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Reduction of pores by means of laser beam oscillation during remote welding of AlMgSi

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ABSTRACT

The influence of a spatial beam oscillation on the dynamics of the capillary and the mechanism leading to an increased or reduced generation of process pores was investigated for deep penetration laser beam welding of the aluminum alloy AlMgSi. Welding with a feed rate of 4 m/min and a welding depth of 4 mm was examined with sinusoidal (longitudinal and lateral) and circular beam oscillation patterns at frequencies of 100 Hz and 200 Hz. The welding processes were analyzed by means of online X-ray imaging with a frame rate of 2 kHz, which provides the temporal and spatial resolution required to resolve the dynamics of the capillary. With conventional rectilinear welding, the weld seams are prone to the formation of process pores. By applying a circular beam oscillation, the weld seams were found to be virtually free from porosity. The mechanism leading to a reduced occurrence of process pores differed for the two investigated beam oscillation frequencies. At an oscillation frequency of 100 Hz bubbles are regularly formed in the melt pool but immediately removed at the subsequent pass of the laser beam by degassing into the vapor capillary. At 200 Hz the formation of process pores is completely avoided from the first. For a sinusoidal beam oscillation in longitudinal direction, the bubbles formed in the weld pool were found to be further inflated at each pass of the laser beam.

1. Introduction

Deep penetration laser beam welding of common aluminum alloys is still challenging due to fluctuations of the welding depth [1], hot-cracking [2] and the formation of process pores [3,4]. Fluctuations of the welding depth and the formation of process pores are mostly caused by an instable vapor capillary [5,6]. These instabilities are understood to cause a repeating cycle of excessive evaporation, bulging of the capillary and release of that bulge as a bubble into the melt pool [7,8]. The typical procedure that accompanies the generation of such a bubble is documented in Fig. 1 by a series of images acquired by online X-ray imaging during rectilinear welding of AlMgSi. Here, the lower part of the capillary bulges (see capillary in the pictures with the time tag 2 and 3 ms in Fig. 1). After that, the capillary constricts above this bulge (4 ms), which subsequently separates from the capillary (5–6 ms) and remains in the melt pool as a new bubble. The laser beam and the capillary move on (7 ms) and if the bubble cannot leave the melt pool before the surrounding metal solidifies, the bubble remains as a pore in the weld seam.

According to the state of the art, the capillary should be stabilized in order to prevent the above described process of bubble generation. Measures to stabilize the capillary have been proposed, such as a double focal technique [9] and its emulation by means of high-frequency (>1000 Hz) oscillation of the laser beam in longitudinal direction (parallel to feed) [10].

Laser beam oscillation at lower frequencies (10 Hz–500 Hz) has been investigated for welding of both aluminum [11,12] and steel [13,14] and found to result in better controllable welding processes.

In case of full-penetration welding of 6xxx series aluminum, laser beam oscillation resulted in an enhancement of the mechanical properties through its impact on the grain structure [15]. A reduction of the amount of pores in the weld seam by the application of beam oscillation for welding die cast aluminum to wrought aluminum in square butt configuration was claimed in [16] but without specifying the oscillation parameters.

For reasons of technical feasibility, mainly sinusoidal oscillations (both lateral (perpendicular) and longitudinal (parallel) to the direction of feed) have been applied so far. The resulting oscillation patterns are sketched in Fig. 2. These stem from an oscillation of the pro-

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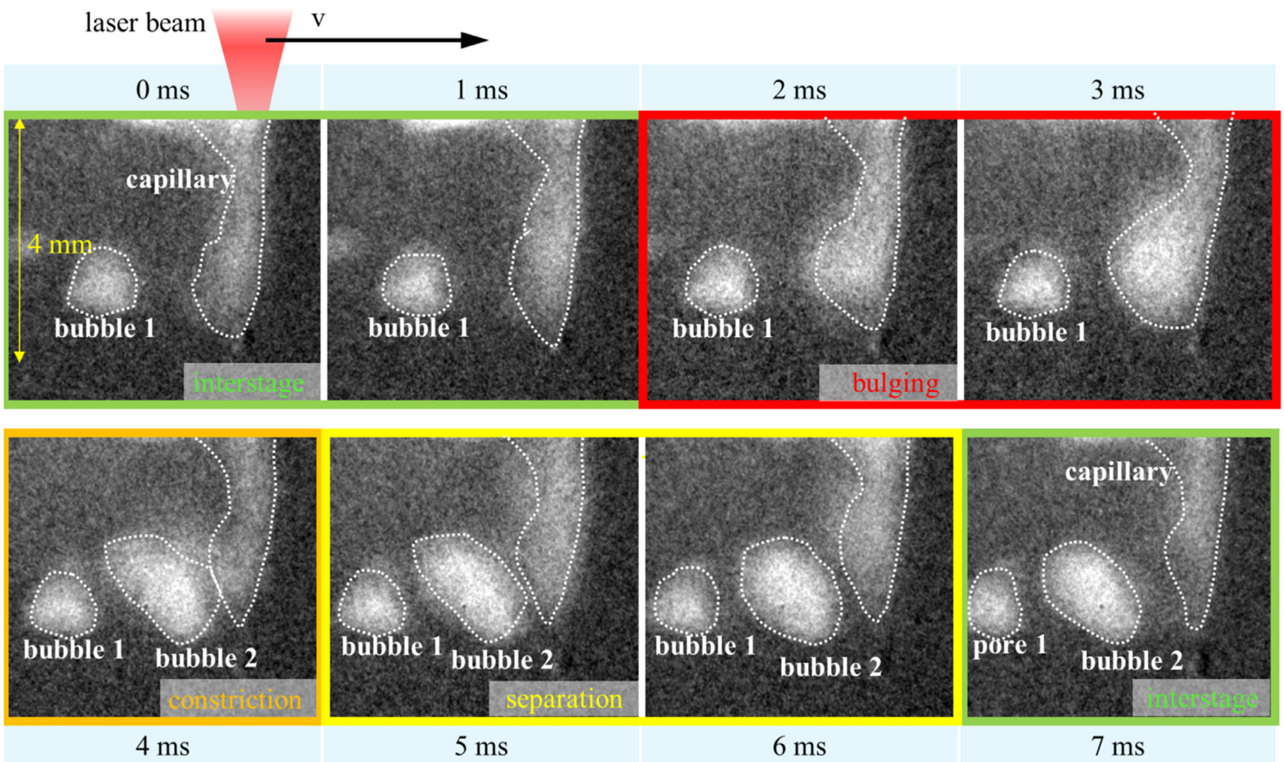

Fig. 1. Series of images out of a high-speed X-ray video showing the formation of a new bubble (bubble 2) during laser beam welding of AlMgSi with $P = 4$ kW, $v = 4$ m/min, $d_f = 560$ µm. The dotted lines highlight the geometries of the voids.

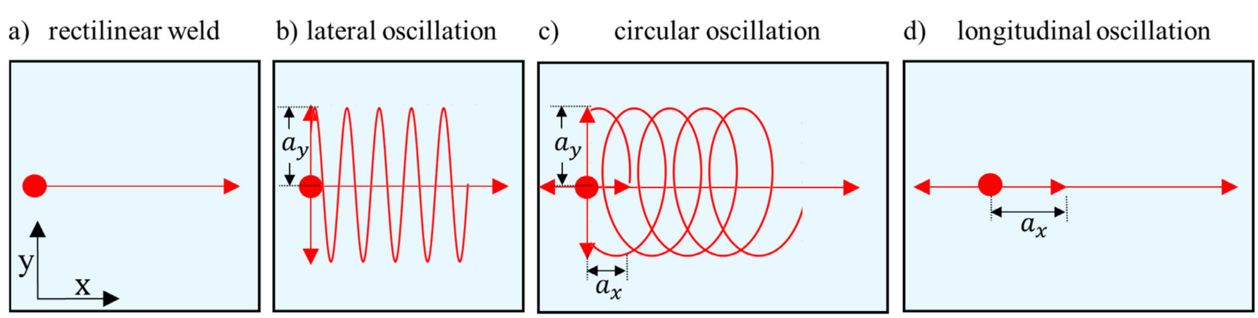

Fig. 2. Applied oscillation patterns and the resulting trajectories of the laser beam path. The amplitudes of the beam oscillation are denoted by $a_{x,y}$.

cessing beam on the surface of the welded sample according to the trajectories

$$\text{rectilinear welding}: \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \begin{pmatrix} v \cdot t \\ 0 \end{pmatrix} \tag{1a}$$

$$\text{lateral oscillation}: \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \begin{pmatrix} v \cdot t \\ a_y \cdot \sin(2\pi f \cdot t) \end{pmatrix} \tag{1b}$$

$$\text{circular oscillation}: \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \begin{pmatrix} v \cdot t + a_x \cdot \sin(2\pi f \cdot t - \pi/2) \\ a_y \cdot \sin(2\pi f \cdot t) \end{pmatrix} \tag{1c}$$

$$\text{longitudinal oscillation}: \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \begin{pmatrix} v \cdot t + a_x \cdot \sin(2\pi f \cdot t - \pi) \\ 0 \end{pmatrix}, \tag{1d}$$

with $a_{x,\,y}$ denoting the amplitudes and f the frequency of the oscillation. The feed rate is denoted by v. These trajectories represent the movement of the laser beam in the coordinate system of the moved sample. In the lab system ($v = 0$) the patterns 1b and 1d would correspond to oscillations on a straight line (lateral and perpendicular to the direction of feed) and 1c on a circle.

The present paper is devoted to the impact of the beam oscillation patterns 1a–d on the geometry of the capillary and the formation of pores during laser beam welding of the aluminum alloy AlMgSi. The geometry and the dynamics of the capillary were measured by means of online X-ray imaging.

The parameters of the experimental setup and the applied oscillation patterns are documented in the following Section 2. The influence of these oscillation patterns on the resultant weld seam quality, the dynamics of the capillary as well as on the increase or reduction of the number of pores is analyzed in Section 3.1–4 and discussed in Section 3.5. Section 4 concludes these findings.

2. Setup & experiments

A disk laser TruDisk 16,002 from TRUMPF with a beam quality factor of $M^2 = 30$ was used for the experiments. A transport fiber with a core diameter of 200 µm delivered the beam to a custom-built scanning unit, which enabled a spatial oscillation of the laser beam. The magnification of the processing optics was 2.8:1, resulting in a diameter of the beam waist of $d_f = 560$ µm and a Rayleigh length of $z_R = 8$ mm. The welded