Novel X-ray System for in-situ Diagnostics of Laser Based Processes – First Experimental Results

Felix Abt*, Meiko Boley, Rudolf Weber, Thomas Graf, Gregor Popko, Siegfried Nau

* Institut für Strahlwerkzeuge IFSW, Pfaffenwaldring 43, 70569 Stuttgart, Germany
b Fraunhofer-Institut für Kurzzeitdynamik Ernst-Mach-Institut, Am Klingelberg 1, 79588 Efringen-Kirchen, Germany

Abstract

The comprehensive diagnostics of melt pool and keyhole dynamics is crucial in the ambitious efforts of understanding the complex behaviour of laser welding and cutting processes. A major drawback for commonly used in-situ diagnostcs is the fact that high-speed cameras and other optical sensors reveal only phenomena on the surface of the process. This paper describes a novel high-speed x-ray diagnostics system that enables the view inside the samples with high spatial as well as high temporal resolution. Calibration images demonstrated the detection of features well below 250 μm in steel. In combination with maximum detection rates exceeding 10,000 Hz it enables outstanding new possibilities for direct observation of the keyhole and fluid dynamics.

Keywords: X-ray; Diagnostics; Capillary Dynamics; Melt Pool Dynamics; Laser Welding; Laser Cutting

1. Introduction

The continuous shortening of development time whilst simultaneously reducing the costs of production processes, is necessary due to global competition. Avoiding rejections can contribute substantially. This requires using safe manufacturing methods as well as reliable monitoring systems. A solid knowledge of the sources of sporadically occurring process instabilities is necessary. Even in manifold industrial applied laser processes for cutting, welding and drilling, this knowledge is not complete. This is due to the difficulty of obtaining information about the process malfunctions on an experimental basis. These usually occur within extremely short time scales and spatial dimensions within the micrometer range, predominantly below the work-piece surface.

The comprehensive diagnostics of melt pool and keyhole dynamics is crucial in the ambitious efforts of understanding the complex behavior of laser welding and cutting processes. A major drawback for the in-situ diagnostics of laser based processes is the fact that high-speed cameras and other optical sensors are only showing phenomena on the surface of the process.

Different approaches already exist to overcome this problem. Welding or cutting behind glass for example allows high frame rates for camera based diagnostics below the melt surface but does not show the actual melt flow inside the molten pool [1], [2]. Furthermore, due to the symmetry disturbance it is influencing the fluid dynamic by the
glass window itself.

The use of radiographic systems that were first used in Japan in the 1990s is another approach to visualize the keyhole and melt pool dynamics of the real and uninfluenced process [3], [4].

State of the art high-brightness lasers allow very high process speeds at minimum focal spot sizes. Hence they require adequate fast and high-resolution diagnostics systems. This paper describes a novel high-speed X-ray diagnostics system that allows both, high spatial and high temporal resolution. By means of this system, the shape of keyholes, cutting kerfs, and drilled holes as well as their temporal development and the resulting melt dynamics during the process can be observed. The results of these observations are key to a better understanding of laser processes, and thus contribute considerably to the improvement of modeling, simulation and process monitoring.

2. Principles of X-ray imaging

For investigating the keyhole dynamics of laser welding processes by means of X-ray video techniques it is necessary to visualize small features at high frame rates. This is challenging due to the fact that high frame rates require a high photon flux. But this deteriorates in general the spatial resolution of the X-ray system. So a careful selection of the system components as well as the operational parameters has to be chosen. The fundamental effects and interdependencies are explained in the following section:

For high-speed X-ray-imaging there are three dominating factors for image quality that are not independent of each other: a) geometric resolution; b) image contrast and c) noise. a) and c) are coupled via the photon flux.

2.1. Geometric shadow projection

Since there are no materials which offer a refraction index significantly different from “1” at X-ray wave lengths in the range of < 1 Å, focussing and imaging are very difficult. Therefore the method of geometric shadow projection is the best solution for our application. The principle of the geometric shadow projection as illustrated in Figure 1. The X-ray source illuminates the object that projects a shadow of itself on the X-ray detector. The geometrical magnification $\beta$ for this projection is given by the theorem on intersecting lines (1). Where $a$ is the object distance, $b$ is the detector distance, $s$ the size of the structure in the object and $S$ the size of its image on the detector.

$$\beta = \frac{b}{a} = \frac{S}{s} \quad (1)$$

$$p = \frac{f}{a} (b-a) = f \cdot \beta - f \quad (2)$$

Figure 1: Scheme of an X-ray projection system according to the principle of geometric shadow projection.

Since an X-ray tube is not an ideal point source, but rather a surface emitting source with a certain focal diameter of the electron beam, the resulting shadows are not perfectly sharp. The size of the penumbra resulting from a
perfectly sharp object edge depends on the focal diameter of the X-ray source according to equation (2), where \( p \) is the size of the penumbra and \( f \) is the focal diameter, i.e. the effective diameter of the X-ray source.

The focal spot size is on his part a monotonic function of the tube current which determines the photon flux. This means that with boosting the dose one increases the focal diameter also.

The size \( p \) of the penumbra directly limits the resolution of the system, as shown in Figure 1.

For features that are smaller than the focal diameter the relation \( \beta_{\text{max}} = f/(f-s) \) (3) is valid. This means that for a given focal diameter of the electron beam \( f \), there is a maximum reasonable geometrical magnification \( \beta_{\text{max}} \). Exceeding this magnification only enlarges the penumbra and does not improve the quality of the image. Equation (3) is intended to calculate the minimal observable structure size \( s \), at a given focal diameter \( f = \text{function(tube current)} \).

Further limiting factors for the total lateral spatial resolution are the display resolution of the scintillator (typical 2 LP/mm at 40% contrast) and the quadratic decay of the X-ray intensity with rising detector distance.

2.2. Image contrast

Besides the lateral spatial resolution the image contrast is the key factor for the visibility of small structures within an object.

\[
\frac{I_{(d-s)}}{I_{(d)}} = \frac{I_0 \cdot e^{-\mu_d(d-s)} \cdot e^{-\mu_s s}}{I_0 \cdot e^{-\mu_d d}} = e^{(\mu_d - \mu_s)s} \quad (4)
\]

Figure 2 (left) shows an object with depth \( d \) and an attenuation coefficient \( \mu_d \) with an embedded cubic structure with the size \( s \) and an attenuation coefficient \( \mu_s \). According to the Beer-Lambert-Law, the contrast between the solid object and the embedded structure on the detector is given by \( \mu_d, \mu_s \), and \( s \) in equation (4).

According to (4) the contrast is independent of the deepness of the object \( d \) and independent of the X-ray intensity \( I_0 \). As long as there is enough X-ray intensity on the detector the contrast is only dependent on the size of the defect \( s \) and the attenuation factors of the base material \( \mu_d \) and the embedded structure \( \mu_s \). Equation (4) shows that on the one hand it is exponentially more difficult to detect small embedded structures compared to slightly larger ones, and on the other hand the bigger the difference of the attenuation factors, the higher the contrast of an embedded structure with a given size.

The attenuation factor of a given material depends on the photon energy of the X-rays. Figure 2 (right) shows the attenuation coefficient and the half-thickness of iron and aluminium over the photon energy [5].
2.3. Signal to noise ratio

Although a spatial detector is homogeneously illuminated with X-rays of a defined intensity, the result will be a more or less noisy image with different grey levels for each pixel and with the mean grey value corresponding to the mean X-ray intensity.

The noise reduces the visibility of small structures in the image. Thus the signal to noise ratio (SNR) is an important factor for the image quality. The imaging with X-ray is a stochastic process that is quantitatively characterized by the Poisson distribution [6]. The SNR is given in equation (5) where \( n^* \) is the expectation value of detecting X-ray quanta [7] and \( D \) the X-ray dose.

\[
SNR = \frac{n^*}{\sqrt{n^*}} = \sqrt{n^*} \propto \sqrt{D}
\]

According to equation (5) the image quality can be increased by using more X-ray quanta, i.e. a higher dose. In the case of high speed X-ray video, the dose is restricted by the short exposure time of a single frame, the power of the X-ray source and the maximum acceptable focal diameter, \( f \). For small dose rates the quantum noise is dominant. According to [6], the SNR should be at least five or higher to ensure the detection of details in an even noise background.

This means that the minimum detectable defect size is also influenced by the signal to noise ratio, because small structures need to have a contrast significantly above the noise level.

3. The X-ray imaging system

3.1. Requirements

The X-ray system of the IFSW is mainly targeting diagnostics of laser welding processes of metals like aluminum and steel. The typical focal diameter of the laser beam is between 50 μm and 600 μm at a laser power in the range of several hundred to several thousand watts. With feeding rates between 0.5 m/min and 50 m/min this leads to penetration depths from approximately 0.5 mm to more than 10 mm. Such laser keyhole welding processes show very high dynamics of the capillary and the melt pool, leading to a stochastic and unpredictable formation of defects like pores or melt ejections.

These process parameters determine the requirements for the time and spatial resolution of the X-ray system. The system must be able to record several seconds of X-ray video with a frame rate of at least 1,000 fps (10,000 fps desired). In addition the spatial resolution must be on the order of 50 μm to 250 μm. The field of view and therefore the magnification of the system have to be adjustable to cover the range of 5 mm x 5 mm to 20 mm x 20 mm at a resolution of 512 px x 512 px.

3.2. Architecture of the imaging system

The imaging system follows a modular concept and is built from discrete components. This offers a maximum flexibility for reconfiguring the system to meet future requirements. Figure 3 (left) shows a sketch of the structure of the imaging system from the X-ray tube to the high-speed camera. Figure 3 (right) shows the actual imaging system with: scintillator 1, telecentric lens 2, image intensifier 3, relay lens 4 and high-speed camera 5.

The imaging system is driven by a microfocus X-ray tube. The X-ray tube has a minimum spot size of 6 μm. Typical spot sizes are in the range of 50 μm to 150 μm, depending on the required frame rate and the target material and depth, respectively. The acceleration voltage can be adjusted between 10 kV and 225 kV with a maximum current of 3 mA.

The target is projected onto a scintillator plate. The magnification can be adjusted by moving the target along the X-ray beam axis to change the object distance. The X-ray intensity on the scintillator can be influenced by changing the tube current or the distance between the tube and the scintillator. The scintillator converts X-rays to visible light, which is imaged by a telecentric optical system to the entrance window of the image intensifier. The image intensifier converts the visible light into electrons that are multiplied in a micro channel plate (MCP) and a booster.
and afterwards converted back into visible light. This intensified intermediate image is finally imaged by a relay lens onto the camera chip of the high speed camera.

Figure 3: Left: Sketch of the structure of the X-ray imaging system. Right: Photo of the setup with scintillator 1, telecentric lens 2, image intensifier 3, relay lens 4 and high-speed camera 5 [8].

3.3. Architecture of the handling system

The target handling system is designed to handle the especially X-ray-designed targets for linear welding processes. The targets are approximately 100 mm long, 40 mm high, and 1 to 15 mm deep. The laser hits the edgewise positioned target from the top and welds on the targets upper face side. The system has two positioning axes to align the laser and the sample relative to each other and one fast axis (v = 40 m/min) for the process itself. Three additional axes are necessary for the alignment of the X-ray imaging system relative to the process, where the X-ray tube and the imaging system are mounted on an electrically coupled gantry axis system. Figure 4 shows the actual setup in the laboratory and a scheme of the welding sample with dimensions and the directions of X-ray and laser beam.

Figure 4: Left: X-ray system with six electro mechanical axes, X-ray tube and imaging system. Right: Scheme of the welding sample with laser and X-ray directions. For full penetration welding the actual thickness of the material is t.

4. Image quality and performance

4.1. Temporal resolution

The effectively usable frame rate of the imaging system is influenced by several factors including the possible frame rate of the camera as well as the effective decay times of the involved active image conversion elements.

At first, the frame rate is limited by the high-speed camera used to acquire the intensified images. In our case the frame rate depends on the used resolution of the camera. Table 1 gives a quick overview of the performance data of the camera. The maximum tested frame rate of 10,000 fps can be reached at a resolution of 384 x 352 px, the maximum resolution of 1024 x 1024 px is possible up to a frame rate of 2,000 fps.
Table 1: Frame rate, resolution and recording time (at max. resolution and at 512 x 512 px) of the used high-speed camera.

| frame rate in Hz | max. resolution in px @ max. res. | recording time in s @ 512x512 |
|------------------|----------------------------------|-------------------------------|
| 1,000            | 1,024                            | 1,024                         |
| 2,000            | 1,024                            | 1,024                         |
| 5,000            | 640                              | 544                           |
| 6,000            | 512                              | 512                           |
| 10,000           | 384                              | 352                           |
| 20,000           | 256                              | 192                           |

The second limiting component in the imaging system is the image intensifier. Since the image intensifier is based on electron-to-photon conversion at the output window, the decay time of the phosphor is very important for the speed of the component. The used phosphor type P46 has two decay times. The fast component from 90% to 10% luminosity lasts 0.3 μs and the slow component from 10% to 1% takes 90 μs. With this specification the image intensifier is able to transmit images with a frame rate of at least 10,000 fps without significant motion blur effect.

The third limiting component is the scintillator plate that converts X-ray to visible radiation. The decay behaviour of the scintillator also consists of a fast and a slow component. The fast, primary component has a time constant of $\tau = 1 \, \mu s$, followed by a slow afterglow of a few percent of the maximum intensity in the range of up to several milliseconds.

Figure 5 shows three frames taken at a frame rate of 10,000 fps. The object is a 3.2 mm deep aluminum disk rotating with a rim speed of 20 m/s. On the rim of the disk is a fitting with a 1.5 mm bore hole in it. Two attached copper wires (0.5 mm and 1.0 mm) serve as high contrast tracers. The comparison of the static object (left) with the moving object (middle) shows virtually no motion blur caused by any decay time or afterglow neither from the scintillator nor from the image intensifier, compared to the right image taken with an unsuited scintillator – with a too long decay time.

Figure 5: High-speed X-ray video taken at a frame rate of 10,000 fps. Left: static object, middle: moving object with $v = 20 \, \text{m/s}$ [8]. Right: moving object with an unsuited scintillator with a too long decay time.

4.2. Raw image quality

The image quality was qualitatively assessed by a visual inspection of X-ray videos. This includes the spatial resolution as well as the contrast and the signal to noise ratio of the images. Figure 6 shows a series of single frames of three X-ray videos taken with a frame rate of 1,000 fps (left), 2,000 fps (middle) and 2,000 fps (right), respectively. Samples were 6 mm deep aluminium plates (middle and left) and a 3 mm deep steel plate (right). The right picture shows a static object with 250 μm and 500 μm bore holes and a triangular lead marker. The middle and left pictures are showing a moving aluminium plate with a lead marker and a bore hole of 500 μm. The feed rates are 5 m/min for the left and 10 m/min for the middle picture. All images are raw data, solely adjusted for brightness and contrast. No further image processing has been performed, in particular no noise reduction, sharpening or shading.
A method giving a quantitative definition of the resolution of detail is the use of a wire penetrameter according to DIN 462-1. A wire penetrameter shows the visibility of a line like structure with a circular cross section in contrast to a base plate of the same material. Figure 7 shows the scheme of the tested sample and the result of such a test with a 4 mm deep steel base plate. At a frame rate of 1,000 fps it was possible to identify the 100 μm wire in the image that leads to an image quality number of W16. In combination with the 4 mm deep steel base plate this leads to a quality-class A according to DIN 462-3.

Figure 6: Left and middle: X-Ray still picture of an aluminium plate with a deepness of 6 mm and a bore hole of 500 μm to the right of a triangular lead marker. Left: Feed rate of 5 m/min at a frame rate of 1,000 fps, middle: Feed rate of 10 m/min at a frame rate of 2,000 fps. Right: X-Ray still picture of a steel plate with a deepness of 3 mm and two bore holes of 250 μm and 500 μm diameter taken at 2,000 fps.

5. Welding experiments

First welding experiments were carried out with the X-ray system, up to now also without any image processing like noise reduction, sharpening or shading. Furthermore, all welding experiments were carried out bead on plate without any filler wire or tracer materials.

The first series of experiments was to visualize the formation of porosity in aluminium welds. Exemplarily two X-ray videos are shown in Figure 8. The welding process was done in a 6 mm deep aluminium plate (AlMgSi) with a Trumpf HL4006D rod laser. The laser power was 4 kW with a spot size of 600 μm and a feed rate of 3 m/min.

The upper three frames in Figure 8 (taken with a frame rate of 1,000 fps) are showing the movement of pores. Without going too much into detail, the videos are showing clearly that the velocity of the pores is not uniform and can vary in a wide range. The pore in the example has a mean velocity of approximately 250 mm/s (15 m/min) and is thereby about five times faster than the feed rate of the sample.
Figure 8: Welding in a 6 mm deep aluminium (AlMgSi) plate, welding direction is from right to left. Laser power is 4 kW at a spot size of 600 μm and a feed rate of 3 m/min. The upper row shows the pore movement in the weld pool with a temporal resolution of 1,000 fps. The lower row shows the formation of a pore within 3 ms, recorded at 5,000 fps. For better visibility in the printed picture a moving average over 5 images was used.

The lower three images in Figure 8 (taken with a frame rate of 5,000 fps) are showing the formation of pores in the same welding process. The hole formation of the pore in this sequence is completed after approximately 3 ms. The left frame shows an unaffected stable capillary. After 2 ms the capillary is virtually completely collapsed and after 3 ms the pore is separated from the keyhole. From the videos it can be clearly seen that it is mandatory to have X-ray videos with frame rates far above 1,000 fps to visualize the pore formation in detail.

The second series of welding experiments was to measure the mean inclination angle of the front keyhole wall in laser welding of stainless steel, for details refer to the work of Weberpals et al. in [9]. The experiments were done on 2 mm thick mild steel with a depth of 5 mm. Laser power was 4 kW at a spot size of 600 μm and the feed rate varies from 4 m/min to 7 m/min. Since the capillary in these process conditions is very stable the method of averaging the frames of the sequence was chosen to generate a picture of the average capillary shape. Figure 9 features the average capillary shape of this process for welding speeds from 4 m/min up to 7 m/min. The inclination angle was determined by fitting a straight line to the desired area of the front keyhole wall.

Figure 9: Measurement of the capillary inclination in laser welding of stainless steel [9]. Material thickness is 2 mm, laser power is 4 kW at a spot size of 600 μm.
6. Image processing

Besides the possibility of optimizing the parameters of the X-ray tube and the imaging system it is possible to improve the image quality by different methods of image processing. Of course there is no possibility to reveal details that are not present in the raw image, but it is possible to uncover details in the image that are not visible due to disturbances or their position in the 12 bit color space.

In the coverage of this paper only the possibilities of image shading will be presented. Other image processing algorithms like noise reduction, sharpening, grey level scaling or deconvolution with the point-spread-function will be discussed in future publications.

Since there are many active and passive optical elements present in the X-ray imaging system there are a lot of factors that lead to vignetting and an uneven luminosity of the resulting images.

Figure 10a and b shows the X-ray image, respectively the 3D grey level distribution, of a step wedge made of stainless steel with a step height of 0.1 mm. The image covers eight steps with a total height difference of 0.8 mm. It is clearly visible that the main image information is disturbed by vignetting mainly in y-direction and a generally uneven luminosity.

To compensate these disturbances it is possible to record the grey level distribution of a perfectly even and homogeneous object, as shown in Figure 10c and d. Using the inverse of this grey level distribution as a shading mask, it is possible to eliminate the vignetting and the static imperfections of the image’s luminosity.

The result of this shading operation is shown in Figure 10e and f. The corrected image contains still the same information as the raw image, but the measurability, the visual impression and the visibility in general have significantly improved.

Figure 10: a) Raw image of a step wedge, b) corresponding grey level distribution. c) Raw image of a homogeneous and even object, d) corresponding grey level distribution. e) Corrected image of the step wedge after the shading operation, f) corresponding grey level distribution.
7. Conclusion and outlook

With the novel high-speed, high resolution X-ray system presented in this paper, a new powerful diagnostic tool is put into operation to observe the inner mechanisms of laser based processes like deep penetration welding, cutting or laser drilling. It was shown that the system is capable of visualizing defect structures of less than 250 μm in steel without the use of tracer materials. This spatial resolution could be shown at frame rates up to 5,000 fps. The system is also capable of frame rates of up to 10,000 fps with reduced brightness and increased noise of the image. The unique performance of the presented in-situ X-ray diagnostics system allows novel insight into the dynamics of high-speed processes as obtainable with actual high-brightness lasers.

The system has proved its capability to observe the highly dynamic process of porosity formation in aluminium welding processes in real time, as well as the ability to visualize the capillary shape for quantitative measurements in stainless steel welding processes.

In future investigations the capabilities of the system will be enhanced with the assistance of additional tracer materials to improve the visibility of defects smaller than 250 μm at frame rates exceeding 5,000 fps. Also additional image processing algorithms will be qualified to improve the quality and measurability of the X-ray images.

Acknowledgements

The development and construction of the High-Speed Space-Resolved X-Ray System was funded by the “Baden-Württemberg Stiftung”.

We also want to thank Mr. Lohmüller, Fa. Hamamatsu Photonics GmbH, for fruitful collaboration and adaption of the image intensifier to the demanding application.

References

[1] Gärtner, P.; Weber, R. (2009) Spatter Formation and Keyhole Observation with High Speed Cameras - Better Understanding of the Keyhole Formation, in Proc. of the 28th International Congress on Applications of Lasers & Electro-Optics, 2009, Orlando, FL, USA.
[2] Arata, Y.: What happens in high energy density beam welding and cutting. Video. Welding Research Institute Osaka, Japan.
[3] Katayama, S.; Seto, N.; Kim, J.D.; Matsunawa, A. (1997) Formation Mechanism and Reduction Method of Porosity in Laser Welding of Stainless Steel, in Proc. of the International Congress on Applications of Lasers & Electro-Optics, 1997, San Diego, CA, USA.
[4] Matsunawa, A.; Seto, N.; Mizutani, M.; Katayama, S. (1998) Liquid Motion in Keyhole Laser Welding, in Proc. of the International Congress on Applications of Lasers & Electro-Optics, 1998, Orlando, FL, USA.
[5] Vogt, H.G.; Schultz, H. (1992) Grundzüge des praktischen Strahlenschutzes, 2. Auflage, Carl Hanser Verlag, Munich, Germany.
[6] Buzug, T.M. (2004) Einführung in die Computertomographie. Springer-Verlag, Berlin, Germany.
[8] Abt, F.; Weber, R.; Graf, T.: Novel X-Ray System for In-Situ Diagnostics of Laser Based Processes, in Proc. of the 29th International Congress on Applications of Lasers & Electro-Optics, 2010, Anaheim, CA, USA.
[9] Weberpals, J.; Hermann, T.; Berger, P.; Singpiel, H.: Utilisation of Thermal Radiation for Process Monitoring, in Physics Procedia, Lasers in Manufacturing, 2011, Munich, Germany.