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Quantification of geometric properties of the melting zone in laser-assisted welding

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Abstract

By using camera systems – suitable for industrial applications – in combination with a large number of different measurement sensors, it is possible to monitor laser welding processes and their results in real-time. However, a low signal to noise ratio at framerates up to 2,400 fps allows only limited statements about the process behavior; especially concerning the analysis of new welding parameters and their impact on the melting bath. This article strives towards research of kinetic and geometric dependencies of the melting zone induced by different laser parameters through usage of a camera system with a high frame rate (1280×800 by 3,140 fps) in combination with model-driven image and data processing.

Keywords: laser welding; image processing; regression analysis

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1. Motivation

3D-MICROMAC AG is the industry leader in laser micromachining. The company develops processes, machines and turnkey solutions at the highest technical and technological level. Its products are used in industries such as photovoltaics, semiconductor and medical technology.

Especially in the latter case, different production processes became established during the last years, for all of which laser beam welding of metallic/non-metallic materials acted as an integral element. In regards to the dimensions of the workpieces in the field of laser microprocessing, these processes bring with them new specific challenges due the boundary conditions. The thickness of the used semi-finished products primarily amounts to between several 10 µm and up to several 100 µm.

Based on (Beske, 1992), the parameters which have an influence on a laser material process can be separated into four groups – parameters of the: laser, machine, material and workpiece. With a skilled manipulation of these parameters, it is possible to raise the quality of the process results or in this case of the welding joints. However, this requires a precise setup of the laser system and a highly accurate analysis of the welding process. The analysis concerning positive or negative effects, which are the consequences of the parameter modifications, takes place after the process, on a random basis test method (e.g. x-ray; metallography; fatigue tests). Another possibility of analysis are high-speed video recordings of the melting bath with 2,000 frames per second at a resolution of 1024×768 pixel. With this method, not only statements about process behavior, but also about the quality of the welding joint are possible. In the area of industrial series laser microprocessing, this will be the only way to prove the quality of the process, because, other methods have a lower resolution or involve a disproportionate amount of time effort. The model-driven image and data processing applied to high speed video footage (Kowerko et al., 2016) proved to be a key element for the quality assurance.

The present article focuses on the research of kinetic and geometric dependencies of the melting zone and consequently of the joint quality due to different laser parameters under usage of model-driven image and data processing. The focus lies on the characterization of the process as a function of time, place and specific parameters, such as laser power, welding speed or gas volume flow. The approach uses the visual appearance of the melting bath as reference. Due to perspective distortion and depending on time it has the shape of an ellipse with variable spatial dimensions. A test version of the software as well as example videos are available for download.

2. Related Work

In contrast to destructive/non-destructive material tests, well-known suppliers such as TRUMPF GMBH & CO. KG or PRECITEC GMBH & CO. KG offers different solutions of online monitoring for laser welding processes. In this way, it is possible to get quantitative and qualitative statements about every single step of the process. Under the use of various measurement equipment, e.g. triangulation measurement system, high-speed camera and other sensors, which is integrated in the processing head numerous data will be collected, processed and protocolled by the evaluation software. There is also the possibility to use controlled variables derived from the measurements to affect the process online, (Precitec GmbH & Co. KG, 2016) and (TRUMPF GmbH & Co. KG (Hrsg.), 2016). Herewith, a complete monitoring of the process is realizable – both in terms of the location of the joining gap (pre-process), its focal spot (in-process) and its finale welded seam (post-process). The associated time/cost-intensive expense of corresponding checks is reduced by the use of such systems and recommends them above all for large series applications. Therefore, the user is in a position to make highly accurate statements about nearly 100 % of its produced welded seams. Thus, these systems are highly effective and to a certain extent capable of learning, but they are based on the "classical" behavior of a laser welding processes. This is also reflected in the design of the single components – e.g. cameras with frame rates between 333 fps and 2,400 fps and resolutions below 1 Megapixel – too low for an exact analysis of micro-welding-processes.

A technology for generating temporally alternating (pulsed) gas flows in the field of laser applications was developed by 3D-Micromac AG and the professorship "Schweißtechnik" Chemnitz University of Technology within a BMBF (Bundesministerium für Bildung und Forschung) "KMU-innovativ" research project. As a result, significant effects of the process influence on different laser-based processes could be determined. The influences of the parameters are subsequently to be recorded and documented with the help of the high-speed video analysis.

In literature, image processing techniques are not standard in the geometric and kinetic analysis of laser welding processes. In (Kawahito et al., 2011), a 10 kW fiber laser beam, driven at welding speeds from 17 mm·s^{-1} to 300 mm·s^{-1}, is recorded in coaxial visual sensing geometry to determine the maximum absorptions of the steel and aluminum. From the high-speed video camera recordings geometric information were presented only as schematic representations deduced from single images. Other authors apply image processing to geometrically analyze stainless steel weld pools and keyhole, again using coaxial visual sensing (Gao et al., 2011). The authors designed an image processing algorithm to identify weld pool front and rear edges and the keyhole. More details about the used algorithm were introduced in (Luo and Shin, 2015) also in the context fiber laser welding processes captured by coaxial imaging. A newly developed edge detection algorithm was developed based on maximum gradient of greyness to extract geometric weld pool information. The weld pool widths are validated by manual measurements of the welding seam and also generated as function of the frame numbers.

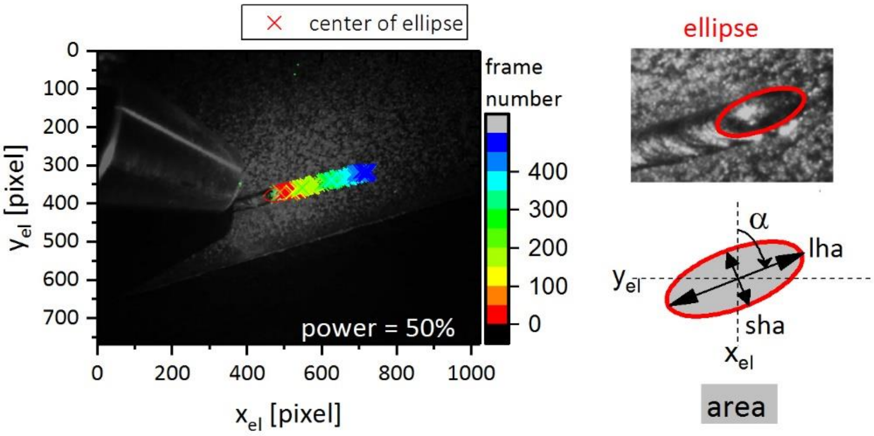
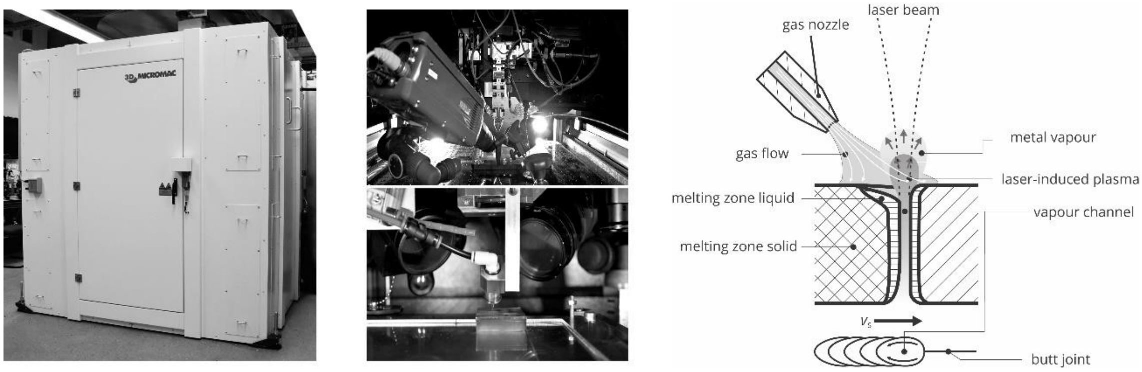


Fig. 1. Single frame from a high speed camera recording showing the inert gas nozzle and a part of the produced melting zone: The color-coded markers indicate the temporal progression of the melting zone center in units of frame numbers (frame rate = 2'000 fps). As indicated on the right, the melting zone will be approximated by an ellipse with its geometric parameters (center, semi-major, semi-minor and the angle α. The distance between nozzle and melting zone remains constant.



(a) (b) (c)

Fig. 2. (a) modular laser processing center “microWELD” - positioning and repeat accuracy less than 10 µm at a speed larger than 1 $\text{m}\cdot\text{s}^{-1}$; (b) front and rear view of the test setup including high-speed camera and lighting system; (c) schematically view of the deep-welded effect with lateral gas nozzle

Compared to other approaches, a diagonal perspective (see Fig. 1) was used, a parameter-optimized image processing algorithm adopted to our video material and present a geometric and kinetic analysis of the weld pool using linear regression. Geometric as well as kinetic parameters were derived for more than 100 videos, each recorded using different device parametrization. This allows for visualization of a broad range of dependencies between device parameters and weld pool geometry and kinetics.

3. Procedure

Here, we will present the experimental setup describing the technical key parameters, their varied range and the obtained video material. An image processing algorithm was developed to localize the weld pool, which was modelled using an ellipse whose parameters are monitored as function of observation time and space during the welding process. Geometric and kinetic parameters of the weld pool are finally correlated to technical parameters like the laser power or the driving direction and velocity of the gas nozzle-laser group. Finally, we present a user-friendly software hosting the complete workflow.

3.1. Specification of the laser machine and the test

By following the technical literature, e.g. (Beske, 1992) or (Poprawe, 2005), material processing under the use of a laser beam is characterized by four groups, amongst others by the properties of the laser (wavelength [λ], beam diameter [d_L], power [P_L], etc.). These are ordered from source through optics to the workpiece. The interaction of these characteristics produces different effects on surface of the workpiece, e.g. depending on the intensity – I_L; see formula (1) – in combination with the exposure time of the beam, a melting zone will be generated. This allows for the creation of compounds of two different materials.

$$I_L = \frac{P_L}{d_L} \tag{1}$$

If I_L reaches a critical value ($I_{L;steel} > 1 \cdot 10^6$ W·cm^{-2}) the energy will be high enough to heat up the material over its evaporating temperature and in the middle of the melting zone a keyhole is formed. The relation between width and penetration of this kind of process is very high – up to 1:10 and bigger – and due the movement of the beam and the keyhole relative to the material a joining will be realized. This is called the deep-welded effect; small seams with high penetration (see Fig. 2c). For the realization of these, special laser processing center are needed like the "microWELD" by 3D-MICROMAC (Fig. 2a). Behind this lies a machine concept with an overheaded gantry – positioning- and repeat accuracy of less than 10 µm at speeds of 1 m·s^{-1}. The system is designed for different applications and uses scanner or fixed optics for positioning of the beam. Likewise, the beam source used is not tied to the system, but is freely selectable. During the research of the localization and the geometrical approximation of the melting zone an IPG Phontonics single mode fiber laser (λ = 1064 nm; P_L = 1000 W) was used.

The recording for the high-speed video analysis was taken under the use of a PHANTOM V310 camera, which was freely integrated into the machine room of the system (Fig. 2b). The camera has a maximum frame rate up to 500,000 fps depending on the resolution. In combination with the exposure system of CAVITAR LTD, which is controlled by the camera and illuminate the object via a pulsed diode laser, every 500 µs a highly accurate still image of the process was recorded and was made available for the analysis. They are the base for the following geometrical research, which are determined through a series of cascaded methods of industrial image processing. For this 95 high-speed videos with up to 1000 frames (1024 x 768 pixel) per video were used – raw data 127 GB. These videos include two different positions of the camera at the same choice of the process parameters.

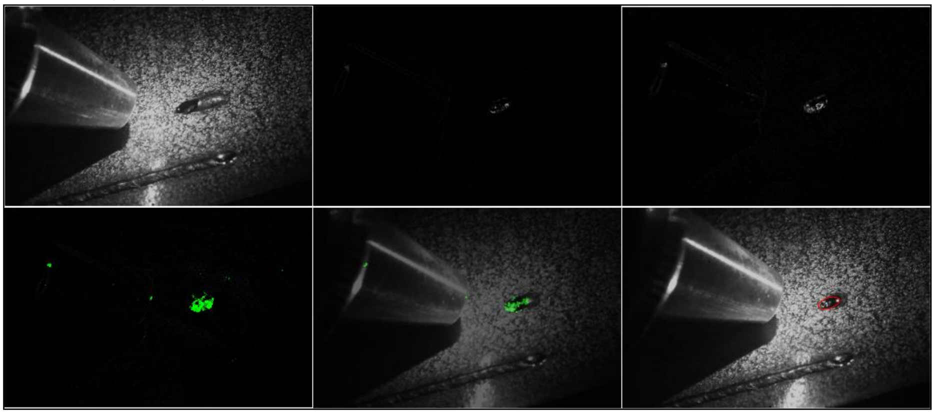


Fig. 3. Image processing steps, from left to right and top to bottom: original image, difference image, Sobel edge image, colorized edge image, morphology image, result image

3.2. Image processing for melting zone localization and spatial description

The technical analysis of the welding zone consists of a two-stage process. In the first step, the image processing process, which is used to detect and approximate the ellipse of the melting zone. Afterwards, the recorded ellipse parameters will be compiled for further processing of their dependencies to the physical parameters of the observed welding process.

The image processing used to determine the ellipse position, angle and size in each image of the video consists of several stages, implemented in EmguCV (Emgu Corporation, 2017), which is a .NET-compatible implementation of OpenCV (Bradski and Kaehler, 2008). The precise workflow was documented in a previous publication of (Kowerko et al., 2016). In Fig. 3, we visualize the specific image processing steps within a single frame. Since the processed videos show the movement of the melting nozzle and its impact on the target material over time, these two components hold the primary changes from one image to another. Therefore, the first steps to create a difference image, which only displays the part of the image where it differs from its predecessor. Since this is susceptible to noise between the images, it is followed by a Gaussian filter with both 3 and 7 pixels as range. Each of the resulting images is subjected to a different edge detection algorithm (Canny for the 7-pixel Gaussian filter, Sobel for the 3-pixel Gaussian filter), which results are subsequently merged into a singular edge difference image.

Using the morphological operations on the resulting edge image allows for a selection of edges based on size, the elimination of elements of miniscule size and unfavourable brightness and the removal of objects with non-continuous edges. This leaves a remaining number of ellipses, which accurately represent the possible basis for further operations. Adjusting the selection parameters through iterative testing over multiple videos of different parameters and perspectives lead to the current configuration, which omits sizable image noise, reflections and other sizable malformations. The remaining object represents the ellipse depicting the melting zone of the current welding process. Its parameters, namely position of the ellipse centre (depicted through x_{el}, y_{el} in *Fig. 1*), its two semi-axes (l_{ha}, s_{ha}), its tilt angle α and its area *A*, are subsequently compiled for each image, allowing for a recording of the time dependency of each parameter.

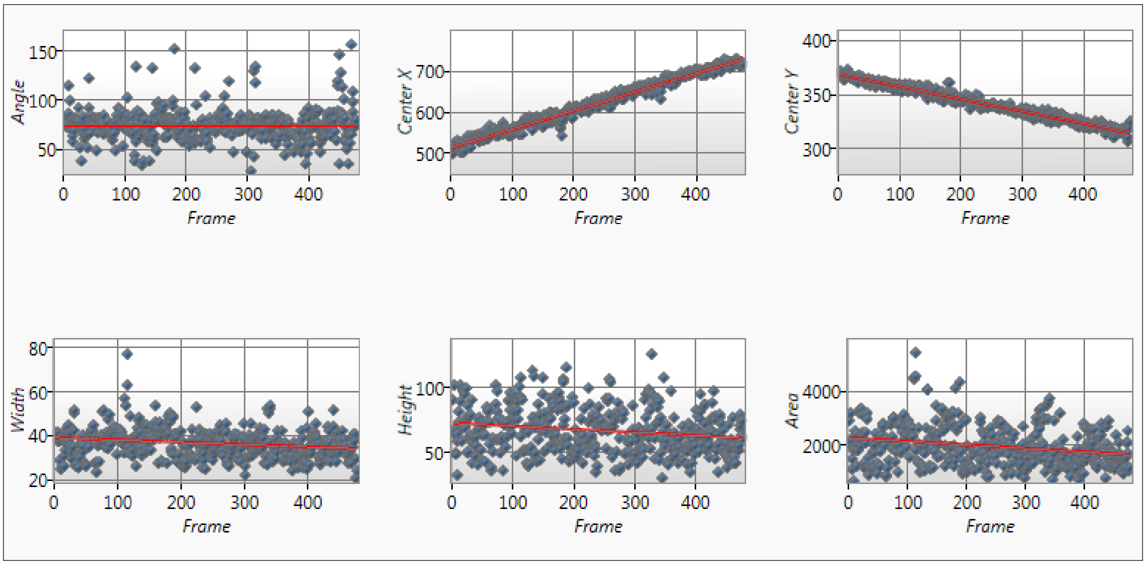


Fig. 4: Screenshot showing the temporal evolution of the ellipse parameters. The red lines represent the linear regression.

3.3. Welding Zone Geometry as function of device parameters

This time dependency allows to deploy linear regression to the ellipse parameters as function of time. The linear fit parameters are less prone to noise or even quantify the noise within the data, e.g. goodness-of-fit measures like mean square deviation. We claim that the amount of scatter within the data is dominated by low local signal to noise ratio and limited local contrast. Slope and absolute term, however, allow for identification of qualitative trends as well as quantitative measures describing the progression of the ellipse over the course of the video. For instance, **Fehler! Verweisquelle konnte nicht gefunden werden.** depicts a steady decrease in overall melting zone size over time. This information can subsequently be paired with the parameters of the welding process displayed in the video. For convenience, those are parsed from the video filenames directly subject to the condition of a predefined filename convention, e.g. "Schweissen_w45-a3-vm0-vg0-f0-p50-vs15_nach.mp4". Given parameters here are camera perspective (first word), angle of nozzle vs. Surface (w), distance (a), pulsed gas flow velocity (V_m), basic gas flow velocity (V_g), gas pulse frequency (f), laser power (P_L), nozzle velocity (v_s) and nozzle motion direction (nach/vor). This allows the creation of a connection between a certain physical/technical parameter of the welding apparatus and the resulting melting zone. In the experiments w and a remain constant (45° and 3 mm, respectively), while other parameters were changed in the following ranges:

- V_m = [0, 5, 10] $l \cdot min^{-1}$,
- V_g = [0, 5, 10] $l \cdot min^{-1}$,
- f = [0, 50, 100, 200, 400, 500] Hz,
- P_L = [0, 10, 30, 50, 70, 90] %,
- v_s = [10, 15, 25, 37.5, 50] $mm \cdot s^{-1}$ and
- direction (in/against process direction) from nozzle.

The results, obtained for 110 recorded videos, are provided as supplementary information at localize-it.de/downloads or Researchgate.net. Fig. 4 a) and b) show the ellipse area at the beginning of each video as function of relative laser power for different nozzle driving directions and camera perspectives.

If these values are broken down to the respective parameters, conclusions can be made about the behaviour/dependence of the melting zone as a function of the parameters. For example, the modification of the laser power affects a change in the size of the melting zone. This is filtered out of the high-speed videos by the analysis software and made available as a diagram for the user (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).

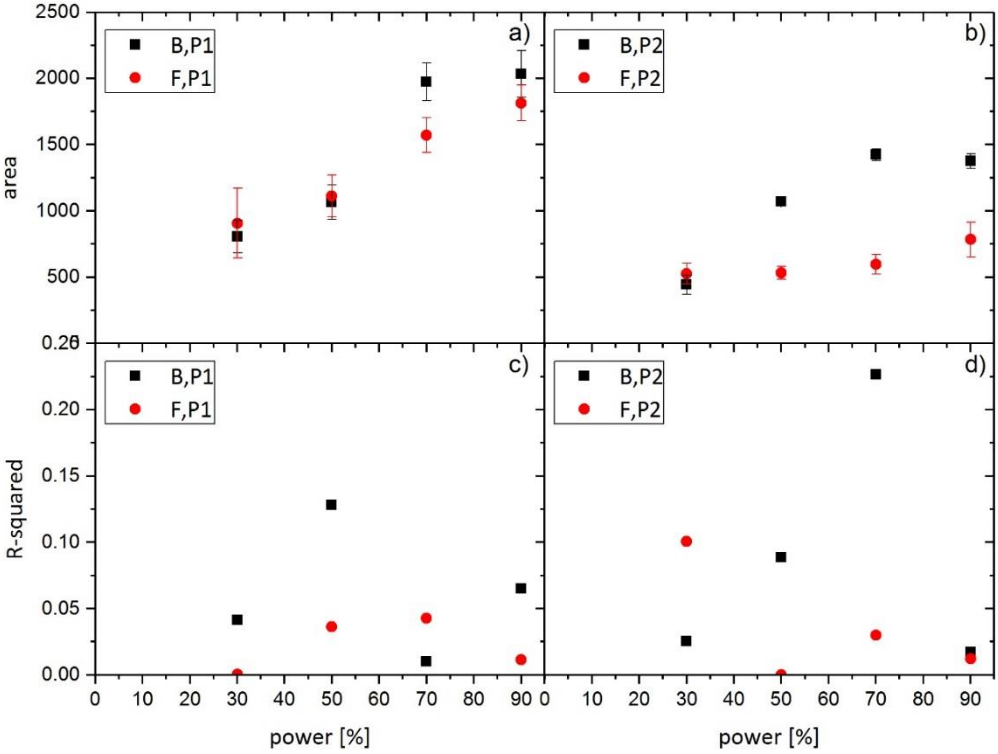


Fig. 4. a) and b) Ellipse area at the beginning of each video recording (frame 0) as function relative laser power in forward (F) and backward (B) driving direction of the gas nozzle and two camera perspectives: a) and c) perspective 1 (P1); b) and d) perspective 2 (P2). c) and d) show R-squared as function of laser power. Other parameters were fixed as follows: w=45°, a = 3 mm, V_m = 5 $l \cdot min^{-1}$, V_g = 0 $l \cdot min^{-1}$, f = 100 Hz and v_s = 15 $mm \cdot s^{-1}$

3.4. WPE – A weld pool analysis software tool

The computations previously described were merged into an intuitive graphical user interface (GUI) based of generalized software application called “WeldPoolEvaluation”, short WPE. It comprises the three modules of the analysis: (i) the image processing module to localize the ellipse, (ii) the ellipse quantification through linear regression and (iii) the visualization of all kind of ellipse and device parameter dependencies. This allows the user to not only process a single file through all steps of the analysis, but also to perform bulk operations, e.g. an overnight processing of a large database of videos, of which the resulting CSV-files can later on be used to analyse the dependencies of the welding parameters on the different ellipse characteristics. Detailed video analysis is possible through a live video of the processing with the possibility to view each step in the image processing chain separately. Furthermore, the creation of an output video or separate PNG-files of every ellipse found can be created with each video processing.

4. Conclusion

A workflow for the analysis of weld pool geometry was presented that allows to correlate laser welding technical parameters with geometric and kinetic parameters of the weld pool. A freely available software tool will be available at localize-it.de/downloads together with all videos and results to motivate further studies inspired by this publication. This method demonstrated its potential of using data set optimized image processing algorithms to quantify weld pools in space and time. Kinetic analysis of geometric and spatial data provides new insights to gain empirical or test physical laws. Alternatively, extracted data are eventually useful as process control parameter during experiments. An almost linear relation between weld pool image projection area and laser power was found. More relations are to be found using the provided software tool and data set.

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