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Influence of beam parameters on the capillary formation and the depth progress in laser spot welding of copper

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Abstract

Laser spot welding of copper with a penetration depth in the range of several millimeters has gained increasing attention due to the growing field of electromobility. Deep spot welds require the formation of a capillary and this again defines the processing time for each weld which is of particular interest for achieving high productivity. The capillary formation and the depth progress are influenced by the laser beam parameters. Spot welding with a laser power of up to 16 kW, a wavelength of 1030 nm and, beam diameters of 200 µm and 600 µm were investigated. High-speed X-ray imaging with a temporal resolution of 0.5 ms during the welding process was used to analyze the capillary depth progress. With the maximum power of 16 kW, a capillary depth of 4 mm was achieved in copper within 5 ms.

Keywords: laser spot welding; copper; depth progress; X-ray imaging; capillary formation

1. Introduction

A challenging area in the field of electromobility is the production of windings of electrical drives. The work of Glaessel et al. 2017 has focused on the challenges and opportunities for the use of infrared lasers for welding of hairpin windings. Due to the high currents, large weld cross-sections with low contact resistances are favourable and therefor spot welds are common here. For a reliable and most productive weld, the spot welding process must be fast deep and have a sufficiently large cross-section. It is assumed that the capillary cross-section is proportional to the diameter. In this work, the influence of laser beam parameters on the spot welding capillary depth in copper was investigated. For time-resolved investigations of the capillary depth, an online highspeed X-ray diagnostics system was used. In this proceeding, the capillary depth

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progress and the average capillary diameter in spot welds in copper with laser powers of 7 kW and 16 kW and beam diameters of 200 µm and 600 µm respectively, will be discussed.

2. Methods

A sketch of the experimental setup is shown in Fig. 1. Spot welds of copper K75 were performed by using a high-power laser (TruDisk 16002) with a wavelength of $\lambda_{Laser} = 1.03$ µm in combination with a focusing optics (Precitec YW52). The focal length of both, the collimating and the focusing lens was 200 mm. In combination with the 200 µm and 600 µm transport fibers, this resulted in a focus diameter of 200 µm and 600 µm, respectivly. The angle of incidence was set to 10°. The focus position was on the samples surface and no process gas was used. The origin of the coordinate system (x,y,z) was set at the center of the laser focus on the surface of the sample. Laser spot welds with a pulse duration of 20 ms were produced in samples with a width in y-direction of 3 mm. Online high-speed X-ray projection in side-view (green arrow, y-direction) was performed to observe the geometry of the capillary. The X-ray diagnostics system consists of a microfocus X-ray tube and a high-speed camera as described in detail in Abt et al. 2011. The so-called X-ray videos were recorded with a frame rate of 2000 fps, with a scale of 68 pixel/mm, and an image size of 768 x 768 pixels. In order to enhance the contrast and to reduce the noise, all X-ray videos were post-processed with a flat-field correction and Kalman filtering (Harvey 1989).

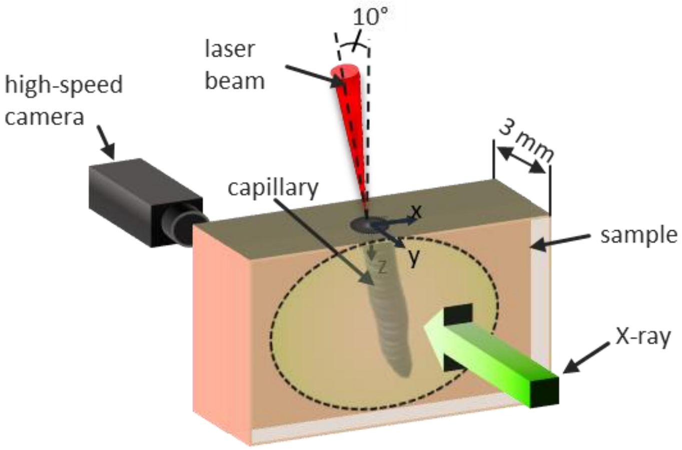

Fig. 1. Sketch of the experimental setup.

Fig. 2 (a) shows the grayscale coded local transmittance of the X-ray radiation through the sample. A clear contrast between the solid sample material (dark, high absorption of X-rays) and the capillary (white, low absorption of X-rays) is visible in the images. The geometry of the capillary was reconstructed using the greyscale values of the X-ray image, as described in detail in the appendix A in Lind et al. 2020. The method to reconstruct the capillary geometry is based on the Lambert-Beer-Law and assumes a mirror symmetrical geometry to the x-z plane. The capillaries were reconstructed with an attenuation coefficient for copper of $\mu_{cu} = 0.27\ mm^{-1}$. Fig. 2 b) and c) show a reconstructed capillary in the x-z plane and the y-z plane, respectively. From this reconstruction, the capillary depth in z-direction, as well as the capillary area in the x-z plane, as outlined by the red dotted line in Fig. 2 b), were determined.

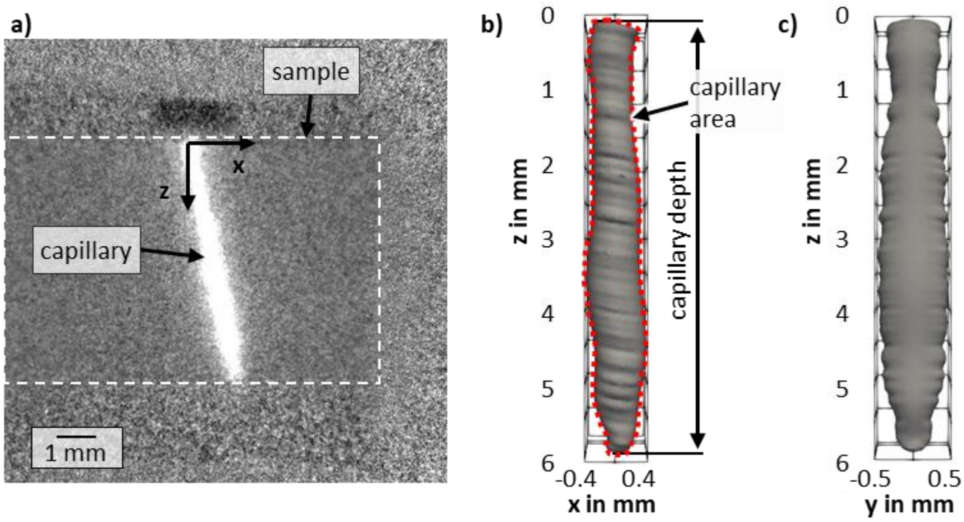

Fig. 2. Image of a single frame from X-ray video a), and reconstructed capillary in the side- and front-view b), c).

3. Results

Fig. 3 a) shows the capillary depth as a function of time (denoted as capillary depth progress in the following) during the spot welding process for a laser power of P = 16 kW and a focus diameter of d_f = 600 µm (green triangles), P = 16 kW and d_f = 200 µm (orange dots) and P = 7 kW and d_f = 200 µm (blue dots), respectively. The data points represent the average of three measurements, the lengths of the error bars indicate the range between the minimum and maximum measured values within the three measurements.

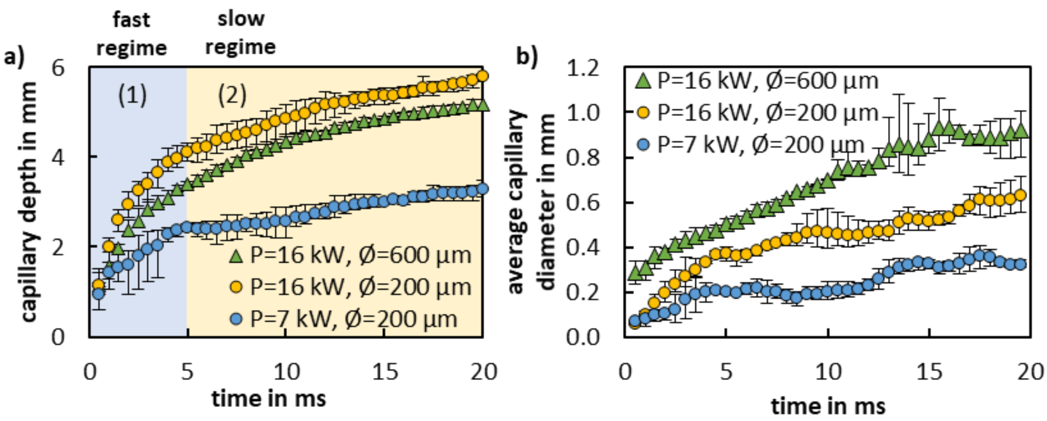

Fig. 3. Capillary depth (a) and average capillary diameter (b) as a function of time for laser spot welds with a laser power of P = 16 kW and a beam diameter of d_f = 600 µm and d_f = 200 µm and with P = 7 kW and d_f = 200 µm.

The capillary depth progress of the laser spot welds (Fig. 2 a)) can be virtually separated in two regimes. In the "fast regime" (highlighted in blue and marked with (1)), the capillary depth is increasing rapidly within about the first 5 ms. In the "slow regime" (highlighted in yellow and marked with (2)), the capillary depth only increases slowly up to 20 ms. After the fast regime, i.e. after 5 ms the capillary depth, achieved with a laser power of P = 16 kW and a beam diameter of d_f = 600 µm (green triangles) is 3.4 mm. Achieved with the same laser power and a beam diameter of d_f = 200 µm (yellow dots) the capillary depth is 4 mm. With a laser power of P = 7 kW and d_f = 200 µm (blue dots) the capillary depth increases in the fast regime to the same extent as with a laser power of P = 16 kW, but the maximum capillary depth is less than 2.5 mm. With 2.28 times the laser power and the same beam diameter of d_f = 200 µm, 1.6 times the maximum capillary depth can be achieved.

Fig. 3 b) shows the average capillary diameter as a function of time during the spot welding process for a laser power of P = 16 kW and a focus diameter of d_f = 600 µm (green triangles), P = 16 kW and d_f = 200 µm (orange dots) and P = 7 kW and d_f = 200 µm (blue dots), respectively. The data points represent the average of three measurements of the capillary area divided by the respective capillary depth, the lengths of the error bars indicate the range between the minimum and maximum measured values within the three measurements. The average capillary diameters increase almost constantly for all three parameter combinations. In the fast regime, both the capillary depth and the average capillary diameter show an almost constant increase for all three measurements. In the slow regime, only the mean capillary diameter increases.

4. Summary

The online X-ray diagnostics system at the IFSW was successfully applied for the analysis of the temporal behavior of the capillary depth progress for laser beam spot welds. The capillary formation was identified in-process taking benefit of the greyscale value contrast between the capillary and the solid material in the X-ray videos. It was seen that the capillary depth progress as a function of time can be seperated into two regimes: (1) the fast increasing one and (2) the slow regime, where the capillary depth only slightly increases. For a reliable and most productive process, the fast regime must be selected. In the slow regime, spot welding is also still possible but not as productive.

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References

Abt, F., Boley, M., Weber, R., Graf, T., Popko, G., Nau, S., 2011. Novel X-ray System for in-situ Diagnostics of Laser Based Processes – First Experimental Results, in "*Physics Procedia",* p. 761–770.

Glaessel, T., Seefried, J. , Franke, J., 2012. Challenges in the manufacturing of hairpin windings and application opportunities of infrared lasers for the contacting process, in "*7th International Electric Drives Production Conference (EDPC)*", pp. 1-7.

Harvey, Andrew C., 1989, Forecasting, Structural Time Series Models and the Kalman Filter, in "*Econom. Theory* 8" (2), p. 293–299.

Lind, J, Fetzer, F., Hagenlocher, C., Blazquez-Sanchez, D., Weber, R., Graf, T., 2020. Transition from Stable Laser Fusion Cutting Conditions to Incomplete Cutting Analysed with High-speed X-ray Imaging, in "*Journal of Manufacturing Processes"* 60, p. 470–480.