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X-Ray and optical videography for 3D measurement of capillary and melt pool geometry in laser welding

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Abstracts

This paper describes a method to reconstruct the 3D shape of the melt pool and the capillary of a laser keyhole welding process. Three different diagnostic methods, including X-Ray and optical videography as well as metallographic cross sections are combined to gain the three dimensional data of the solidus-liquidus-surface. A detailed description of the experimental setup and a discussion of different methods to combine the 2D data sets of the three different diagnostic methods to a 3D-model will be given. The result will be a static 3D description of the welding process.

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Keywords: 3D; X-Ray; video; welding; laser; diagnostics; steel; aluminium

1. Introduction

For the understanding of laser keyhole welding processes the comprehensive diagnostics of the three dimensional melt pool and keyhole geometry is extremely beneficial. With high-speed cameras and other optical sensors only geometries on the surface of the process are visible. To enable insight into the process such as the shape and movement of the capillary or the actual melt flow in the weld bead and its geometry, the high-speed x-ray videography system of the IFSW [1], [2], is an ideal instrument. In combination with high speed cameras in the visual spectrum and metallographic cross sections it is possible to generate spatial information of the process in all three dimensions – length, width and depth.

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This three dimensional information on the size and shape of the molten pool is beneficial in various ways. It helps for example to improve the understanding of process fundamentals in laser welding, as well as it can be used to calibrate or verify process simulations.

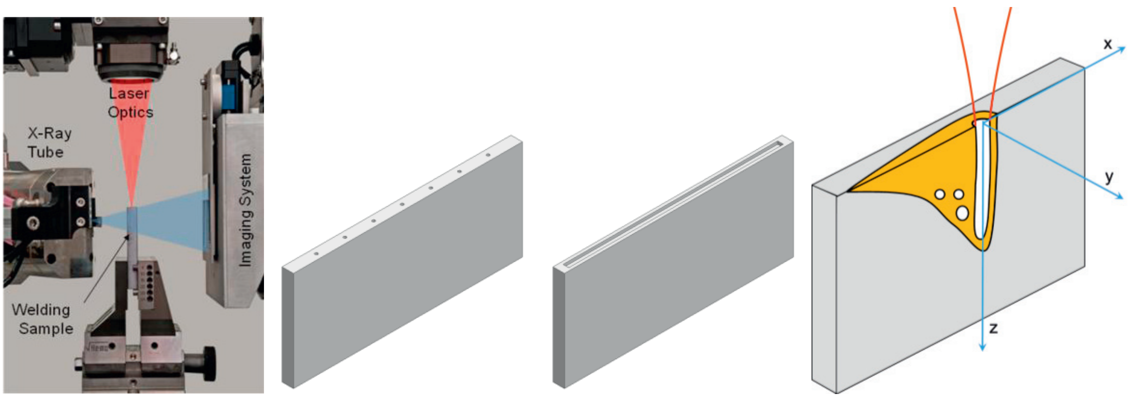
2. Experimental Setup

The experimental setup was built around the x-ray system at the IFSW. The laser optics and the imaging system - x-ray as well as visual - are stationary, whereas the welding sample is mounted on a linear axis providing the process feed. Fig. 1a shows the scheme of the setup during a laser welding process. The welding process is observed from the side by the x-ray camera and from the top – coaxially to the laser beam – by a camera in the visual spectrum.

This setup provides two orthogonal views of the process: One visual view from the top and one x-ray view from the side. Combined with a cross-section taken after the process, three different orthogonal views of the same process are available.

Since the melt-pool has no significantly different absorption compared to the solid material, it's impossible to see the melt-pool geometry directly in the x-ray image. Therefore tracer material has to be added to the welding process. For several reasons tungsten powder is a good tracer: It has high absorption in respect of x-ray, as well as it has a very high melting point and remains as solid particles in the molten pool.

The samples are prepared to hold tracer-powder. Two geometries, as shown in Fig. 1b and Fig. 1c, where used to fulfill this task: Holes with a diameter of 500 μm and a slot with a depth of 100 to 300 μm (b). These where filled with tungsten carbide powder with a grain size between 50 μm (base material Al) and 150 μm (base material Fe). The hole geometry offers a better mixing when welding with high penetration depth whereas the slot geometry is more beneficial for shallow process geometries



(a) (b) (c) (d)

Fig. 1. (a) Experimental setup. (b) Sample with laser-drilled holes with a diameter of 500 μm. (c) slot with a depth of 100 to 300 μm. (d) Coordinate system for the experiments. Feed direction is x, laser propagation z and x-rays propagate in y direction.

3. Extraction of Process Geometry

In a first step, all three views (x-ray, visual and cross-section) are processed to obtain the shapes of the melt pool. The visual and the cross-section are quite simple but the x-ray view needs some advanced image processing. For orientation a coordinate system is introduced, which is shown in Fig. 1d.

3.1. Visual Video

To extract the shape of the melt pool in the visual view of the process it is possible to use single frames out of the video taken during the welding process, see Fig 2 on the left. Since we are interested in the average shape of the melt pool during the process it is beneficial to use an average image of the process, as it is shown in Fig. 3 right. By the use of thresholding algorithms it is possible to extract the boundary of the melt pool – the solidus-liquidus line drawn in red in Fig. 2 right.

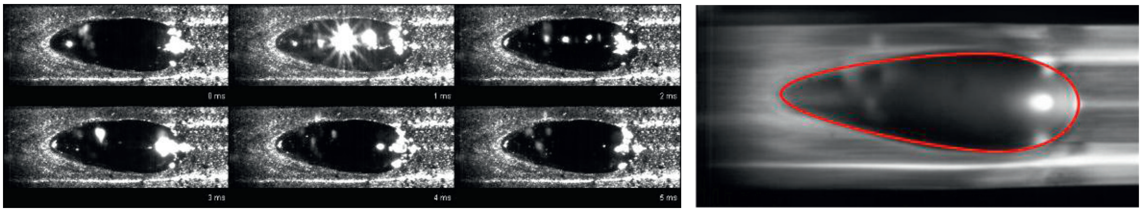


Fig. 2. Coaxial view on the observed process. Single frames from the video of the welding process on the left, averaged with marked melt pool geometry on the right.

3.2. Cross-Section

In the cross-section of a laser-welded seam, it’s quite easy to identify the solidification line and measure the maximum depth of the process as well as the widest width.

A typical cross-section of low speed welding in steel is shown in Fig. 3. When examining the cross-section more closely, more than one solidification line is visible. Together with the observation that maximum penetration depth is not at the same x-position as the maximum weld width, this leads to the conclusion that the cross section shows different points in time in one image. The highest penetration occurs right after the capillary, whereas the heat needs some time to spread to the sides and expand the melt pool in lateral direction.

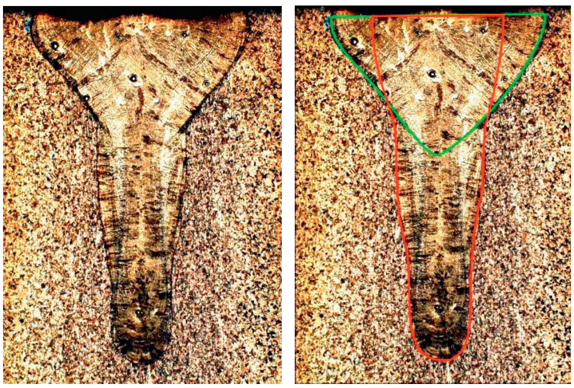


Fig. 3. Cross-section in steel at low speed. Raw image on the left and on the right with marked solidification lines. Red shows the penetration depth right after the capillary and green some time later.

3.3. X-ray video

Extracting the melt-pool shape from the x-ray images requires more sophisticated image processing than in the other two cases described above. The first step is to create a minimum projection of the whole image sequence. This results in a picture like it is shown in Fig. 4.

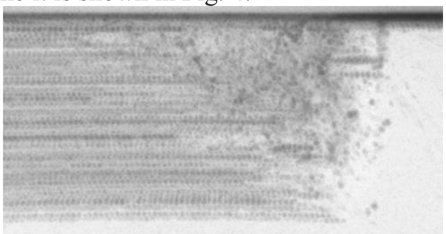


Fig. 4. Minimum projection of a x-ray video sequence. The processed material moves from right to left while the laser and the imaging system are stationary.

A particle in the melt-pool moves in three dimensions x, y and z. With only one x-ray imaging system it's impossible to gain information about the y-position and it's therefore assumed, that a particle only moves in the xy-plane. Since the welding sample moves only along the x-axis a particle that freezes at the solidus-liquidus-line will also only move in x-direction. This behavior is illustrated in Fig. 5 for one single particle over a period of 10 ms. In the first 5 ms the particle moves to the lower right until it freezes around the 6 ms mark. From then on it only moves to the left in a straight line.

By examining as many particles as possible, a series of "freezing points" can be created. In Fig. 6 left these freezing points where added to the minimum projection image. The yellow area marks the possible variance of the melt pool end. The melt pool front (red) follows the shape of the capillary (blue). Since the particles freeze at different points in time the temporal resolution is zero. Since particles can freeze at different y-positions it is assumed, that particles more to the left show the back end of the melt pool and those freezing earlier hit the side walls. Fig. 6 right shows a possible shape of the melt pool from the x-ray view.

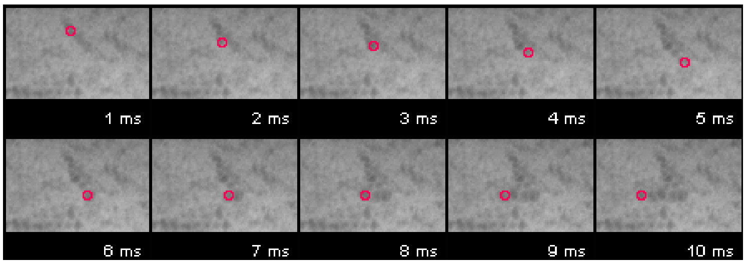


Fig. 5. Tracking one particle in the melt pool.

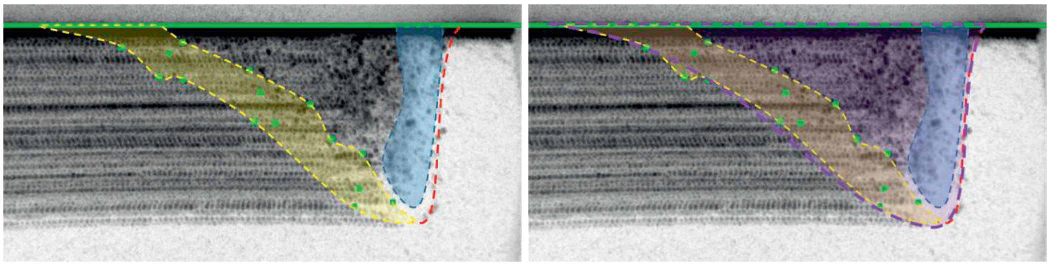


Fig. 6. left: Minimum projection of a x-ray image sequence. The green dots are freezing points. The yellow marked area is the possible region for the melt pool back end. The blue represents the capillary and red is the corresponding melt pool front. Right: Extracted melt pool geometry in purple. It follows the capillary in the front. On the back side a most left particles are used, because particles might also freeze on the side walls of the melt pool

4. 3D Reconstruction

After extracting the melt pool geometry from the three orthogonal views, the molten volume can be determined. Three different models will be presented to generate a 3D volume model of the molten pool. Each model increases the number of assumptions but also improves the shape of the process volume.

4.1. Machined cuboid

The easiest of the three presented models is the “machined cuboid”. The model assumes that each plane shows the maximum extension of the molten pool along its perpendicular axis. The creation process starts with a cuboid on which sides the according planes are projected as it is shown in Fig. 7.

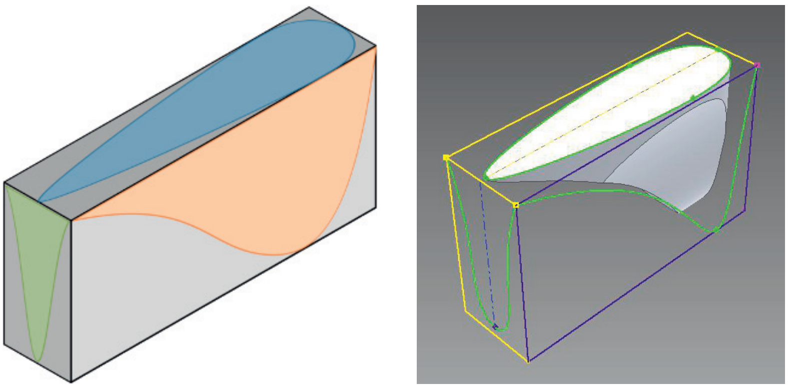


Fig. 7 Machined cuboid. Visual view in blue, green represents the cross-section and orange is the projected plane gained from the x-ray.

Since it is assumed that every plane shows the maximum extension any material “outside” the coloured areas is removed. This procedure results in the three-dimensional volume shown in Fig. 8.

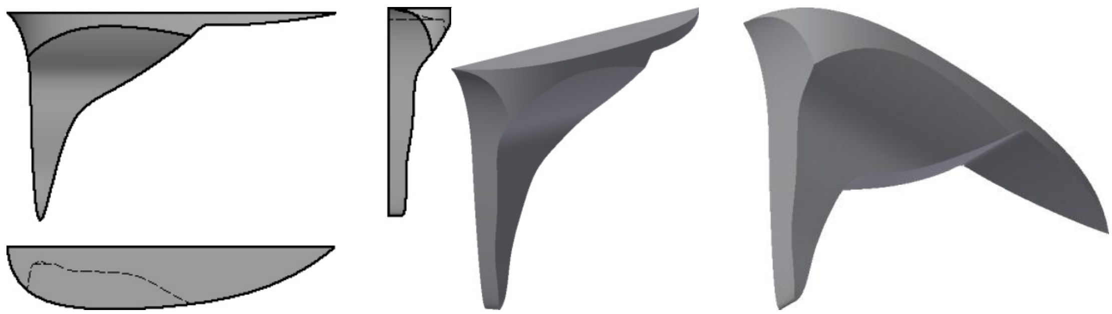


Fig. 8 Machined cuboid with material removed. . (left to right) Parallel projection, view from the front, view from the lower front.

The advantages of this model are that it is easy to create, it includes very few assumptions and it shows the maximum volume of the molten pool. The main disadvantage is that it shows sharp edges that contradict with melt flow and heat conduction mechanisms.

4.2. Simple-frame model

Since laser-welding is a thermal process edges and planar surfaces are not very likely to appear. To reduce this drawback of the machined cuboid model another assumption is introduced for the so called simple frame model. When slicing the molten volume at different positions along an axis, it's expected that the slices look more or less similar to each other. By using one of the three planes (x-ray, visual or cross-section) as the main frame and stacking it along its perpendicular axis a volume is created. To match the conditions set by the other planes, the main frame is scaled according to the other two planes. If, for example the cross section is used as the main frame, the stacking direction is x. The visual plane in this case scales the width and the x-ray scales the depth of the main frame, as shown in Fig. 9 left.

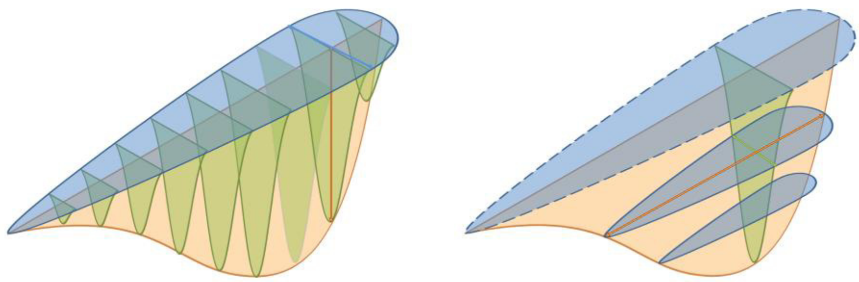


Fig. 9 Simple frame model, left shows the cross-section as main frame and on the right the visual plane was used.

Using the same data as in chapter 4.1, the "simple-frame model" results in the 3D-volume shown in the image. Fig. 10. The parallel projections in the main axis are looking identical to the machined cuboid and the three original frames. But when rotating the 3D-volume, the smooth surfaces are revealed. On the sides waves can be observed. These waves originate from the wavy shape of the cross section.

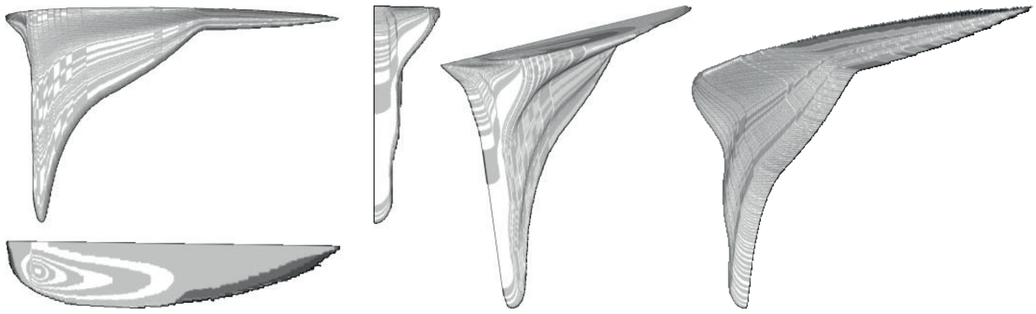


Fig. 10 Simple-frame model. (left to right) Parallel-projection, view from the front, view from the back.

The advantages of this model are its moderate complexity to create the volume, it includes only a few simple assumptions and it shows a more realistic shape of the molten pool without sharp edges and flat planes. The main disadvantage is that it assumes the similar shape of the cross section in front of the capillary and in the back. Since this part of the process volume is defined by melting mechanisms rather than solidification, this is an assumption that contradicts the physics of the process in this part of the volume.

4.3. Advanced frame model

There are still things to criticize on the simple frame model: The waves on the sides don't seem to be realistic and the melt pool front is shaped by a plane that results from the solidification process. When having a closer look on the cross-section, multiple solidification lines can be seen. By assuming that one area solidified later then the other, the cross-section contains two shapes (Fig. 3 right). One shape that shows a higher penetration depth (red line) and one that shows a wider weld (green line).

The wide and shallow shape is used from the back end to the position where the melt pool has its maximum extension in the width. From there the shape is transformed from the widest into the deepest shape. The melt pool front, as the third part along the x-axis, is approached by an arch that is stacked along the z-axis and scaled by the x-ray and the cross-section. Fig. 11 shows the different parts of the process geometry.

This results in the volume shown in Fig. 12. The waves on the sides are gone and the melt pool front now looks like it was shaped by heat transfer. The volume looks more or less realistic.

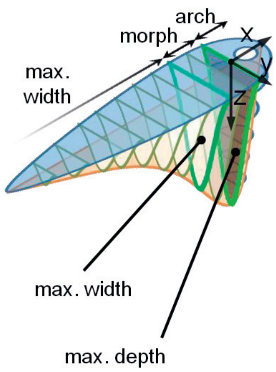


Fig. 11 Advanced frame model. It's split in three areas: In the first area from the back to the position of the maximum width the green shape (maximum width) from the cross-section is used. In the next part the green shape is transformed into the red shape. The last area (marked with arch) uses an arch which is stacked along the z-axis and scaled by the x-ray and cross-section shapes.

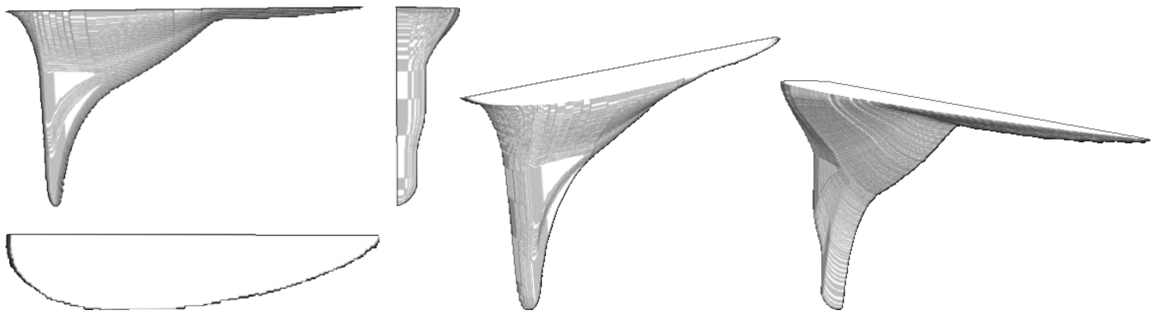


Fig. 12 Advaced frame model. (left to right) Parallel projection, view from the front, view from the back.

The advantages of this model are the more realistic shape of the molten pool compared to the simple-frame model or even the machined cuboid. The drawbacks are the high complexity of the model and the high number of assumptions that are necessary to create the smoother shape of the molten pool.

5. Conclusion

With the x-ray videography system of the IFSW in combination with visual high-speed cameras and simple cut-and-etch techniques it was possible to create a three-dimensional volume model of the molten pool of a laser welding process.

Three different methods were shown to create 3D-volumes out of the three different orthogonal views of the welding process. The models are different in complexity and physical assumptions. But even the simplest of them – the machined cuboid – shows at least the maximum sizes of the molten pool.

This helps to improve the understanding of the process fundamentals of laser welding and offers the possibility to calibrate or verify computer-aided process simulations.

Acknowledgements

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