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Increase of deposition rates in laser hot wire cladding (LHWC) by use of beam-oscillation for appropriate energy deposition and thermal closed loop control

Dieter Tyralla[a*], Thomas Seefeld[a]

[a]*BIAS – Bremer Institut für angewandte Strahltechnik GmbH, Klagenfurter Straße 5, 28359 Bremen, Germany*

Abstract

Laser hot wire cladding (LHWC) obtains high deposition rates by the combination of electrical preheating of a wire and the power of a laser. However, the quality of the weld usually was not as good as in processes like laser powder cladding.

The present study demonstrates LHWC with high quality and high deposition rate. Therefore appropriate deposition of energy by beam-oscillation strategy is used. In addition, a novel temperature field measurement system observes the process zone. The melt pool size is measured by an emissivity compensated camera and is controlled by the help of the laser power. The electrical heating is matched to the laser power to maintain the total energy in the process and to keep the thermal conditions constant. High deposition rates of more than 2 kg per hour were obtained with less than 1 kW of laser power.

Keywords: laser cladding; hot wire; beam oscillation; temperature field measurement; melt pool geometry

1. Introduction

Laser cladding is a commonly used industrial technique for modification of metallic part surfaces. Cheap and easily processable substrate materials can be modified by alloys with a high chemical or high wear resistance as well as damaged parts can be repaired. The laser assisted cladding technology stands out by its ability to deposit only as much energy as necessary for the melting process. Thereby it is possible to clad thin

* Corresponding author. Tel.: +49-421-218-58114; fax: +49-421-218-58063.
E-mail address: tyralla@bias.de.

walled parts like heat exchanger pipes in the power plant industry which require several square kilometers of coated surfaces (Köhler et al., 2018).

Laser hot wire cladding (LHWC) obtains high deposition rates compared to powder based processes by the combination of electrical preheating of the wire and the power of the laser. In contrast to the mentioned process types with deposition rates of typically less than 1 kg/h (Steen et al., 2010), wire based processes reach 2 kg/h or 3 kg/h (Bombach et al., 2018). The deposition rates can be increased to 6 kg/h by using more than one wire (Freiße et al., 2018) or up to 14 kg/h using strips instead of wire (Tuominen et al., 2019). A homogeneous energy deposition over the whole welding area requires high laser power (Andersson et al., 2014) or in some cases the energy is distributed by beam oscillation. The inefficiently distributed energy of a common gaussian heat source is redistributed in form of a line perpendicular to the feed direction to increase the energy deposition on the wire (Tuominen et al., 2013). Depending on the used typ of oscillator, a sinusoidal intensity profile is generated in most cases and results in a deep penetration depth at the turning points (Tuominen et al., 2013).

The energy deposition usually is not adjusted to the utilized filler geometry, which may lead to inhomogeneous layer properties. The most important properties in this context are the geometry of the weld bead and the dilution. Typical values for dilution are about 5 % to 20 % (Bliedner et al., 2013). The stability of the welding condition, especially of energy deposition and heat sink condition determine the regularity of layer height and dilution. In the case of cladding over hours with a high cladding speed and high deposition rate, observation and control systems are desired to respond to dynamic irregularities or shifting process conditions. Most observation approaches mention the temperature in the process zone as important factor for quality. Different temperature values like maximum temperature (Doubenskaia et al., 2006), temperature gradient (Goecke et al. 2018) or melt pool sizes (Köhler et al., 2010) are measured and maintained constant by adjusting laser power (Köhler et al., 2014) or welding speed (Meriaudeau et al. 2012). Real time monitoring and control of such processes is a demanding task because of the demand on the evaluation system to acquire data with high frequency and to calculate the necessary values in a short time.

Up to now a control system for LHWC is missing that exploits the full potential of electrical preheating. Therefore the present study investigates the energy deposition during cladding by a beam oscillation system. Further the thermal condition in laser based cladding processes is observed by a ratio pyrometer camera. The data of the observation are utilized for a monitoring and control approach that monitor the status of the process and control the energy deposition on the basis of the melt pool geometry by adjustments of the laser power.

2. Experimental – Equipment, Material & Procedure

A modified ALO-3 laser processing head (Scansonic) is used for the experiments. The laser head is characterized by a 2-D beam oscillator. The optic permits up to 4 kW of laser power. The TruDisk 12002 (TRUMPF) is utilized as laser power source. The spot size can be varied between 200 µm and 2 mm by defocussing without an adaption of the distance between work piece and processing head. The filler material is fed at 45° to the work piece in leading position. It can be fed in form of solid wire or metal cored wire by the Masterliner MF1 (Abicor Binzel) which enables feed velocities of up to 10 m/min. The power source HWT220 (Lorch) enables currents of 220 A with a duty-cycle of 40 % and a maximum continuous current of around 170 A. A robot system is used as handling machine to move the processing head above the rotationally symmetrical work piece.

Two types of work pieces are used. The first one is S235 (1.0038) tube with an outer diameter of 100 mm and a wall thickness of 8 mm and the second one is a 42CrMo4 (1.7225) tube with a diameter of 50 mm and a wall thickness of 5 mm. Solid wires with diameters of 1.0 mm and 1.2 mm of the stainless steel 316lSi (1.4430) are investigated. Figure 1a show the experimental setup.

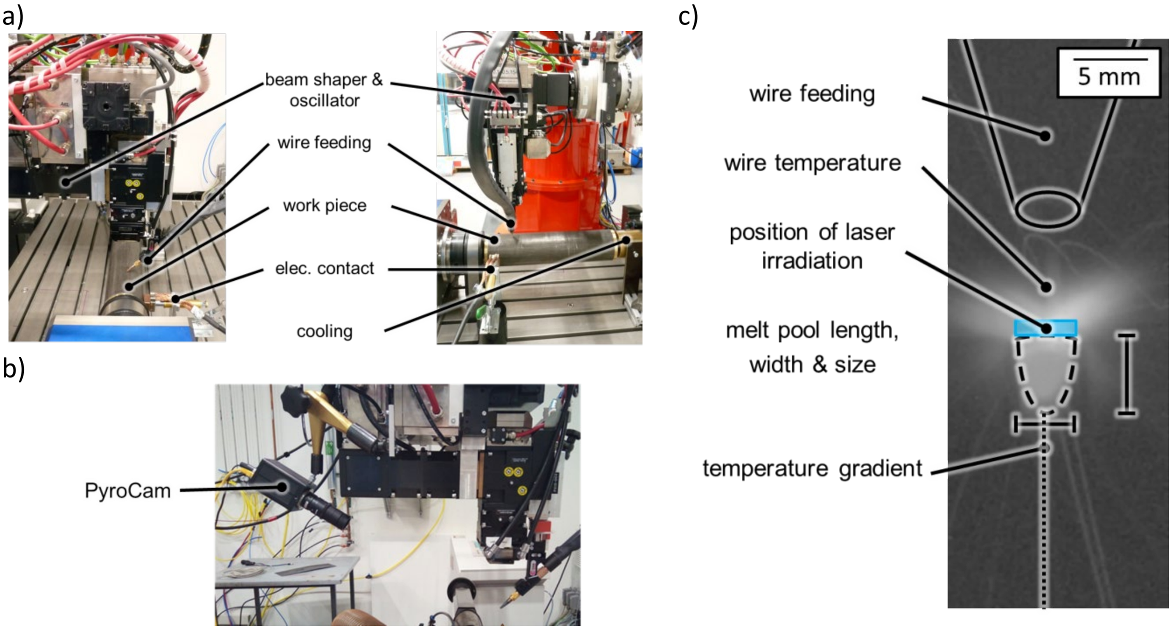


Fig. 1. Front and side view of experimental setup (BIAS ID 181380) (a); Experimental setup of temperature measurement system (b); Greyscale representation of PyroCam image (BIAS ID 181381) (c)

Current and voltage of the power source are measured by a P1000-S3 process sensor (HKS) with a high frequency of at least 100 kHz. The temperature field in the process zone is observed by an emissivity compensated camera PyroCam (Hutter et al., 2009), shown in figure 1b which enables spatially resolved temperature measurements in a range of 600 °C to 1900 °C. Optical filters are used to avoid back reflections and stray-light on the camera which could influence the accuracy of the camera. The camera is used to measure different values of the melt pool geometry which are hold for characterizing the process. Figure 1c illustrates the LabView based approach for the measurement of temperature values:

- Determination of wire temperature at specified position
- Determination of laser irradiation position
- Detection of melt pool geometry in relation to irradiation position
- Determination of melt pool length
- Determination of melt pool width at a specified distance to irradiation position
- Determination of melt pool size
- Determination of specified cooling rates

For the investigation of oscillation strategies work pieces of S235 with a diameter of 100 mm are cladded with stainless steel. The work piece is cooled from the inside during welding. A welding velocity of 1 m/min is used and a wire feed rate of 6 m/min. Single tracks are generated with different oscillation strategies and a laser power of 1500 W, a spot size of 200 µm and a preheating current of 160 A. All oscillation strategies are

performed with a frequency of 200 Hz and an amplitude of 1.8 mm. Afterwards the resulting cross sections of the generated tracks are evaluated qualitatively and dilution is compared quantitatively.
For the development of a novel approach for a control system continuous layers of filler material 316lSi are generated on 42CrMo4 work pieces with a welding speed of 4 m/min, a wire diameter of 1.2 mm, a wire feed rate of 5 m/min, a laser power of about 3500 W, a spot size of 1 mm, a triangle oscillation strategy with 200 Hz and an amplitude of 1.8 mm. The work piece is not cooled. In this work the melt pool length is used for the development of a temperature control system.

3. Results

In the first part energy deposition by gaussian beam and different oscillation strategies are investigated. Figure 2 shows the oscillation paths, their corresponding intensity distribution and the resulting cross section with a value for the dilution.

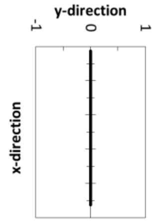
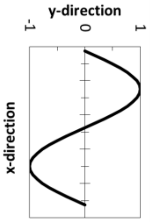
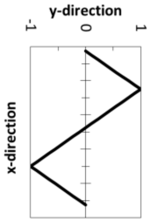
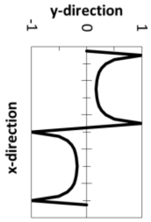
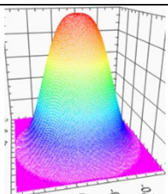
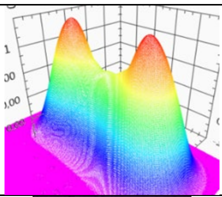
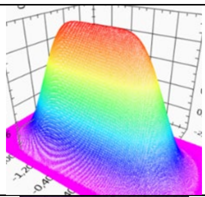
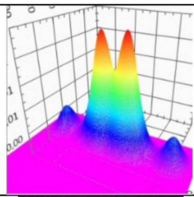
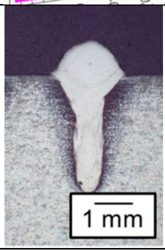
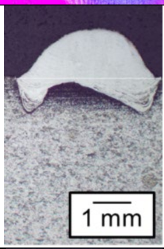
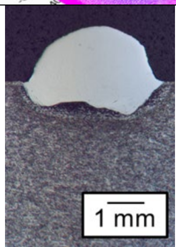
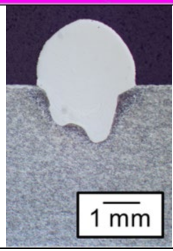
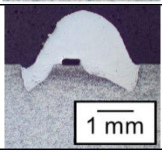
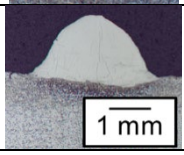
name	without oscillation	sinus wave	triangle wave	sinus^{-1}
oscillation path				
intensity distribution				
cross section 2000 W				
cross section 1500 W				
Dilution (2000 W) [%]	87	32	37	36
deposition rate (2000 W) [kg/h]	0.8	1.6	1.8	1.2

Fig. 2. Comparison of gaussian beam and different oscillation strategies regarding oscillation path, intensity distribution, cross section for different laser powers and dilution

A focused beam without oscillation leads to keyhole welding with a deep root penetration in the center and high dilution occurs. If oscillation is applied for laser cladding, often a simple oscillating mirror is used for beam oscillation. This results in a sinusoidal oscillation path because of the acceleration and deceleration at the turning points. The intensity is distributed to a wider area, but peak intensities at the turning points occur. The dilution decreases significantly. If the power of the laser is decreased to get lower dilution, the root penetration becomes smaller, but imperfections occur in the center because there is not enough energy to melt the whole wire. The triangle waveform is used to generate a top hat shaped intensity profile with a constant distributed intensity along the oscillation path. The triangle oscillation strategy generates a nearly homogeneous root penetration which results in a low dilution value. The constant root penetration enables a reduction of laser power for lower dilution without imperfections in the center area. The triangle waveform seems to be appropriate for the present case of low wire diameter and feed rate. In case of bigger diameter or higher feed rate, the increasing mass of filler material may require more intensity at the center. Therefore an oscillation path that looks like an inverted sinus function is tested, too. More intensity is accumulated in the center of the irradiation area and more wire can be melted. In the present case this intensity distribution causes a deeper root penetration and high dilution and therefore is not suitable.

The dilution is very high for all tested strategies, but deposition rates are also high. Lower dilution requires a reduction of laser power. If laser power is reduced, the form of root penetration becomes an important factor and limits the minimum value of dilution, like shown in 4th row (cross section 1500 W) of figure 2. In case of sinus oscillation the lower intensity in the center area causes imperfections. The homogeneous form of the root penetration of the triangle oscillation enables low dilution without imperfections. Therefore it is chosen for the following experiments.

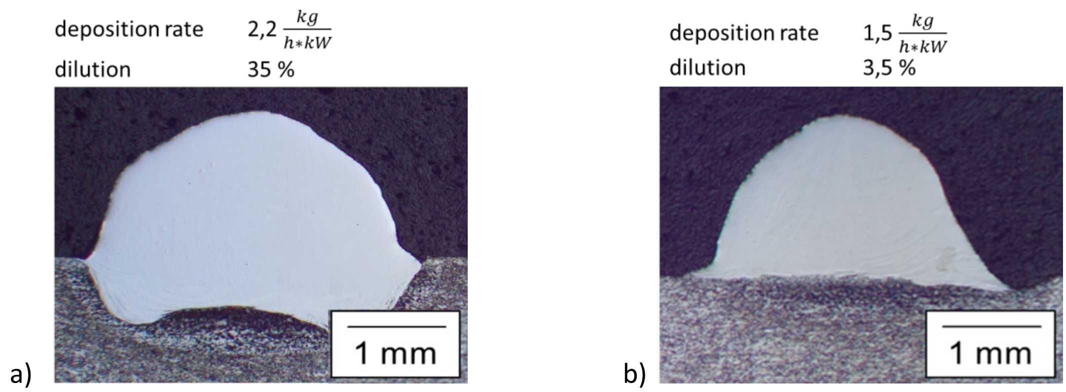


Fig. 3. Cross section of a parameter with high deposition rate. Laser power: 1000 W, spot-Ø: 200 µm, current: 160 A, wire feed rate: 6 m/min (Ø: 1 mm), welding speed: 1 m/min; oscillation: triangle, amplitude: 2 mm, frequency: 200 Hz; (a); Cross section of a parameter with high quality. Laser power: 1250 W, spot-Ø: 1 mm, current: 160 A, wire feed rate: 5 m/min (Ø: 1 mm), welding speed: 1 m/min; oscillation: triangle, amplitude: 2 mm, frequency: 200 Hz (BIAS ID181382) (b)

Figure 3 shows the results of cladding single welding tracks with triangle oscillation. The distribution of laser power by beam oscillation enables an efficient melting process. More energy can be used for melting the wire. In addition, the current of electrical preheating is increased. Thereby the deposition rate per laser power can be increased by the help of beam oscillation and the high preheating. Figure 3a shows a welding track with 2.2 kg/h*kW. The dilution is about 35 %. In this case only 1000 W laser power is used to melt down a wire with a diameter of 1 mm and a wire feed rate of 6 m/min. The electrical heating uses a current of about 160 A. The parameter suits for cladding similar materials because of the high dilution.

A reduction of dilution is possible by decreasing the laser power intensity. The form of the root penetration enables low dilution without imperfections, like shown in figure 3b. The deposition rate per laser power reaches a value of 1.5 kg/h*kW and the dilution is 3.5 %. In this case also a high electrical heating of 160 A and a wire feed rate of 5 m/min generate a high deposition rate with a low laser power of 1250 W. Thereby a high deposition rate and high quality can be realized. The low dilution enables the utilization of this parameter for the generation of dissimilar functional layers on a low-alloy substrate material.

In the second part of the investigation a control approach for the LHWC is demonstrated. A control algorithm is developed that calculates the melt pool length during welding and adapts the laser power to maintain the length to a set value. Laser power is limited to a value of 4000 W. In the first experiment the set value is changed manually during the process to trigger a reaction of the control algorithm. The step function responses are used to calculate optimal values for the PID parameter. In this case the PID control is designed to compensate the shifts of thermal condition that are usual for long term cladding of thin walled tubes. Figure 4 shows the measured melt pool length, the set value and the laser power.

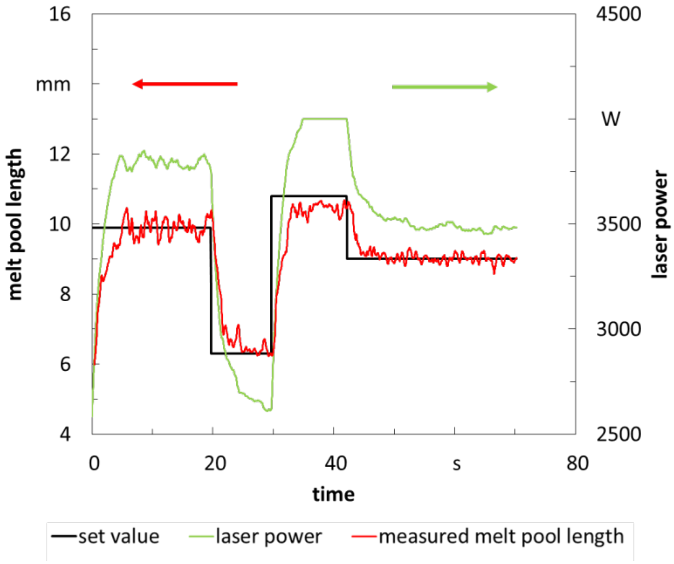


Fig. 4. Variation of melt pool length set value (black line). The measured melt pool length (red line) is maintained to the set value by an adaption of the laser power (green line) (BIAS ID18383)

It could be seen, that the measured value follows the set value within a reaction time of less than about 5 s. After steady state the melt pool length can be maintained to the set value within a standard deviation of less than 0.2 mm (2.5 %).

Figure 5 highlights the differences between uncontrolled und controlled cladding experiments. Figure 5a shows the recorded values of the uncontrolled process. It demonstrates that the melt pool length increases slightly during process duration from 8.5 mm to 9.5 mm. It can be assumed that the substrate is heated by previous cladding tracks and surplus energy increases the melt pool until thermal balance. For a continuous size of the melt pool the PID control is adapted to maintain the length of the melt pool which is measured by PyroCam. The deposited energy is reduced by decreasing the laser power, like shown in figure 5b. The power of the laser is reduced during process duration by 200 W from 3675 W to 3475 W. The measured melt pool length in steady state has a standard deviation of less than 0.2 mm (2 %).

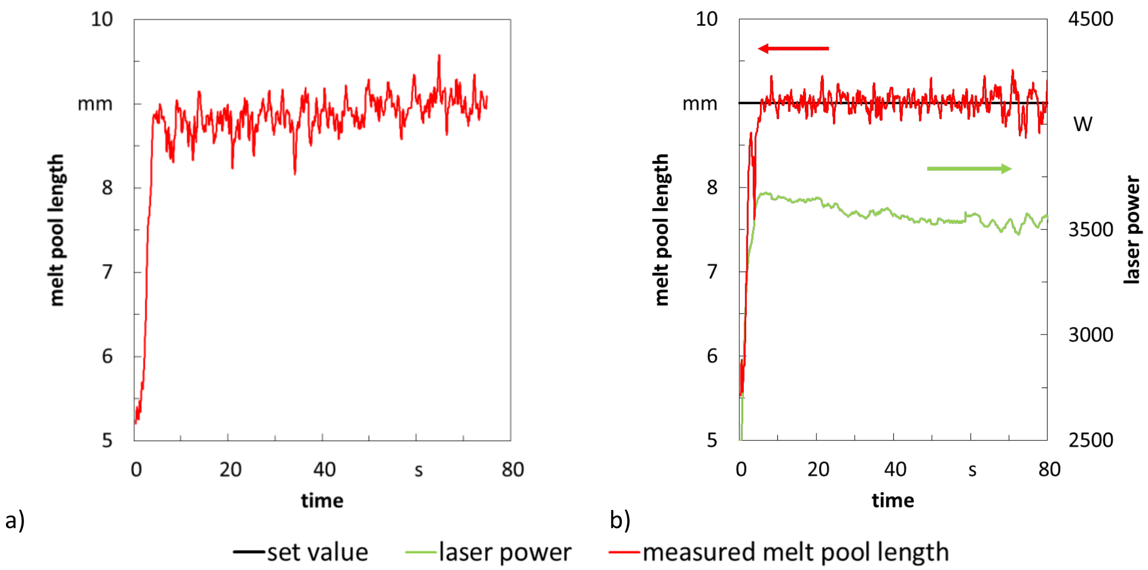


Fig. 5. Comparison of controlled and uncontrolled cladding experiments. Welding speed 4 m/min, wire feed rate 6 m/min, current of 170 A, triangle oscillation, 200 Hz with an amplitude of 1.8 mm. Laser power is set to 3500 W in uncontrolled case. A: Measured melt pool length (red line) in uncontrolled cladding experiment (BIAS ID18384) (a); Closed loop control of melt pool length (red line) by adaption of laser power (green line). The set value of melt pool length (black line) was 9 mm (BIAS ID18385) (b)

4. Discussion

Often a defocused gaussian beam is used for LHWC to create a huge melt pool that contributes to melting the plunging filler wire. Bigger melt pools are necessary to melt more wire mass and get higher deposition rates. Thereby dilution increases at the same time. The present study melts the wire directly with a focused or a weak defocused laser beam to avoid huge melt pools and gain independence of dilution from deposition rate. Special intensity distributions are necessary for LHWC to archive high deposition rates and a low dilution with homogeneous root penetration. A commonly used method is an oscillating mirror. Because of the acceleration and deceleration at the turning points of oscillation a sinusoidal oscillation path is generated which leads to an intensity distribution with high intensity peaks at the borders. A more suitable intensity distribution can be achieved by the adaption of laser power during oscillation path. But high oscillation frequencies and rising times of the laser source complicate this. A galvometric oscillator enables arbitrary oscillation paths like square wave or triangle waveforms and modification of intensity distribution becomes possible without adaption of laser power during oscillation. A triangle oscillation path can be used for LHWC in case of low wire diameters or slow wire feed rate. The continuous distribution of intensity over the whole oscillation path leads to a homogenous form of root penetration along the cross section.

In the second part of the investigation a thermal monitoring and control system for LHWC of thin walled tubes is developed. The heating of such tubes in a long term process influences the energy deposition and increases the dilution. The present study demonstrates a control approach that measures the melt pool geometry by the help of an emissivity compensated camera PyroCam and adapts the laser power to maintain the melt pool length. In this case the accuracy of temperature measurement which enables the evaluation of melt pool geometry is not important for the control algorithm because an arbitrary set value is maintained by laser power adaption. A suitable value is determined in sample claddings without control. However, the control algorithm can maintain accurately the set value.

In this case the melt pool length was suitable for the control approach although it may not be the optimal value for thermal control algorithms because of the time delay of the response. Therefore the algorithm is not applied for fast changes of process conditions like fluctuation of wire feed rate or of the electrical preheating system but for thermally caused shifts in energy deposition and long term cladding.

5. Conclusion

The investigation demonstrates that beam oscillation is a feasible method for appropriate energy deposition in LHWC. The distribution of laser power along wire cross section enables the improvement of deposition rates up to 2 kg/h*kW. At the same time dilution is kept small at values of less than 3.5 %.

Furthermore, a control algorithm could be developed for LHWC of tubes with a thin wall thickness. The control system in-situ measures the melt pool length, recognizes a deviation to a set value and adapts the laser power to maintain the melt pool length. The experiments demonstrate a small deviation in melt pool length of about 0.2 mm (2 %). Thereby the shift of thermal conditions can be automatically suppressed and layers of constant quality are possible.

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