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Controlled metal transfer from a wire by a laser-induced boiling front

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Abstract

The addition of wire is an option during laser welding, laser cladding or laser additive manufacturing. By high speed imaging of leading wire addition during fibre laser keyhole welding it was observed that for the 40 experiments under consideration the wire tip always established a concave boiling front. The front appears similar to a keyhole front and is sort of a continuation of the keyhole, owing to the leading wire employment. For most of the parameters the melt is transferred downwards from the wire tip into the melt pool surrounding the keyhole front. In other words, hardly any uncontrolled spatter to the sides was observed. A trailing wire would normally tend to a completely different behaviour. Typical as well as limiting phenomena of the wire melt transfer mechanism are presented and discussed. Controlled vertical melt transfer of the wire through the ablation pressure from a laser-induced boiling front, either in contact with the workpiece surface or positioned higher above, can be a desirable mechanism of metal deposition for the different techniques, namely welding, surface treatment or LAM. By suitable choice of the laser power density above the boiling threshold, the here observed mechanism can be applied in a controllable manner. An interesting technique option is lateral beam oscillation for example by a galvanometer optics which shears off the melt in a manner similar to remote fusion cutting. The process limits become different to the static technique. The wire melt transfer technique has the potential to be developed further towards a highly controllable remote drop transfer, e.g. in terms of direction.

Keywords: wire addition; melt transfer; laser-induced boiling front; keyhole welding; LAM

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1. Introduction

Here research results are presented on the recently discovered phenomenon that melt transfer from wire addition during laser materials processing can take place via a boiling front at the tip of the wire, driving the melt downwards in direction of the laser beam in a controlled manner. For more details and complementary results we refer to Torkamany et al., 2015, where the phenomenon was reported for the first time.

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). Three different advantages of this method interested a number of workers in this field, Dilthey and Schneegans, 1994: (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; (iii) The ability to employ multi pass techniques to fill heavy section workpieces.

Salminen and Kujanpää, 2003 and Salminen, 2010, 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., 1994, 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, Tsukamoto et al., 2011, and Yu et al., 2013.

The melting tip of the wire interacts with the laser beam and reflects a considerable amount of the laser power, Salminen and Kujanpää, 2003. 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 45-60° to the horizontal, Salminen, 2010.

Recently, wire addition was observed and analyzed in more detail by applying high speed imaging. Yu et al., 2013, 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 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., 2013, focused on geometrical and energy aspects, the results 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 be advantageous in order to optimize solidification mechanics, promoting epitaxial growth along with vertical dendritic solidification to the side walls, Wen et al., 2011. 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, Shiqing et al., 2013. Further studies concern the impact of gravity on the wire transition depending on the welding position, Fujinaga et al., 2004, and high speed imaging for CO_2-laser welding of aluminium alloys, Takahashi et al., 2002.

Based on the former observations, calculations and understanding of the melt transfer from wire addition, the present study addresses 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.

2. Methodological Approach

Totally 74 laser welding experiments were carried out for butt joints while adding filler wire. 40 of the experiments were observed by high speed imaging. For some of the experiments the laser beam was laterally oscillated.

In Fig. 1(c) the experimental set-up can be seen, also in a typical frame from the high speed imaging in Fig. 1(b) and as a sketch in Fig. 1(a). The wire (steel, type Sandvik 22.8.3.L 2209) with a diameter of 1 mm was employed in a leading position, 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.

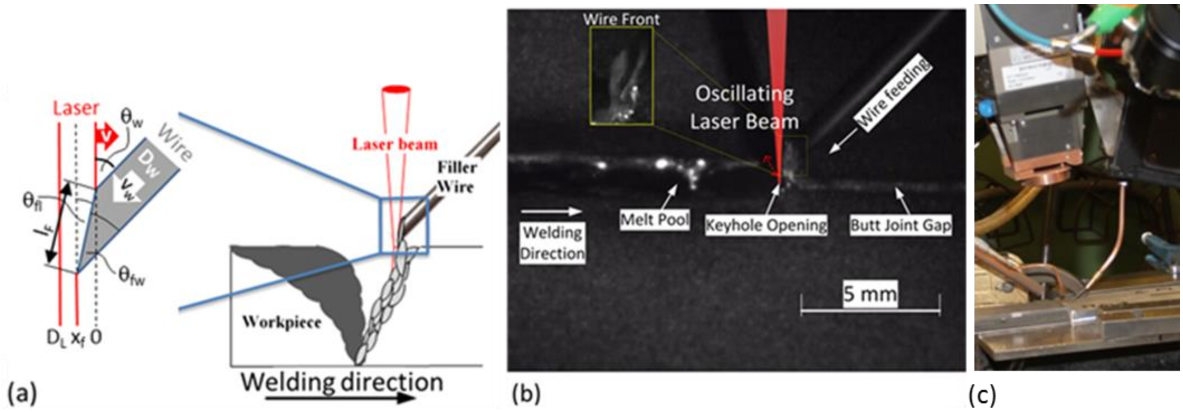


Fig. 1. (a) Sketch (and magnification) of the melt transfer and weld pool in laser keyhole welding with leading filler wire addition; (b) a typical high speed image (and magnification) of the laser welding process with leading filler wire addition; (c) experimental set-up.

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. 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 the typical indicative 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/cm2 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.

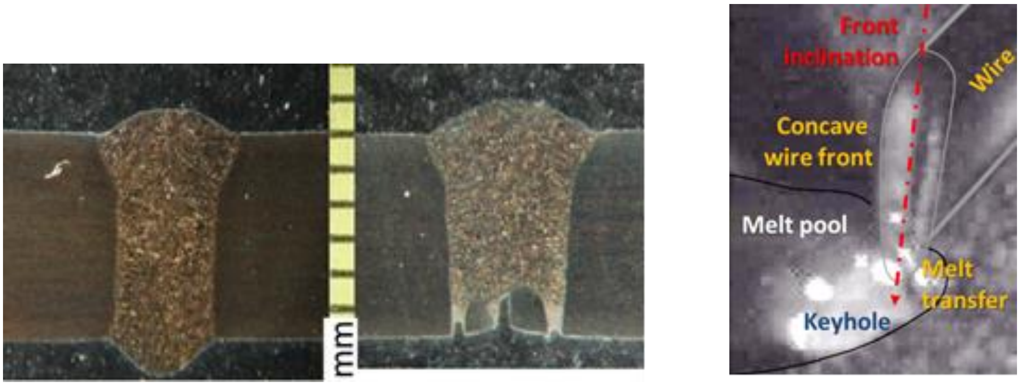
When scanning the laser beam, frequencies between 20-200 Hz and amplitudes ranging 0.7-5.0 mm were applied. Different wire feeding speeds were tested, matched to the plate thickness and welding speed. The plate thicknesses for butt welding ranged from 6 to 15 mm. The 8 and 15 mm thick samples were duplex 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 304L) and 6 mm plates were 2507 super duplex stainless steel. More experimental details can be found in Torkamany et al., 2015.

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 images.

3. Results and Discussion

In the following selected results are presented, in a complementary manner to the results shown in the pioneer paper by Torkamany et al., 2015.

A typical 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). However, it should be noted that the weld itself is not in the centre of the presented results, it just serves as an orientation in the wider picture.



(a) (b) (c)

Fig. 2. Weld cross sections of two laser welds (plate thickness: 6 mm, see scale) with filler wire addition: (a) no oscillation; (b) lateral sinusoidal beam oscillation; (c) Typical magnified frame of HSI, showing the concave wire front, the melt transfer from the boiling front to the laser created keyhole and the melt pool (P_L 12 kW, v_w 7.6 m/min, wire line energy E_w 94 J/mm; for scale: wire diameter is 1 mm)

A magnified view of a typical high speed image, HSI, of the wire tip is shown in Fig. 2(c). From the shadow (related to the positioning of the illumination laser) it is apparent that the front shape is of concave nature. This in turn is evidence for boiling action, similar to a keyhole front, which is the continuation of the wire front. The front is slightly inclined, to catch up part of the projected laser beam, i.e. absorbed power converted to heat mainly through the geometrical projection geometry. The melt flows downwards from the wire tip (towards the keyhole and its surrounding melt pool). From the appearance of the wire tip front it was concluded that it is a boiling front. A boiling front means recoil pressure (ablation pressure from boiling) on the melt. This in turn accelerates the melt. It was recently shown for keyhole welding, Eriksson et al., 2010, that the front develops waves that move downwards, i.e. generating a vertically directed flow from the recoil pressure on the humps that cause a momentum facing downwards. The same can be expected to be true for the wire tip as soon as the boiling point is exceeded. The observations for downstreaming flow were made for a fibre laser with a wavelength of 1070 nm. The absorptivity of fibre lasers (here on steel) favours the amplification of valleys on the front topology and in turn a thrust directed downwards. Calculations by Kaplan, 2015, have shown that for CO_2-lasers (wavelength: 10.6 µm) this behaviour might be different or at least less pronounced. Therefore the here presented wire melt transfer mechanism is controllable for lasers with about 1 µm wavelength (fibre, disc, Nd:YAG or diode lasers) but not yet confirmed for the CO_2-laser.

4. Results and Discussion

Figure 3 shows a sequence of high speed images for a non-oscillating laser beam. A stable concave boiling front establishes, accompanied by melt transfer downwards to the keyhole. Figure 4 shows a sequence of images for a laterally oscillating laser beam. The front is still concave but twists by following the beam movement. This front behaviour is similar to remote fusion laser cutting, see also Matti and Kaplan, 2014. The top of the wire is cut-off in a certain sense. In extreme parameter cases the wire will be chopped into solid pieces dropping into the melt, see Fig. 5, which nonetheless might enable a stable metal transfer, though in a different manner (the melt pool then heats and melts the solid pieces dropping into it).

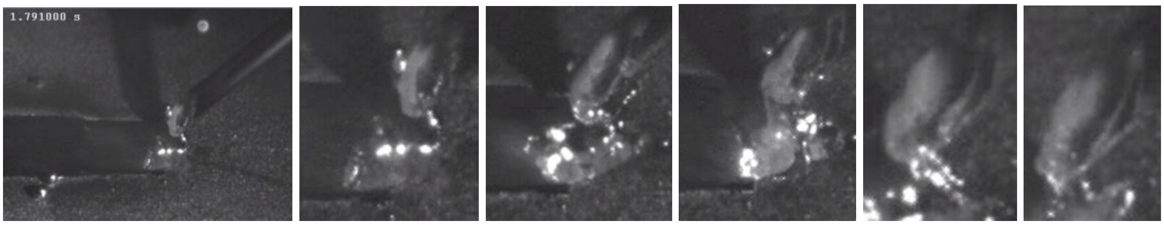


Fig. 3. Survey picture and sequence (time steps: 250 µs) of high speed images of the concave boiling front at the wire tip for a non-oscillating laser beam.

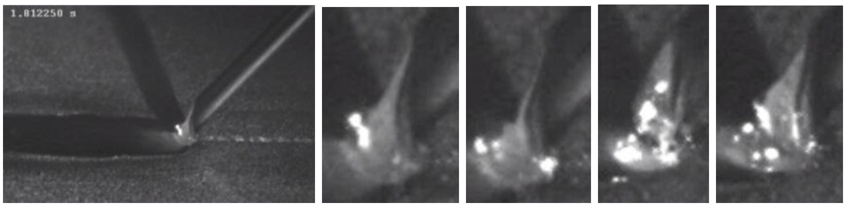


Fig. 4. Survey picture and sequence (time steps: 1 ms) of high speed images of the twisting dynamic boiling front at the wire tip for a laterally oscillating laser beam (60 Hz).

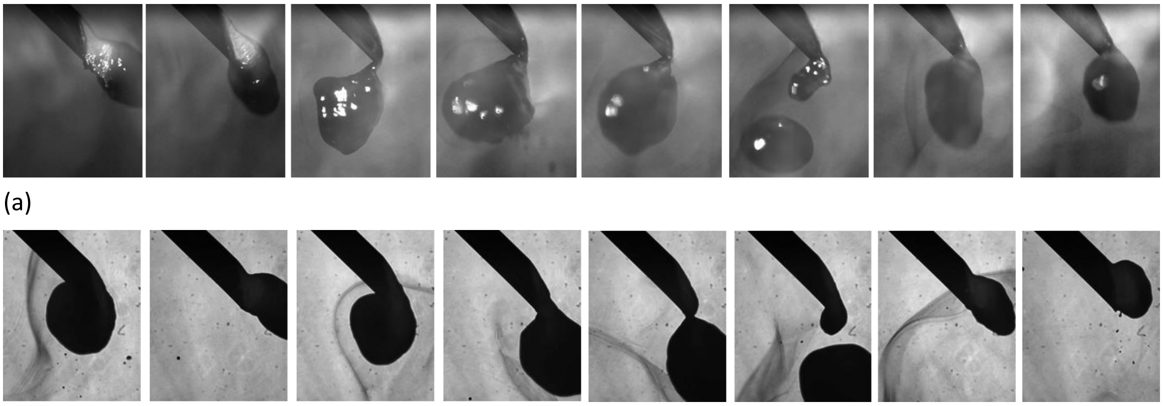
Fig. 5. Survey picture and sequence of high speed images (250 µs) when chopping the wire into solid pieces by a laterally oscillating laser beam (60 Hz).

Typical appearances of the boiling front at the wire tip and of the accompanying melt transfer mechanism downwards are shown in Fig. 6. Further examples, particularly for limiting situations of a stable process can be found in Torkamany et al., 2015. Figure 6(a) shows an example of proper melt transfer operation when no oscillation takes place. The melt streams quasi-continuously into the keyhole. For strong boiling action the downstreaming melt can be pulled back to the wire before detaching, as shown in Fig. 6(b). Figure 6(c) shows a seldom observed drop transfer because the vertical stand-off distance of the wire to the workpiece was relatively high.

(a) (b) (c)

Fig. 6. Various observations of the melt transfer mechanism; (a) representative transfer for proper operation (no osc.), (b) the liquid metal stream is pulled towards the back side of the wire while moving down (no osc.), (c) melt transfer by individual droplets (f_{osc} 60 Hz, w_{osc} 0.9 mm) (P_L 12/12/10 kW, v_w 7.6/7.6/4.6 m/min, E_W 94/94/118 J/mm)

For comparison, Fig. 7 shows high speed imaging sequences (by two different ways of illumination) for the drop transfer from wire melt transfer by a CO_2-laser (here without welding and without a workpiece). A laser beam power density of 17 MW/cm^2 was applied, for which again boiling conditions are achieved at the front. A corresponding boiling front seems to form, while larger drops are ejected from the wire tip. One hypothesis is a less strong and less directed shearing mechanism at the front for this different wavelength, perhaps drop ejection even by gravity forces.



(a)

(b)

Fig. 7. High speed image sequences for wire melt transfer for irradiation by a high power CO_2-laser beam (17 MW/cm^2): (a) image front illumination, (b) image back illumination.

At least for the 1 µm-wavelength lasers the theoretical description of the controlled drop transfer from the wire tip via a boiling front can be described as in Fig. 8. Figure 8(a) illustrates the point that that the wire tip develops an inclined boiling front. Waves form on this boiling front. On the upper shoulders of the waves (catching more beam irradiation) the absorption is highest, which induces peak temperatures and local boiling. Ablation pressure from this boiling accelerates the melt downwards (see also the keyhole wave findings from Eriksson et al., 2013), transferring it from the wire to the workpiece below, either as a stream or in droplets. A quasi-steady state front is formed that has a concave shape, matched to the laser beam. The front continuously redirects the melted wire vertically downwards. This technique of wire deposition by vertical melt transfer can be used, in the case of partial laser beam transmission, Fig. 8(b), for welding at a sufficiently low wire feeding rate. High wire feeding rates with no beam transmission, Fig. 8(c) can be used for laser cladding or direct metal deposition (rapid prototyping, additive manufacturing).

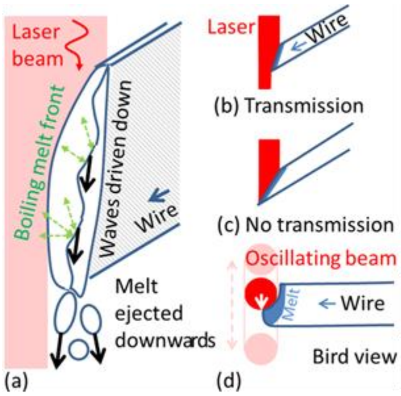


Fig. 8. (a) Theoretical illustration of the process mechanisms at the wire tip front (vertical section), (b) sketch (side view) of the interaction for partial transmission, e.g. in wire-assisted keyhole laser welding, (c) interaction without transmission, e.g. for laser cladding or rapid prototyping, (d) sketch (plan view) of the asymmetric process for a laterally oscillating beam, ejecting the melt downwards.

Note that the orientation is not necessarily downwards (position PA in welding nomenclature, i.e. laser oriented vertically, moving horizontally). The melt ejection could be directed in other directions (e.g. PC, horizontally). Another option for the transmitting case is a laterally oscillating laser beam as a robust technique to carry out the wire melting and transfer. In this case the conditions become asymmetric, see Fig. 8(d), and the technique becomes similar to remote fusion cutting. Finally it should be emphasized that unlike several other melt transfer mechanisms for wire assisted laser welding published previously, the techniques presented here are governed by the ablation pressure from a boiling front, in a very controllable manner. Although these mechanisms were involved in former studies, this is the first time they have been identified and explained.

5. Conclusions

(i) For sufficiently high power density a laser beam irradiating the end of a wire can develop a boiling front with continuous, controlled melt transfer that is directed downwards. This was confirmed by high speed imaging for various parameter combinations.

(ii) The laser beam needs to reach the full width of the wire. This can be achieved by defocussing or by lateral beam oscillation, within certain energy and mass balance limits.

(iii) Lasers with a wavelength of about 1 µm tend to induce waves on the melt surface. The ablation pressure on the waves directs them downwards in the direction of the propagating beam and the melt is sheared off the wire tip in a controlled manner

(iv) This controlled filler wire deposition technique can be applied for cladding or additive manufacturing as well as welding, depending on the chosen parameters, particularly the wire feeding rate

(v) CO_2-lasers appear to cause a similar metal transfer from the wire tip by establishing a boiling front, but the larger drops that form could indicate gravity as a main detachment force, which has to be proven further.

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