Understanding Pore Formation in Laser Beam Welding

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Abstract

The mechanisms leading to process pores in deep penetration laser beam welding are discussed in this paper. Process pores were observed since the beginning of laser welding. Although there are differences in the number, size and location of the pores depending on the used laser type and beam parameters, process pores are a common problem for all laser sources. To clarify the mechanisms, basic experiments with transparent materials were performed. During those experiments high-speed videos were recorded and subsequently analysed. Several very interesting insights concerning fluid flow and pore generation could be obtained.

Keywords: Welding; Quality; Instabilities; Porosity; Pore Formation

1. Introduction

Several papers describe methods to reduce or avoid process pores in laser beam welding. The used process strategies are based on different approaches, e.g. optimizing shielding gases, applying two-beam technology, using a modulated laser power or an oscillating beam or using devices for the generation of Lorentz forces in the weld pool. These investigations were performed, although only little knowledge about the formation of pores is available.

Arata [1] and Antonov et al. [2] were probably the first who made welding experiments with transparent materials to elucidate the basic physical mechanisms underlying the welding process. Besides experiments using an online X-ray facility, Arata also performed welding experiments in glass as model material, whereas Antonov et al. used water. Experiments with other liquids and ice are also known from literature, e.g. [3], [4].

For the investigations reported in this paper water and ice were used as transparent model materials. Although some material properties differ significantly from those of metals typically used for welding, some other important material properties are very similar. First, the low thermal conductivity of water and ice has to be mentioned. This variable affects the Péclet number \( Pe = (v \cdot d) / k \), which describes the relation between convective and conductive heat transport (\( v \) is the process velocity, \( d \) a typical dimension, e.g. the laser beam diameter, and \( k \) is the thermal conductivity). If \( v \) is not adapted to the low value of \( k \), the Péclet number gets large, indicating, that the weld pool width becomes narrow, whereas the weld pool length will be enlarged. The small difference between melting and evaporation temperature leads on the one hand side to a wider seam, which compensates the effect of a large Péclet
number partly. As a consequence, the welding velocities can be chosen in a similar range as in welding of metals. This leads to similar liquid film widths around the capillary. On the other hand, the weld pool length is further increased. But if only phenomena occurring in the beam-material interaction zone shell be investigated, this is negligible. From more importance is the similarity of the flow field close to the capillary. In order to achieve this, the Reynolds number has to be in a similar range. In this context, it is helpful that the viscosity of water is almost identical with that of liquid Aluminium. To compare the results with iron, it has to be considered that the viscosity of iron is almost one order of magnitude larger. Finally, the surface tension shall be addressed. This value is much smaller than for metals. This means that instabilities of the surface are more probable and, if they occur, probably more pronounced. But for principal investigations this might be helpful, because basic mechanisms should be identified more clearly.

2. Experiments with water and ice

First experiments were performed in water. A CO₂ laser was used as a beam source, because the absorption behaviour for large angles of incident is pretty much the same as for Aluminium above the Brewster angle. Also important is the fact that water vapour as well as Aluminium vapour is transparent for the radiation, whereas condensed droplets (like fog) absorb the laser energy. The relative velocity between water and the laser beam was varied between 0 and 74 m/min.

In all the experiments bubbles were generated and in all experiments two types of bubbles could be distinguished. One type of bubbles disappeared within one millisecond after generation (see Figure 1). Whereas the collapse within 1 ms of a capillary or droplet with a typical diameter of some hundred micrometers embedded in liquid metal can be explained by the closing forces induced by surface tension, rough estimations for a droplet in water with a diameter of \( d_{kap} \approx 2 \text{ mm} \) lead to the insight that there must be an additional closing force. The hydrostatic pressure, however, in a depth of some millimetres is too small to fulfil the requirements. In consequence, we assume that the vapour inside the bubble condenses very rapidly generating a vacuum. Therefore, an additional pressure difference of about \( 10^5 \text{ Pa} \) is generated which can account for the fast closing.

![Figure 1: Sequence of a film, recorded with 9000 fps showing the collapse of a capillary in water generated by a CO₂ laser (relative velocity between laser and water: 7.5 m/min, laser power: 500 W). Depth of the capillary about 12 mm. In frame 1 and 2 a throat close to the middle of the capillary can be detected; at this position the capillary collapses in frame 3; the isolated bubble below this position starts to collapse at this point of time; after 0.77 ms in the last frame the bubble finally disappeared completely (only a shadow remains, this shadow originates from diffraction of the light used for illumination at the hot water originally surrounding the bubble).](image-url)

A second type of bubbles shows a completely different behaviour. Bubbles of this second kind exist over a very long time. Usually they leave the region of interest after seconds. Because the water remains relatively cold in some distance of the capillary, vapour cannot exist over such a time period within the bubble. As a consequence, it has to be assumed that the bubbles contain ambient air. This is in good agreement with Japanese investigations which show that in bubbles from welding experiments shielding gas can be found [5]. Many bubbles show a mixed behaviour between type one and two indicating that the capillary is partly filled with vapour and partly with ambient gas.
In a next set of experiments the region of the generation of bubbles was investigated. For low process velocities, everywhere at the rear side of the capillary relatively large bubbles were generated. In these cases the rear wall of the capillary was very unstable. Figure 2 shows the results of two experiments made at an enhanced velocity of 6.7 m/min. In these experiments bubbles were generated at the bottom of the capillary and at certain convexities.

The question arises how ambient air can reach such deep positions within the capillary. The vacuum assumed to exist for a short time period in the bubbles of first kind can help to explain this. The vacuum not only helps to close the bubble very rapidly, it also leads to a very low pressure close to the tip of the capillary (above the bubble). From calculations made in the 1980s it is known that the pressure within a stable capillary should be between $10^4$ and $10^5$ Pa. Therefore, the pressure drop due to the existence of a vacuum dominates the pressure balance and ambient gas can be sucked in. The fact that evaporation is localized to some steps at the capillary front if it is not even, which is assumed to be the case for low and medium welding velocities [6], might help to give some space that air can enter the capillary.

![Figure 2: Interaction of a laser beam (wave length 10.6 µm) with flowing water (at 6.7 m/min); the short arrows on the left-hand side indicate the incoming flow; the long arrows depict the paths of the bubbles and identify therewith the flow direction in the ambiance of the capillary, the horizontal lines at the rear side of the flow channel have a spacing of 1 mm. The two images are snapshots from two films and the small dots show the positions of bubbles from preceding consecutive frames, focal diameter: 0.3 mm, laser power: left: 1000 W, right: 500 W.]

Much more details can be recognized analyzing the videos taken during welding experiments in ice. Figure 3 gives an overview over the typical shapes and phenomena which are clearly visible. Whereas the front is slightly inclined and bent, but absolutely smooth (within the optical resolution of 50 µm/pixel), the rear side shows a very instable permanently changing shape. The bubbles which are generated during the welding process can be used as an indicator of the flow field; no additional tracer material disturbing the interaction with the laser is necessary.

![Figure 3: Main flow directions during ice welding with a CO₂ laser, laser power: 500 W, welding velocity: 2 m/min](image3.png)

The fastest motion which can be recognized by the movement of the bubbles is a shuttle following the volume change of the capillary. In several welding experiments also an eddy at the tip of the capillary appears which generates a very fast flow (see Figure 3). It is interesting that this eddy does not permanently exist but it appears more or less periodically with a high frequency. This phenomenon will be described in more detail below. A further process which can be clearly observed is the generation of splatter at the rear wall of the capillary. Here, from time...
to time “fingers” of melt are generated by the interaction with the wind of the exhausting vapour. If such a finger gets close to the capillary front wall, it is sucked towards the front wall by the low pressure (according to Bernoulli’s law) in the fast flowing vapour between the front wall and the tip of the finger. Mostly a high pressure below such a finger builds up which ejects the finger in the direction indicated by the red arrows close to the capillaries’ orifice in Figure 3 [7].

In contrast to the large number of bubbles generated under the process conditions of Figure 3, the process is much more stable under the conditions of Figure 4.

![Figure 4](image1)

Figure 4: Two capillaries from one high speed film taken with 4500 fps, material: ice, laser power: 1000 W, welding velocity: 5 m/min, focal position: 10 mm above surface, the capillary was illuminated in a way that it appears light.

Sometimes it happens that under these relative stable conditions bubbles are generated. Figure 5 clarifies the steps leading to a bubble.

![Figure 5](image2)

Figure 5: Six capillaries of the same film as in Figure 4 depicting the steps leading to a bubble at the rear side of the capillary. The time between two consecutive pictures is approx. 2 ms.
In the first frame of Figure 5, a stable situation can be seen, similar to the pictures of Figure 4. Approximately 2 ms later, the capillary tip disappeared changing the geometry slightly which obviously leads to a higher absorption and to a violent evaporation at this location. As a consequence, a local bulging of the capillary appears on the rear side which increases over about 5 ms. In the fifth frame of Figure 5 (at 145.33 ms), the gas inside this bulge condenses and the bulge starts to disappear. In the last frame, two small bubbles remained at the position of the former bulge. By comparison with the experiments in water, described above, one can conclude that the larger part of the volume of the bulge was filled with vaporized water and a smaller content, which remained after the collapse, was filled with air. Within 10 or 20 ms such a bubble is driven upward parallel to the rear wall of the capillary because the strong wind inside the capillary accelerates the circumfluent melt. It can be assumed that in this case the generation of a bubble will not lead to pore formation.

![Figure 6: Fifteen capillaries showing the generation of pores at the tip of the capillary, laser power: 500 W, welding velocity: 2 m/min, height of frame: 17.5 mm, 9000 fps. The time step between consecutive pictures is 0.22 ms, except for the first two pictures, where it is 1 ms.](image)

In the case of lower welding speed – compared to the experiments presented in Figures 4 and 5 – the rear wall is more instable and more bubbles are generated (see Figure 6). Furthermore, the process of pore generation differs slightly from that described above. Starting from a relatively stable situation in the first frame of Figure 6, “fingers” grow from the rear side towards the front wall in the second picture leading to an obstacle close to the keyholes’ orifice. From the third frame on (starting at 10.22 ms), the width of this obstacle growth rapidly downwards. Consequently, the volume of the keyhole shrinks within 0.5 ms drastically. This can only be explained by condensation processes at this region. A very fast flow of water following the collapsing keyhole is induced. This water jet reaches the capillary front between 0.5 to 0.7 ms after the start of the growth of the obstacle (between
11.56 and 11.78 ms) separating the lower from the upper part of the capillary. The lower part becomes decomposed into several bubbles during the next 0.5 ms. Whereas the two lower bubbles are encased in a spike, the third bubble above the spike begins to rotate violently, indicating a strong eddy. This eddy is enforced by the “drilling” process when the capillary growth again and the melt below is pushed downward. In this experiment, all the generated bubbles rest more or less in the region where they are generated – some encaged in a spike and some rotating in the eddy. Finally they will result in pores within the frozen material. The complete chain of processes described here is repeated with a high frequency in many welding experiments.

![Flow downwards – in front and behind the capillary](image)

Figure 7: Path of a tungsten particle in a welding process of aluminium observed by X-ray technique; the two arrows indicate the regions where the highest velocities can be observed and the direction of acceleration.

Similar flow paths were observed with X-ray technique during welding experiments with different metals as well (see e.g. [8]). The mechanisms observed in the welding experiments performed in ice and described above are one possibility to explain the mechanisms leading to such a flow field with a strong eddy at the tip of the capillary. But there might be further mechanisms supporting these phenomena, such as moving steps at the capillary front [9], [10], [6], [7].

3. Summary

Experiments in water and ice were performed in order to observe directly the behavior of the capillary and the flow field in the weld pool. Although there are significant differences in the material properties of water and metals commonly used in welding, several important properties are similar. Therefore, the authors believe that most phenomena observed in the experiments with water and ice will also appear in real welding tasks with metals. This sentence is supported by the fact that several phenomena could already be observed for both materials.

From the observations two different behaviors during the collapse of a capillary could be distinguished. Either the gas filled volume disappeared within approximately 1 ms or it rests over a very long time period. Many bubbles show a mixed behaviour between type one and two indicating that the capillary is partly filled with vapour and partly with ambient gas. The bubbles were generated at the rear side and at the tip of the capillary. At the rear side, the process of bubble generation was accompanied with a bulging of the capillary followed by a fast shrinking of the bulge. The bubble generation at the tip of the capillary was mostly more complex. It was further accompanied by a jet of melted material streaming towards the capillary and than downwards resulting in a strong eddy at the tip of the capillary.

Although the parameters leading to different regimes of bubble generation were not yet investigated, from the examples presented in this paper it becomes clear that there are several different regimes and the welding velocity plays an important role.
References