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Spiking behavior and capillary instabilities observed during welding of ice

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Abstract

The spiking phenomenon is well known in partial penetration welding of metals. Depending on the welding parameters, pore filled spikes can be found in longitudinal sections. Unfortunately, the generation of those spikes cannot be observed even with X-ray videography due to the highly dynamic behavior and small size of the capillary tip. Transparent materials such as ice, however, allow direct inspection of the capillary's dynamic behavior with high local and temporal resolution. The pores inside of spikes indicate that the spiking process is at least sometimes accompanied by capillary instabilities. These instabilities can also be visualized during welding of ice. It was found that the frequency of capillary fluctuations can be much higher than the spiking frequency. Measurements of the capillary depth with inline coherent imaging confirm this behavior also for the case of welding metals.

Keywords: laser welding; spiking; capillary; high-speed observation; simulation

1. Introduction

The deep-penetration welding process of metals is limited by a series of instabilities. One of these is the spiking process, which occurs in partial-penetration welding and can be described by repeated sudden changes of the welding depth. After Wei et al., 2012, the root spiking process can be observed in laser-, electron-beam and even arc welding. Often, the spikes, which can be identified in longitudinal sections, contain voids. An example of a weld seam with spikes containing voids can be seen in Fig 1.

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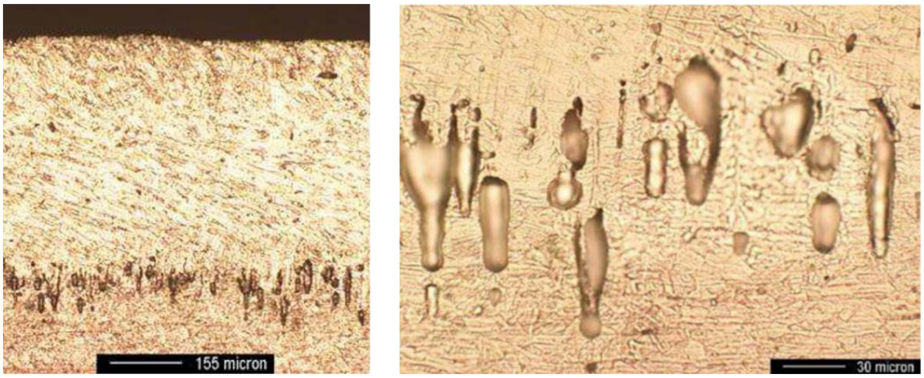

Fig. 1. (a) Longitudinal section of a weld performed in steel 4310 with a thin-disc laser, *P* = 100 W, *v* = 3 m/min, ▯▯= 515 nm; (b) detail of the left figure, showing the voids within the spikes, Bayer, 2009

In many publications it is assumed that the spikes are caused by fluctuations of the capillary length, see e.g. literature overview in Wei et al., 2012. In order to correlate the capillary growth and shrinkage with the spike formation, both the solid/liquid and the liquid/vapor interfaces have to be observed. With inline coherent imaging (see e.g. Webster, 2010) it is possible to observe the capillary fluctuations in the real process, Boley et al., 2013. The liquid/solid boundary, however, cannot be observed with this technology. Also state of the art X-ray technology is not capable to detect this interface clearly. Therefore, a transparent material has to be used. Cho et al., 2003 have used frozen glycerin for this purpose. In our group bubble-free frozen water is used instead since many years, see Berger et al., 2011.

2. Experimental set-up

The laser interaction zone was observed with a high-speed video camera placed on the side of an ice block with a width of 1 cm in viewing direction of the camera. The depth of the ice block was 10 cm (in direction of the laser beam) and the length was 20 cm (in feeding direction). The wavelength of the laser radiation was 10.6 µm (CO_2 laser TLF 5000). The laser power used for the presented experiments was 750 W. A focusing optics with a focus length of 280 mm was used which generated a focus with a diameter of 430 µm and a Rayleigh length of approximately 6 mm. The camera system as well as the laser head were fixed in space, whereas the ice block was moved by a stage with 2 m/min in one of the presented experiments and with 4 m/min in the other. The weld path was 140 mm long. During this path the focal position was continuously moved from a position 10 mm above the workpiece's surface to a position 10 mm below the surface. This course of action guaranteed that the process started in a stable mode, got more unstable when the focus position was close to the surface and got more stable again when the focus position was deep inside the workpiece.

3. Spiking phenomenon and instabilities

In a previous publication on the spiking phenomenon Berger, 2016 reported that the spiking phenomenon during the partial penetration welding process occurs independently from the presence of melt instabilities.

Melt instabilities can alter the frequency of the growth and retraction of the capillary (liquid/vapor interface). Observed were increases of this frequency up to a factor of 5. Caused by these changes, the standard deviation of the spike length increased. The average spiking frequency, however, was not altered by these instabilities. It stayed constant over the total weld path at a value of 37 spikes/s for the experiment with a welding velocity of 2 m/min and at a value of 75 spikes/s for 4/min. As the frequency doubled when the welding speed doubled, the spacing between two spikes remained constant at 1.1 mm. This is very similar to the value of 1.3 mm obtained from welding experiments with frozen glycerin, Cho et al., 2003. In metals (see e.g. Fig 1) the spacing between spikes is some ten up to some 100 micrometers.

In Berger, 2016, additionally the frequency of the shoulders running down the capillary front was investigated to clarify whether the shoulders could cause the spiking process. The frequency of the shoulders was in the range of 1500 Hz and their average velocity was 16 m/s, which is close to the velocity observed by Eriksson et al., 2011 during welding of 3 mm 304 stainless steel with 10 kW and 10 m/min. They observed shoulders at a velocities between 6 and 12 m/s. Due to the large difference of the spiking frequency in comparison to the frequency of the shoulders, it is unlikely that the shoulders initiate the spiking mechanism directly.

Having a closer look on the stability of the process, one finds a pretty stable process as long as the focus position is far above the workpiece. A stable process means in this context that the capillary is always open and has a smooth and stable front wall geometry and a slightly changing rear wall. The laser beam can illuminate the front wall unhindered. Nevertheless, also in this case the capillary length grows and retracts periodically generating a spike with each advance. The retraction velocity is always higher than the drilling velocity.

When the focus comes closer to the workpiece surface, the capillary retracts in a "jump"-like manner from one frame to the next (within 0.2 ms). The jump distance increases as the focus approaches the ice surface. From a special point in time on, a pore remains in the capillary after each jump-like retraction, marked red in Fig 2.

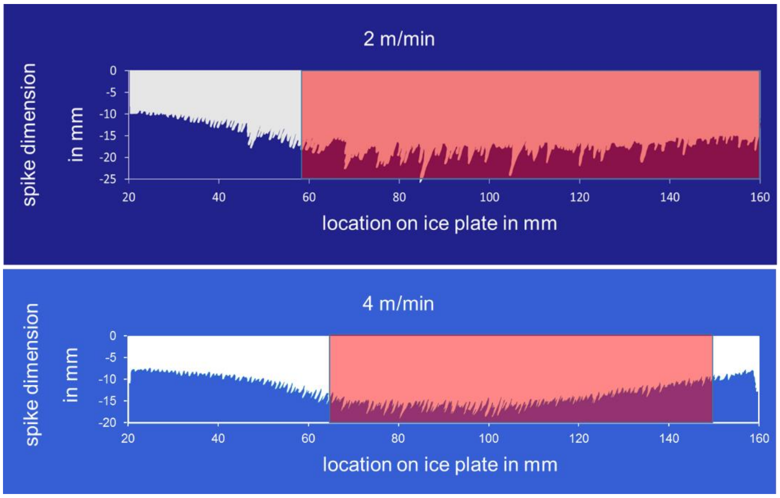

Fig. 2. Welding depth/spike dimension along the welding path for a feeding velocity of (a) 2 m/min and (b) 4 m/min; in case (a) 37 spikes/s and in case (b) 75 spikes/s are generated, this means that in both cases the spacing between 2 spikes in in average 1.1 mm, the regions where bubbles are generated are marked in red

It should be mentioned that in the beginning the sudden retraction is completely within a spike and no change of the melt flow can be observed. When the focus position is very close to the focus position, the distance of retraction is longer than a spike and the capillary tip reaches a position above the spike. In this case an eddy is generated at the tip of the capillary above the spike. In the most instable zone, the capillary length can vary in a jump-like manner not only during retraction but also during growth. This, however, does not mean that the spiking frequency is increased. Instead the capillary penetrates the same spike several times. This behavior was also observed during welding of AlMg3, see Fig 3.

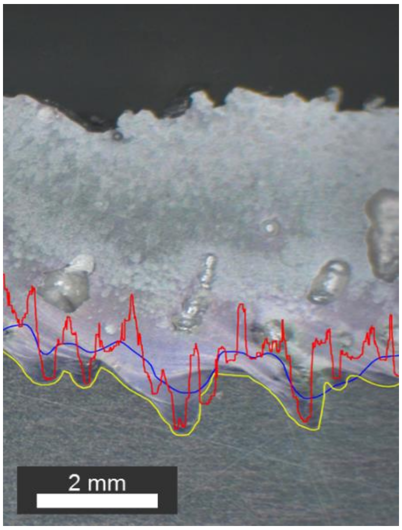

Fig. 3. longitudinal section of a weld seam in AlMg3, P = 5 kW, v = 3 m/min, Boley, 2016; The red line is the depth measured by inline coherent imaging, the blue line the depth measured by X-ray technique (smeared out due to the relative long exposure time of 1 ms) and the yellow line is the calculated solid/liquid interface using the capillary depth measured with inline coherent imaging for the location of the heat source

4. Summary

During welding of ice, instabilities of the capillary's retraction have been identified. Starting with a stable process caused by a high focus position and entering an instable process by lowering the focus position, the capillary length first varies continuously, then starts with small jumps during the retraction phase and ends up with long jumps during the retraction and growth phases. After several jumps which leave a melt-filled spike back, pores are generated during each sudden retraction.

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