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Wire deposition by a laser-induced boiling front

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ABSTRACT

In laser materials processing the addition of material by wire is an option for techniques like laser welding, laser cladding or rapid prototyping. The stability of the wire deposition is strongly dependent on the wire interaction with the laser beam. For leading position wire feeding, high speed imaging was applied to study the melt transfer from the wire tip to the workpiece during keyhole welding. The observations revealed that a very stable concave processing front forms at the wire tip. A boiling front is established as an extension of the keyhole and the melt film at the front is sheared downwards by the ablation pressure of boiling. The deposition of the molten wire into the weld zone is smooth and controllable. Various wire front geometries and melt transitions are compared for different parameters. The option of laterally oscillating the laser beam is investigated and the interaction mechanism involved is discussed. Wire deposition by inducing a boiling front is explained here for the first time, which should promote future applications use of this very promising technique.

1. Introduction

In laser materials processing the addition of material by wire is an option for techniques like laser welding (conduction or keyhole mode), laser cladding or rapid prototyping/rapid manufacturing (particularly direct metal deposition, DMD). The use of filler wire in laser welding goes back to the eighties when researchers concentrated on the addition of filler wire to high power CO_2-laser welding of thick plates [1]. Three different advantages of this method interested a number of workers in this field [2]: (i) the increase in the robustness of the laser welding process by bridging the air gap between the weld parts; (ii) the improvement of the metallurgical properties and composition of the weld metal by adding a filler wire of suitable chemical composition to the melt pool; and (iii) the ability to employ multi-pass techniques to fill heavy section workpieces, (even when using low power, less expensive lasers [3]).

Salminen et al. [4–6] have studied laser welding with filler wire (LWFW) for many years. Proper positioning of the filler wire is the most critical factor of LWFW, due to lateral and vertical fading of the wire tip. One option is lateral beam oscillation. Coste et al. [7] reported the first use of beam oscillation with filler wire assisted laser welding, using a 20 kW CO_2 laser source to weld 8 mm thick plates of grade E690 steel. It was demonstrated that even with a 2 mm gap between the plates' edges a reliable weld can be obtained. Similar results have since been demonstrated by other researchers [8,9].

The melting tip of the wire interacts with the laser beam and reflects a considerable amount of the laser power [5]. The reflectivity of the wire tip is at least 50–60% according to Fresnel absorption for circularly polarized high power lasers. The processing front geometry changes with variations in the filler wire diameter, angle and feeding rate and welding speed. These parameters also change the energy input vs. the interacting wire volume. The best weld quality is associated with a wire feed angle between 45° and 60° to the horizontal [4].

Recently, wire addition was observed and analysed in more detail by applying high speed imaging [3,8]. Yamazaki et al. [3] successfully examined LWFW for thick materials with beam oscillation at various frequencies and amplitudes to properly fill the gap. Certain mechanisms were explained for a very wide weld pool, for this specific joint configuration. In particular, wire chopping was demonstrated and explained, although the image resolution was too low to clearly study the mass transfer and geometrical conditions at the wire tip.

Yu et al. [8] identified the wire feeding rate and the vertical wire position as two of the most critical parameters for a stable process. This was documented by a process diagram. Three different

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mechanisms of melt dynamics were distinguished: explosion, big droplet and liquid bridge. The work concentrated on the geometrical positioning of the wire relative to the laser beam and the corresponding energetic relationships, observed by high speed imaging. Gravity and surface tension were discussed as important forces for melt transfer. Moreover, the drag force by ejection of metal vapour/plasma from the keyhole was addressed. Although the resolution of the high speed images is lower than those presented in this paper, a concave front formation can be seen for the liquid bridge, which is likely to be the type of boiling front addressed here. While Yu et al. focused on geometrical and energy aspects, the results presented in the present paper describe and interpret the phenomenon that the wire tip often develops a concave boiling front as one of the key transfer mechanisms. The oscillating beam can also lead to chopping of the solid wire, a mechanism also experienced in the present study.

Further studies on wire addition in laser welding address (beside metallurgical studies) process options like wire preheating, which can enhance process efficiency. Electrical preheating of the wire can to be advantageous in order to optimize solidification mechanics, promoting epitaxial growth along with vertical dendritic solidification to the side walls [10]. The thermodynamic conditions in a preheated wire were calculated in order to state a criterion for sufficiently early wire melting before entering the melt pool [11]. Further studies concern the impact of gravity on the wire transition depending on the welding position [12] and high speed imaging for CO_2-laser welding of aluminium alloys [13].

Based on the former observations, calculations and understanding of the melt transfer from wire addition, the present study addresses for the first time a specific mechanism, melt transfer from the wire to the workpiece by a vertical melt film flow which is laser induced via a concave boiling front.

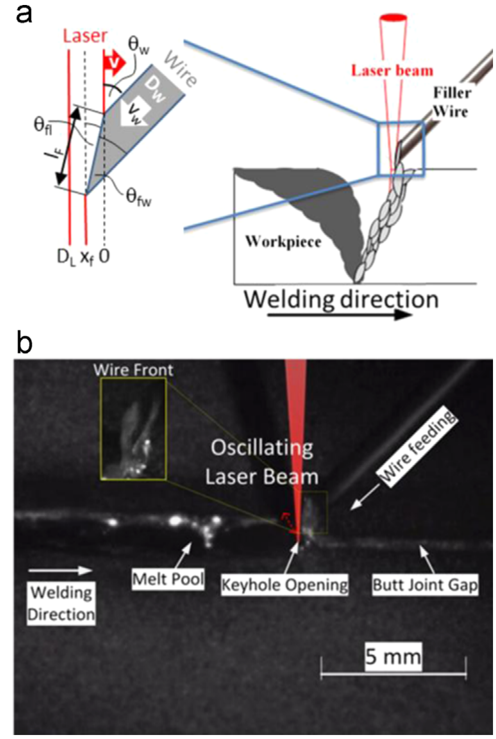

Fig. 1. (a) Sketch (and magnification) of the melt transfer and weld pool in laser keyhole welding with leading filler wire addition; and (b) a typical high speed image (and magnification) of the laser welding process with leading filler wire addition.

2. Methodology

Totally 74 laser welding experiments were carried out for butt joints while adding filler wire. Most of the experiments were observed by high speed imaging. For some of the experiments the laser beam was laterally oscillated.

In Fig. 1(b) the experimental set-up can be seen in a typical frame from the high speed imaging, as sketched in Fig. 1(a). The wire (type Sandvik 22.8.3.L 2209) with a diameter of 1 mm was employed in a leading position (CRC-Evans Capstan wire feeder), at a vertical angle of 45°. For most experiments the wire was placed at the workpiece surface, except for a few samples where it was placed 1 mm above the surface (measured at the laser beam axis). The wire tip position and angle however in practice varied during the experiments. In some cases the laser beam was oscillated laterally, varying the amplitude and frequency. A weld cross section for a regular weld with filler wire addition is shown in Fig. 2(a), while Fig. 2(b) shows a weld cross section achieved when oscillating the laser beam (at sufficiently low frequency).

The welding experiments were performed with a 15 kW Yb:fibre laser manufactured by IPG Laser GmbH. The welding head was a modified Precitec YW-50 with an extra cooling block and a DC-scanner manufactured by the company ILV. A 250 mm focal length lens was used to focus the laser beam after the scanner, for a fibre with a core diameter of 0.2 mm and a beam parameter product of 10.4 mm · mrad. A focal spot diameter of 0.33 mm was generated, with a Rayleigh length of $\pm$2.7 mm. The focal plane was positioned between the surface and the middle of the workpiece thickness (i.e. about 4–7 mm below the wire tip). The beam diameter at the wire position was in the range 0.7–1.0 mm, which is similar to the wire diameter. The power density in the focal plane was approximately 10–15 MW/cm^2 and the wire tip was therefore irradiated by several MW/cm^2, which is above a well known threshold of 1 MW/cm^2 for the generation of a boiling keyhole in steel. The power density to reach the boiling temperature at the wire tip front can be calculated as 20–200 kW/cm^2 for a feeding rate of 1–10 m/min, but the required beam power density is higher because the strongly inclined wire involves a larger projected area, and reflection losses must also be considered. The laser beam was tilted 7° to suppress back reflection. When scanning the laser beam, frequencies between 20 and 200 Hz and amplitudes ranging 0.7–5.0 mm were applied. Argon was applied as the shielding gas, at a flow rate of 20 l/min (a tube with 10 mm diameter was located 21 mm from the process zone). Different wire feeding speeds were tested, matched to the plate thickness and welding speed. Three different types of sheet edge preparation (laser-cut, water-cut and mechanically cut edges) were tested. Plate thicknesses for butt welding ranged from 6 to 15 mm. The 8 and 15 mm thick samples were duplex stainless steel according to the standard EN 1.4462 (Outokumpu2205). The 10 mm thick plates were austenitic stainless steel according to the standard EN 1.4307 (AISI 304 L) and 6 mm plates were 2507 super duplex stainless steel.

The laser power was varied from 7 up to 15 kW and the welding speed was changed between 1 and 2 m/min. The lowest heat input into the workpiece was 0.36 kJ/mm and the highest was 0.6 kJ/mm. All welding processes were recorded using a high speed imaging (HSI) system. A high speed camera (MotionProX3 Plus) was operated at 4000 frames per second (250 μs time steps) the weld area that was illuminated with a pulsed Cavitar Cavilux HF diode laser system. The camera had a narrow band-pass filter for the illumination laser wavelength (808 nm). The camera was positioned at an angle of 45° to the surface. Beside qualitative analysis, quantitative measurements were taken from the images. For improved analysis, image enhancement was carried out, concentrating on brightness and contrast. The inclination angle of the processing front was measured from the high speed imaging stills.