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# An autonomous laser weld seam planning and tracking system by integrating OCT to scanner-based laser machines

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**Abstract**

Within the field of laser material processing for mass production items, standardized, automated machine systems are widely available on the market. Process geometries as well as process stability parameters can be tuned reaching an optimum system performance. But when it comes to small batch or one-piece manufacturing, this set-up effort drastically effects the overall product costs due to high personal investments and large machine downtimes. Automated seam-tracking and quality control systems offer a great opportunity for increasing such laser welding systems' performance. By implementing an OCT (optical coherence tomography) seam tracking system into a scanner-based laser welding system, the whole set-up procedure can be reduced to teaching a starting point and a starting vector, with the laser welding's control sensing and advance-planning the final weld geometry in real time without the need of a dry-run. This contribution is mainly about the hard- and software interaction for the developed autonomous weld seam detection system.

*Keywords: "optical coherence tomography; automomous weld seam planning; laser welding quality control; reduced set-up effort"*

## 1. Introduction

The impacts of optimized processes, standardized workflows and maximized tool-operation time are usually regarded as the key elements for offering market-adequate and competitive products within the sector of material processing (Krause & Gebhardt 2018). As this is also applicable for products being manufactured by laser-based processes, such as laser welding, the maximization of the laser-on time of a specific machine system is to be aimed for (Vyas 2019). For large batch-size productions, this can be achieved via cyle-time optimization by reducing the positioning times between several welds as well as the minimalization of the part-to-part exchange time. But when it comes to small-batch size manufacturing or even one-piece manufacturing, there are other, more significant factors influencing the worker-machine-systems efficiency. As those highly individual tasks can require largely different sets of parameters, programming and clamping fixtures, the ratio of machine set-up, including all previously mentioned factors to the actual processing time is usually far from ideal, resulting in highly inefficient and cost-intensive procedures. Therefore, in most cases, the technology of laser-based processes is still restricted to products with lager batch sizes. Nevertheless, the batch size required for an appropriately time- and cost-efficient laser process is constantly decreasing, but when it comes to one-piece product individualization, laser processing still not reachable in most cases (Kos et al. 2019). As machine set-up times consist of creating improvised fixtures, programming the individual weld seam geometry, checking the correct positioning of the weld seam and determining the correct process parameters, this set-up procedure can easily take up to several hours per individual part. With the welding action itself usually only taking a few mere seconds of time, the laser-on time and the actual machine running times are very low, resulting in on the one hand a low part output of the whole system and on the other hand high machine-running and personnel costs, which need to be charged for (Kiesch & Bautze 2018). Furthermore, the usage of improvised, low-cost fixtures usually does not allow for an exact re-positioning of the parts, resulting in a correction loop, where the NC-program needs to be adapted to the current weld seam position. This all comes down to parts being produced at very high cost, which offers great potential for optimization. In order to decrease the machine set-up time, the goal needs to be to reduce the amount of programming, seam planning and positioning correction, which furthermore needs to be done by highly skilled workers. Such an

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improvement can be done by developing and implementing an autonomous seam-planning procedure based upon weld seam detection systems, interacting closely with the machine system's control. Thereby, the set-up time can be decreased by a significant amount of time, as the machine systems reacts to the automatically detected weld seam position, generating and adjusting its welding trajectory by advance-planning the upcoming axis positions. Furthermore, when it comes to critical parts being produced, quality control and process stability are largely requested to a great extent by customers. To the current state of the art, this is usually taken care of by producing shift-repeating etched cross-sections of welded parts in order to show that the process is still running according to its specifications. With small batch-size manufacturing, such a procedure cannot be performed, as the quantity of available parts and the available timeline usually do not allow for destroying parts repeatedly for quality assessment procedures. Nevertheless, manufactures are still to guarantee for an exact weld seam positioning with a specified quality like e.g. the welding depth. This describes one issue, where this contribution aims to propose one possible solution about how to address this specific problem. This contribution is mainly about the development and implementation of such a seam tracking system into a laser machine system and the subsequent development of an autonomous seam planning system and to use the outcoming information to guarantee part quality even with small batch sizes. The mechanical, optical and system control adaptions are closely regarded.

## 2. State of the Art

Apart from the machine system being the basis for the implementation of such an autonomous seam planning tool, the seam tracking sensors are the key element for the development of such a system. In the following, the state of the art of such sensors is described. Seam tracking systems determine the position and the geometry of the weld seam based upon the sensor's measured data, acquiring the signal directly from the to be processed part itself and can therefore react to even minute misalignments or part deviations. Based upon this information, the position of the tool is corrected, in order to match each time with the current part geometry (Reek 2000b). In general, it can be distinguished between two major groups of sensors: tactile sensors and non-tactile sensors (Horn 1994). Within the group of tactile sensors, one has to cope with dynamic measurement effects such as wear effects and collision danger. Therefore, non-tactile sensors are usually preferred, which can further be divided into non-optical and optical sensors. Non-optical sensors rely on detecting geometric variations of the part by using different methods such as measuring different effects by using capacitive, acoustic, pneumatic or inductive methods. Those principles are proven concepts for very specific use cases, but when it comes to creating an universal system, those sensors have different limiting weaknesses. Pneumatic sensors are characterized by very small working distances, inductive sensors are restricted to metallic materials, capacitive sensors are limited within the detection resolution of objects (Zhao 1990). Optical sensors on the other hand are non-tactile and possess a high degree of precision, flexibility, robustness and the availability of imaging 3D-contours (Hesse &Schnell 2018). As an optical sensor always consists of an emitting and a detecting unit, the light signal transmitted from the emitter has a known set of parameters such as the amplitude, polarization, phase or direction. The changes to theses parameters due to the interaction with the workpiece can then be detected, measured and analyzed (Sackewitz 2014). There are different methods known to measure optically geometries. One possibility is to use stereo-image processing. Thereby a combination of triangulation and contrast changes are used to generate, based upon image processing algorithms, the shape of the workpiece. Opposed to stereo imaging, runtime-measurement and phase analysis rely on the pure optical characteristics of the reflected light. Based upon the specifications of the autonomous weld seam planning system, requirements for such an optical sensor system can be derived, which are:

- 3D-pointcloud determination of the weld seam and part geometry
- Resolution according to the measurement-resolution principle (equipment 10 times more precise than the scale to be measured): at least 10 µm
- Adjustable scanning position free of main movement system (2D-orientability)
- Working distance at least 150 mm in order to avoid damaging/influences due to process emissions

According to the described requirements, light-section sensors cannot be used for the underlying task due to their resolution, working distance and missing orientation freedom. One possible solution, which may be suitable is coming towards the industrial market in the last few years: the optical coherence tomography (OCT), figuring a measurement system based upon phase deviations and coherence patterns of different wavelengths interacting with the workpiece. The OCT usually aims for the gathering of 3D-tomography imaging of blurred media (Itoh et al. 2006). This measurement principle has then been adapted for the imaging of material topography, shaping the exact outline of a measured part (Dupriez & Truckenbrodt 2016). The OCT measurement is performed at specific points and the tomographic sectional image is generated by scanning with a movable mirror. When using a setup with two mirrors, three-dimensional scans can also be generated by scanning flat shapes. The information about the part geometry is generated via the detection of coherence deviations along the optical axis (Michelson Interferometer), resulting in extremely high resolutions along the beam direction of under 10 µm. Combined with adequate galvanometric scanner systems, 3D-imaging can be done within the same range of resolution (Sackewitz 2014). The following figure 1 shows the principle of the OCT system.

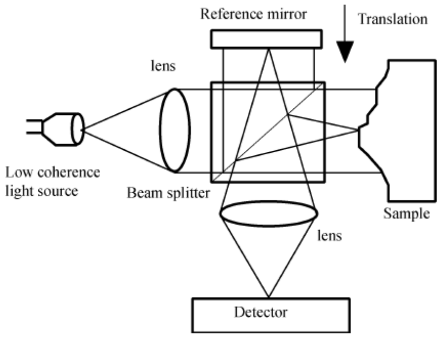

Fig. 1. Schematic set-up of OCT measurement system based upon a Michelson Interferometer (acc. Itoh et al. 2006).

Such OCT systems are already used for seam position correction systems (Sokolov et al. 2020) and therefore meets all the requirements described above. One step further is the in this contribution proposed autonomous seam planning system.

## 3. Implementation of the autonomous weld seam planning by using OCT

In the following, the optical, mechanical and NC-control implementation is described. The whole system has been developed at a german SME-manufacturer for custom-designed laser welding machines. The adequate machine system basis, which is already designed to meet the demands of product- process and performance flexibility for the manufacturing of customer-individualized products, is the **ER**LASER® Universal 522 laser welding system and is therefore used for the implementation of such an autonomous seam planning system. The following figure 2 shows the schematic machine system concept.

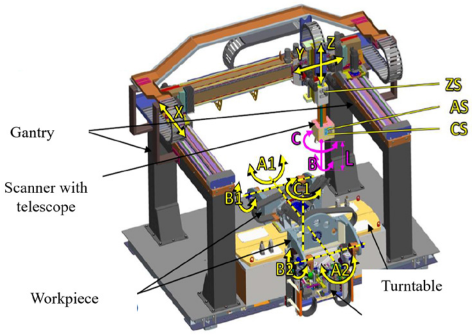

Fig. 2. Schematic set-up of the **ER**LASER® Universal 522 (**ER**LAS 2020)

The system is a full five-axis machine system with a hybrid kinematic, as the A and B axis are built as a turn/tilt table underneath the gantry system, resulting in an absolute positioning accuracy of <0.1 mm. The laser welding optic is a scanner-based system with telescopic focal point adjustment, mounted at the Z-Axis, allowing for maximum flexibility and low processing times. During the integration of the OCT system, several requirements had to be met regarding the mechanical and optical setup. First of all, as the OCT is placed within the same beam path as the process laser, a dicrotic mirror needs to be placed into the beam path, allowing the OCT's scanning laser to enter the general optic path. Furthermore, the already integrated visual camera reference system was still to be in order to simplify the teaching process, resulting in a second dichroitic mirror. As those two additional optical elements change the length of the optical set-up, the telescopic focus point adjustment is compromised. In order to counteract, the existing optical design needed to be shrunk by the amount of length added by the two dichroitic mirrors. These dichroitic mirrors are custom-made, as they need very specific characteristics in order to allow the process laser, guiding laser, OCT laser and visual camera image to reflect or transmit at the right place. In terms of NC-Control integration, one major step is to align the focal points and coordinate systems of process laser and OCT in order to refer amongst them without losing time for transformation calculations. Regarding the autonomous seam planning algorithm, there is a major difference to existing OCT seam correction systems, where an already known seam geometry is only corrected position-wise to the real part. The autonomous seam planning system uses the OCT scanning system to determine the weld seam in front of the processing laser in order to calculate in real-time within the calculation-tact of the NC-control the position, where the processing laser is to be moved to next. This is made possible by cross-calculating the current welding direction vector with the OCT-scanning vector perpendicular to it and placed in front of the keyhole perimeter. By detecting the vector deviation in advance, the position the welding spot needs to be at a specific coordinate is known and can be stored. By constantly checking in a recursive function which of the stored weld seam points is closest to the current one, the machine can autonomously decide where to move the processing laser next. This results in a welding process where the weld seam is not known in advance, only the seam geometry (e.g. butt joint) needs to be specified. By constantly keeping track of the already welded position, the system can also determine, if the welding geometry is a closed shape like e.g. a circle, if the starting position has been reached and can automatically end the welding process. For coping with the alternating orientation of the welding vector when welding non-linear contours and therefore alternating OCT scanline directions, a signal containing the current welding vector is transferred every 0.5 ms to the OCT control system and is used to calculate the perpendicular orientation of the scanline. This transformation is key for the recursive advance-planning of the weld seam, as therefore one part of the weld seam offset position can be considered as constant. This constant is defined by the scanline offset from the process lasers tool center point and is usually defined by the least distance from which point on no process emissions like e.g. weld splatters distort the signal (approx. 2 mm).The usage of such an OCT system also allows for an in-process quality control concerning the welding depth. Due to the high positioning speeds of the OCT scanner, scan lines can be placed not only in front of the keyhole for the determination of the weld seam but also within the tool center point, measuring in-process the depth of the keyhole ground relative to the parts surface. With this feature, 100% of the parts can be checked for proper weld seam positioning and weld seam depth, improving the quality control to a large extent and reducing the amount cross-sections needed to a minimum.

## 4. Conclusion and outlook

In general, there is a strong competition in the OCT market, with several competing products supplied e.g. by Precitec, Laserline or Lessmüller. As the proposed autonomous tracking system does strongly depend on the the access to raw, processable data finally leads to the chosen supplier. All in all, the described system is able to reduce the set-up time for unknown parts with small batch sizes by up to 60%, as the worker only needs to teach a starting point and a first, rough weld direction vector. The complete seam planning of the welding path in three dimensions within a position accuracy of < 0.1 mm is achieved by the implementation of the OCT sensor scanning system and the recursive point cloud algorithm within the NC-core of the welding system. Nevertheless, the integration of such a system is highly cost-intensive due to large initial development costs and still high material costs. But with OCT systems just taking off in the industrial market, it is expected that prices will reach into more economically efficient regions. At the current state of the project, the welding speed of the system is still limited to a few m/s. Further improvements on the recursive programming of the algorithm are to be made in order to be able to weld with speeds that are even higher. This results in a larger field of application, directly leading an increased customer target group with a greater production part field.

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