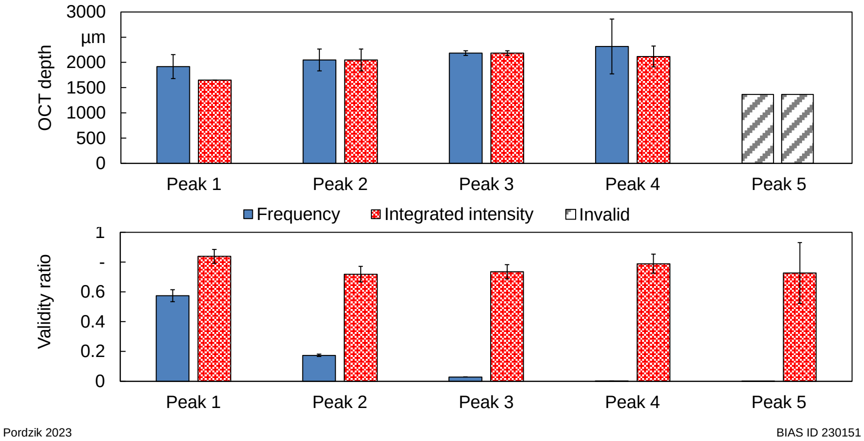


Fig. 6. Distribution of the keyhole depths and validity ratios obtained from LLP-analyses of single OCT peak data sorted by the peak orders for the two counting methods by data point frequency and integrated intensity for the welding of nickel at 200 mm/s

The integrated intensities on the other hand can be associated with the quality of depth information contained in the data. Fig. 6 shows a comparison between the validity ratios for both counting methods depending on the peak orders. With increasing peak order, the frequency distribution becomes increasingly sparse, therefore resulting in a much lower validity ratio and effective measuring frequency respectively for higher order depth peaks.

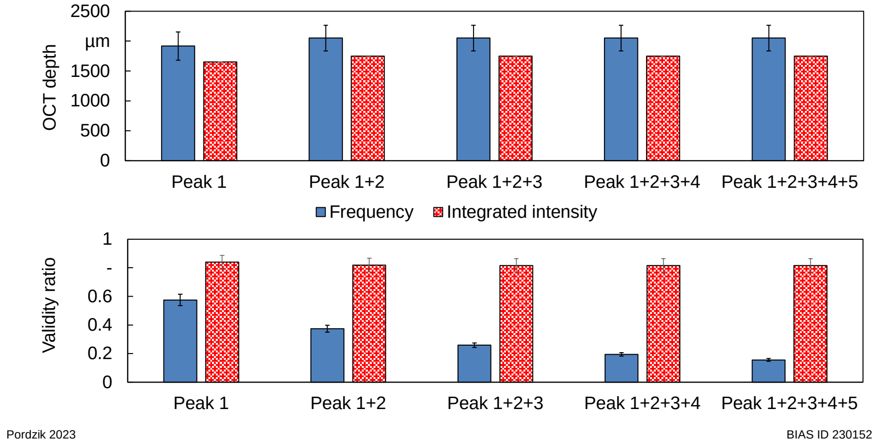


Fig. 7. Distribution of the keyhole depths and ratios of valid counts obtained from LLP-analyses of successively combined OCT peak data sorted by the peak order combinations for the two counting methods by data point frequency and integrated intensity for the welding of nickel at 200 mm/s

The validity ratio of the integrated intensity on the other hand is only mildly affected by the peak order as peaks below intensity threshold do not contribute significantly to the total intensity of all data points. So, even though much fewer data points are considered for evaluation in the case of higher order depth peaks those few data points still contain almost the complete amount of peak intensity.

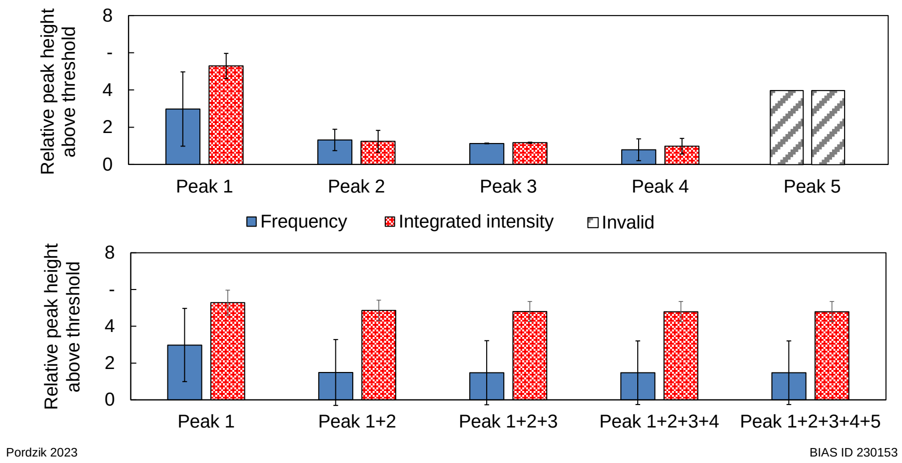


Fig. 8. Distributions of the relative peak heights above the significance threshold sorted by the OCT depth peak order for the two counting methods by data point frequency and integrated intensity for the welding of nickel at 200 mm/s

Secondly, investigations of the peak order related depth analysis were conducted. The results shown in fig. 6 indicate that the highest 4 depth peaks yield similar values while the data point distribution derived from the 5th order peak yielded no peak above the significance threshold. During the other processes all 5 peaks yielded similar depth values in the range of the expected weld depth. Regarding the counting method both methods yield depth values very close to each other while the standard deviation between the measurements is significantly lower for the intensity weighted counting. As the frequency distributions for different depth peak orders yield similar depth values for the LLP-analysis it seems advisable to combine the peaks of different orders successively to a united data set to make use of their complementary composition. The results depicted in fig. 7 for the experiments performed on nickel at 200 mm/s show that combining the different distributions has almost no impact on the extracted weld depth despite a reduced standard deviation for the frequency-based analysis. Nonetheless, the two different counting methods applied for the histographic analysis yield depth values that differ significantly by about 300 µm. For the other process parameters, the discrepancy in depth vanishes with the inclusion of higher depth peak orders. The significance of the LLP-analysis as aforementioned characterized by the relative LLP-height above the significance threshold is shown in fig. 8. The relative height decreases drastically with increasing peak order. Furthermore, the intensity-weighted frequency distributions show significantly higher values for the 1st order peak while for peaks of higher order the values for both counting methods are close to each other. For the weldments in nickel at 200 mm/s this behavior is most pronounced while for the other experiments both counting methods show similar values for the significance of the LLP. At all process velocities investigated the integrated intensity method shows slightly higher significances for welding pure nickel.

4. Discussion

The increasing sparseness of the data point distributions for higher order peaks is in good accordance with the expectations as peaks with lower intensity are more unlikely to surpass the intensity threshold. Depending on the choice of the intensity threshold, which in this case was set to a value of 25, the neglection of data points only leads to a small loss of intensity, thus only mildly affecting the overall intensity considered for evaluation. The influence of including higher order depth peaks in the LLP-analysis decreases with increasing peak order, yet the contributions of 2nd and 3rd order peaks are still significant. Analyzing the weld depth for each peak order individually mostly depth values in the expected range of the weld depth are found despite some significantly higher values for the 4th and 5th order. While the higher depth values can be attributed to multiple reflections of the OCT probe beam inside the keyhole, the permanent absence of smaller values indicates, based on the functioning principle of the LLP-analysis method, that for all peak orders most of the peaks either originates from the keyhole bottom or from multiple reflections, thus identifying the depth information carried by the peaks of different order as complementary to each other. The discrepancy in depth resulting from the LLP-analyses based on the two different counting methods indicate that the majority of data points does not necessarily coincide with the highest intensities on average. To validate the more accurate method comparisons with a statistically sufficient amount of metallographically obtained weld depths will be necessary in future investigations. The significances of the LLP-analyses deviations depend strongly on the process velocities. As the process velocity has a major impact on the process dynamics and the keyhole fluctuations it seems plausible that the statistical properties of the OCT-based depth distributions depend on this parameter. The intensity-weighted counting method exhibits significantly higher values for the relative LLP height indicating an increased unambiguity and significance of the weld depth measurement. This also means that those measurements that are accumulated in the LLP also yield the highest intensities by average.

5. Conclusions

In this study the influence of different peak orders from the FD-OCT depth spectrum on the histographic depth analysis has been investigated regarding the keyhole depth obtained from an LLP-analysis alongside the significances of the results by measures of the relative LLP-height above the significance threshold. Furthermore, the ratios of valid counts for the two different counting methods, either by the data point frequency per depth bin or the integrated intensity, were evaluated. Answering the initially posed research questions the following conclusions are drawn:

- The depth distribution derived from different peak orders from the OCT depth spectrum yield similar depth values. Therefore, including higher order peaks in the OCT data scope increases the reliability of the LLP-filtering method for keyhole depth analysis.
- Weighting the data points by the peak intensities yields higher significances of the LLP for all five peak orders that were considered for analysis.
- For the investigated processes the deviations of relative LLP-heights above significance threshold regarding the two proposed counting methods indicate that data points that accumulate in the LLP also yield higher intensities on average. Therefore, a significant correlation between peak intensities and data point frequencies of the OCT-measurements can be concluded.
- Effectively it can be stated that including higher peak orders and applying intensity-weighted counting sharpens the last local peak in the frequency distribution, thus increasing the measurements' reliability and raising the potential of increasing the time resolution for LLP-filtered depth measurements.

Acknowledgements

The authors gratefully acknowledge funding from the German Federal Ministry of Education and Research (Funding number: 03HY119F).

References

Bautze, T., Kogel-Hollacher, M., 2014. Keyhole Depth is just a Distance, Laser Technik Journal 11, p. 39

Huang, D., Swanson, E., Lin, C., Schuman, J., Stinson, W., Chang, W., Hee, M., Flotte, T., Gregory, K., Puliafito, C., 1991. Optical coherence tomography, Science (New York, N.Y.) 254, p. 1178

Kawahito, Y., Matsumoto, N., Abe, Y., Katayama, S., 2011. Relationship of laser absorption to keyhole behavior in high power fiber laser welding of stainless steel and aluminum alloy, Journal of Materials Processing Technology 211, p. 1563

Mittelstädt, C., Seefeld, T., Kogel-Hollacher, M., 2019. Novel approach for weld depth determination using optical coherence tomography measurement in laser deep penetration welding of aluminum and steel, Journal of Laser Applicatons 31, p. 022007

Pordzik, R.; Mattulat, T., Woizeschke, P., 2022. Effects of reduced ambient pressure on the OCT-based weld depth measurement signal in laser welding of aluminum and steel, Procedia CIRP 111, p. 541

Schmoeller, Maximilian; Weiss, Tony; Goetz, Korbinian; Stadter, Christian; Bernauer, Christian; Zaeh, Michael F., 2022. Inline Weld Depth Evaluation and Control Based on OCT Keyhole Depth Measurement and Fuzzy Control, Processes 10, p. 1422

Schou, C., Semak, V., McCay, T., 1994. Acoustic emission at the laser weld site as an indicator of weld quality, Proceedings of the Laser Materials Processing Conference: October 17 - 20, 1994, p. 41

Sokolov, M., Franciosa, P., Al Botros, R., Ceglarek, D., 2022. Keyhole mapping to enable closed-loop weld penetration depth control for remote laser welding of aluminum components using optical coherence tomography, Journal of Laser Applications 32, p. 032004

Stadter, C., Schmoeller, M., Zeitler, M., Tueretkan, V., Munzert, U., Zaeh, M., 2019. Process control and quality assurance in remote laser beam welding by optical coherence tomography, Journal of Laser Applications 31, p. 022408