Lasers in Manufacturing Conference 2017

Experimental and numerical investigation of the capillary front and side walls during laser beam welding

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Abstract

In deep penetration laser beam welding the distribution of absorbed laser intensity on the walls of the capillary determines local recoil pressure which is a driver for melt flow. This again influences the distribution of absorbed laser power and pressure at the capillary.
High speed imaging of melting and evaporation caused by laser irradiation of edges of pure iron sheets is performed with the aim to visualize these phenomena at the capillary walls. High speed recordings with a frame rate of up to 100 kHz are acquired. These experiments are used to validate transient simulations of the capillary front wall in laser beam welding by applying an approach where ray-tracing calculations are coupled to a Smoothed Particle Hydrodynamics simulation of the fluid dynamics.

Keywords: laser beam welding; simulations; Smoothed Particle Hydrodynamics; evaporation

1. Introduction

Laser beam welding is of great interest in modern welding applications due to the high degree of automatability and the well-defined energy input which results in low thermal loads on the welded parts as Katayama, S., 2004 described. When welding in deep penetration mode, a so-called vapour capillary is generated by excess evaporation through which the laser energy is introduced into the material as described in Hügel, H. et al., 2009. Most of the laser power is absorbed at the front wall of this capillary and highly dynamic phenomena occur, such as melt flow patterns moving at velocities of several m/s, as reported by

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Arata, Y., 1980 and step-like structures, investigated by Berger, P. et al., 2011. These phenomena are expected to exert significant influence on the distribution of the absorbed laser irradiation and thereby on the dynamics and stability of the welding process. Therefore, the physical phenomena occurring at this front wall are subject to continuing research and recently investigations of these phenomena by means of high-speed imaging have been conducted by Samarjy, R. S. M. et al., 2016, furthermore by Matti, R. S. et al., 2014 and Eriksson, I. et al., 2013.

In the present proceeding we present results of investigations of these phenomena with both experimental studies by means of imaging with high temporal resolution and multi-physical simulations. We focus on the laser irradiation of metal edges.

This geometry allows detailed observation of the irradiated front wall. We show that Smoothed Particle Hydrodynamics (SPH) simulations of the thermo- and fluid dynamics coupled to a ray-tracing scheme is able to replicate key features in welding complex and dynamic geometries.

2. Experimental investigations

High speed imaging of the processing of the edge of pure iron samples irradiated by a solid state laser with a wavelength of 1.03 µm and an M^2 of 12 was performed. The applied laser power was 8 kW and the laser was defocused so that the diameter of the focal spot at the upper edge of the sample was 1 mm. The sample was moved through the stationary laser beam with feed rates varying from 0.3 m/min to 1.2 m/min. In Fig. 1 three successive images from a high speed video of this process acquired at 100 kHz are shown, representing snapshots of the process at 5 ms, 10 ms and 15 ms. The process of melting and partial evaporation and the resultant dynamics of the molten material can be seen in these images. Step-like structures below 100 µm in size moving at several meters per second at the front and side walls are found (marked with the arrows).

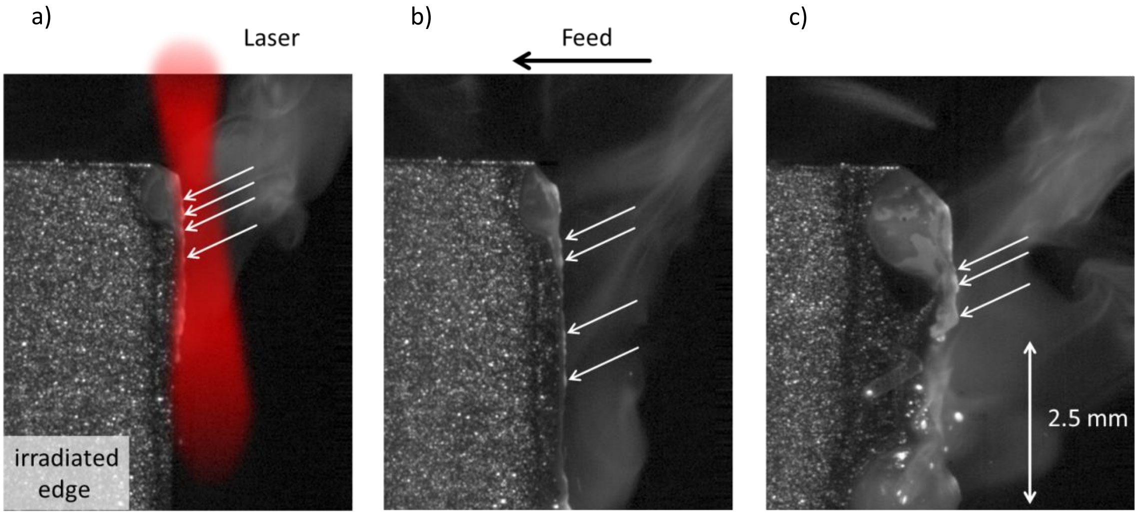

Fig. 2. Three single frames out of a high speed video of laser irradiation of edges of rectangular-shaped iron samples acquired at 100 kHz. (a) 5 ms of processing time; (b) at 10 ms, and (c) at 15 ms. Processing parameters: P = 8 kW; v = 0.3 m/s; d_f =1 mm.

3. Transient Modelling Approach

The coupling of ray-tracing calculations to an SPH simulation is used as an approach for the transient modelling of the dynamic phenomena at the laser irradiated front wall. SPH is a meshless approach capable of simulating large deformations, phase changes and species mixing in an efficient manner, as summarized by Monaghan, J. J., 2012. Due to its Lagrangian approach dynamic shapes are intrinsically covered by the SPH method. Recently SPH methods have been applied to the simulation of laser beam welding in heat conduction mode by Hu, H. et al., 2016a and the simulation of the transition from heat conduction welding to deep penetration welding by Hu, H. et al., 2016b. In the present proceeding the coupling of an SPH simulation to a ray-tracing scheme is described with the aim to simulate the melting and evaporation edge-like geometries of iron under laser irradiation. Ray-tracing was used to calculate the intensity distribution of the absorbed laser irradiation on the workpiece. The approximations applied in the geometrical ray-tracing approach lead to a negligible error for most geometries relevant in laser beam welding as shown by Qin, Y. et al., 2012. In the present approach a ray-tracing code was employed based on the method introduced by Michalowski, A., 2014. In each time step of the simulation the current surface elements are retrieved from the SPH program and are then transferred to a triangulated surface, which is used as input geometry to calculate the absorbed intensity distribution with the ray-tracing code. The absorbed intensity distribution then acts as source of thermal energy for the fluid dynamics simulation.

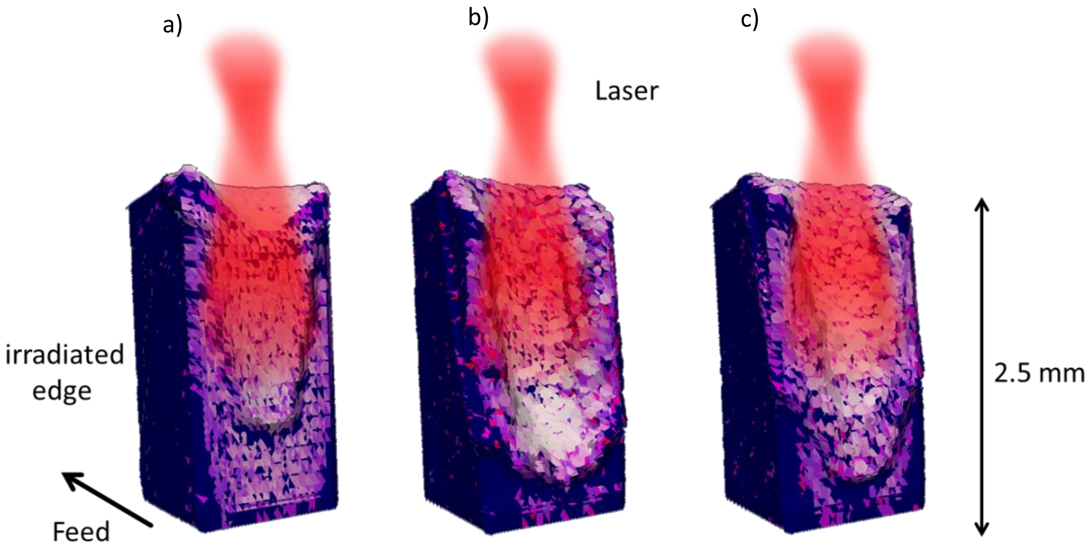

Fig. 2. Geometries of the processed iron samples as resulting from the SPH simulation coupled to ray-tracing calculation, which is used to determine the distribution of absorbed intensity on the molten metal front wall. The simulated times correspond to 2 ms in a), 6 ms in b) and 10 ms in c). Processing parameters: P = 8 kW; v = 0.3 m/s; df = 1 mm.

The implementation of the thermodynamics is based on the approach introduced in Hu, H. et al., 2016b. A recoil pressure p_s acting on the evaporated surface given by

$$p_S = \frac{Q_S}{AH_v}\sqrt{\frac{\pi k_B T_S}{2m_v}} \qquad (1)$$

is implemented, following Chen, X. et al., 2001. Here Q_s denotes the laser power that is spent in evaporation, k_B the Boltzmann constant, m_v the molar mass of a vapour molecule, H_v the latent heat of evaporation and T_s the local surface temperature. This pressure acts as a driver for the melt flow.

Three typical geometries resulting from the above described simulations and the same process parameters as in the experiment are shown in Fig. 2, which illustrate the development of the front wall geometry. The kerf generated by melting of the material and driving of this melt by evaporation can be seen. The resultant development of the irradiated geometry agrees well with the images from the high-speed recordings in Fig 2. Additionally, the simulation allows to track unobservable features, such as the total fraction of absorbed laser power which is spent in melting and evaporation.

Acknowledgements

The research leading to the presented results has received funding from the German Research Foundation (DFG) under the projects EB 195/13-1 and GR 3172/18-1 “Modelling of the capillary in laser beam penetration welding with the Smoothed Particle Hydrodynamics Method”. This support is highly appreciated.

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