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Controlled laser hardening and laser metal deposition with flexible beam shaping

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Abstract

Productivity and reliability of laser transformation hardening (LTH) and laser metal deposition (LMD) processes benefit from optimizing the energy input into the part. We report on a new high-performance laser controller enabling flexible beam shaping for laser material processing. A dynamic galvo-scanner is integrated into the beam path and rapid 2-dimensional beam oscillations can be superimposed to the movement of the laser head. Our FlexiBeam-Controller analyses beam positions at 25 kHz update rates. Optimized intensity distributions for laser hardening and LMD applications are generated by adapting oscillation parameters and synchronizing laser output power with the trajectories of the laser beam. In combination with a two-colour pyrometer the laser control system can monitor and maintain desired temperature profiles in the laser interaction zone. Our study presents first applications of this advanced laser process control for laser hardening on steel 1.1191 (C45E) and LMD of Hastelloy X on stainless steel 1.4404 (AISI 316L) indicating clear benefits for industrial laser processing.

Keywords: Laser Metal Deposition; LMD; Laser Transformation Hardening; LTH; Pyrometer; Closed Loop; Temperature Controlled; FPGA; Hastelloy X; 1.4404; 1.1191

1. Introduction

Laser metal deposition (LMD) has been introduced in the 1980s and it was the first additive laser method for metal processing reaching industrial maturity. Its basic process fundamentals have been explored by Frenk and Kurz, 1992. Driven by significant technology developments in the area of high-power lasers, an increasing number of industrial applications have emerged during the last two decades. Examples are the refurbishment of high-value components in turbomachinery (Hoebel et al. 2003) or the deposition of wear resistant coatings (Brueckner et al., 2012; Schopphoven et al., 2017). Much of the productivity improvements stem from the

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increased output power and brilliance of modern laser beam sources. Today, multi-kW diode lasers or fiber laser systems are standard for LMD, and machines have proven their robustness in production environments.

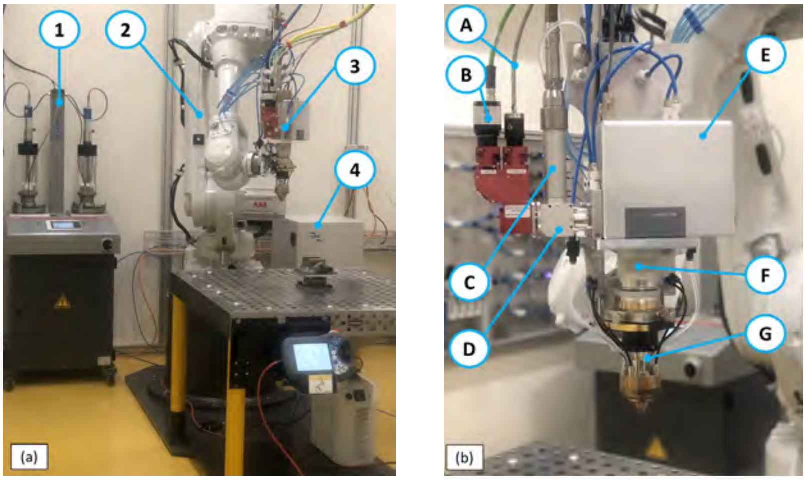
Whereas the output and beam quality of industrial LMD setups today meets the requirements of users, there is still a limited control of the energy input into the part. Usually, laser power is delivered to the process head via multi-mode fibers and a top-hat like intensity distribution is generated. Some systems allow a control of the spot size with zoom optics, but a given laser intensity profile cannot be changed during processing. This leads to limitations in controlling the interaction of the laser beam with the powder and substrate. Laskin et al., 2018 have shown that top-hat intensity distributions produce overheating in the centre of the laser spot. For more uniform temperature distributions, donut-like temperature profiles would be desirable. In an earlier research work Burger, 1988 had already shown that for optimum laser hardening even more sophisticated beam shaping would be favourable. Klocke et al., 2017 have realized such complex intensity distributions with freeform optics, but the beam shaping would be specific for one application only.

Wobble techniques are commonly used in laser welding, and they have been applied for beam shaping. Special processing heads integrate oscillating mirrors into the beam path (Bonss et al. 2007; Fetzer et al. 2018; Klocke et al. 2010; Pekkarinen et al. 2012). Generally, the scanner produces a rapid one- or two-dimensional oscillation superimposed to the movement of the CNC or robot. A challenge is the large variation of the energy input during the oscillation as the velocity of the laser beam continuously varies along the oscillation path. At the reversal points the laser power must be quickly ramped down to avoid local overheating. At higher oscillation frequencies the exact synchronization between the laser power modulation and the laser trajectory becomes more and more difficult.

2. Experimental Setup

2.1. Facility

In this work we combine flexible beam shaping with on-line process control using a novel FPGA based laser controller (FlexiBeam-Controller), developed by project partner PI Electronics AG. All elements have been implemented in a new prototype laser facility at the Institute of Product and Production Engineering at the University of Applied Sciences and Arts Northwestern Switzerland (FHNW).



(1) Powder feeder
(2) Industrial robot
(3) Processing head
(4) Air filtration

(A) Pyrometer fiber
(B) CCD camera
(C) Collimator
(D) Dichroic mirror
(E) Scanner
(F) Focusing optics
(G) Powder nozzle

Fig. 1. (a) Prototype laser facility at FHNW; (b) Processing head with powder nozzle for LMD

The work cell is designed for developments and process validations in a production like environment. The equipment consists of a 2 kW fiber laser (IPG YLR-2000-SM) and an industrial 6-axis robot (IRB4600-45/2.05, IRC5 controller). The programming of the robot path is based on a custom-made plugin for ABB RobotStudio22 (RobotWare 6.12.04). Flexible beam shaping is realised by integrating a Scanlab excelliSCAN20 galvo scanner into the beam path between fiber collimator and focusing optics. A METCO TWIN150 dual hopper powder feeder supplies the metal powders. The powder stream is directed through a mixer to a coaxial powder nozzle (Fraunhofer COAX14) and then onto the work piece, which is usually placed 13 mm below the nozzle rim.

The optical path is made up of a 400 µm delivery fiber, a fiber collimator and a f250 focusing lens generating a laser spot of 1.44 mm diameter with a top-hat profile. The Rayleigh length of this beam shaping setup is approx. 35.2 mm. For temperature measurements a two-colour pyrometer (Mergenthaler LPC04-2CDC-X-15k) with up to 15 kHz sampling rate is integrated using a dichroic mirror between the fiber collimator and the entrance of the scanner. In our setup a temperature monitoring spot of 1 mm diameter is produced at the centre of the laser spot. The core of the facility is the novel FlexiBeam-Controller described in the next section.

2.2. Control Concept

The IRC5 controller of the industrial robot is defined as the master, controlling the signal communication. All signals which are not time critical (e.g., control of the powder feeder operation) are transferred via PROFINET to the connected devices. The response time of this communication is below 2 ms.

A much faster signal transmission is required for the synchronous modulation of the laser power and for controlling surface temperatures during laser processing. For these time critical signals between the pyrometer, FlexiBeam-Controller, laser source and galvo scanner, a fast signal transmission is implemented.

(a)
(b)

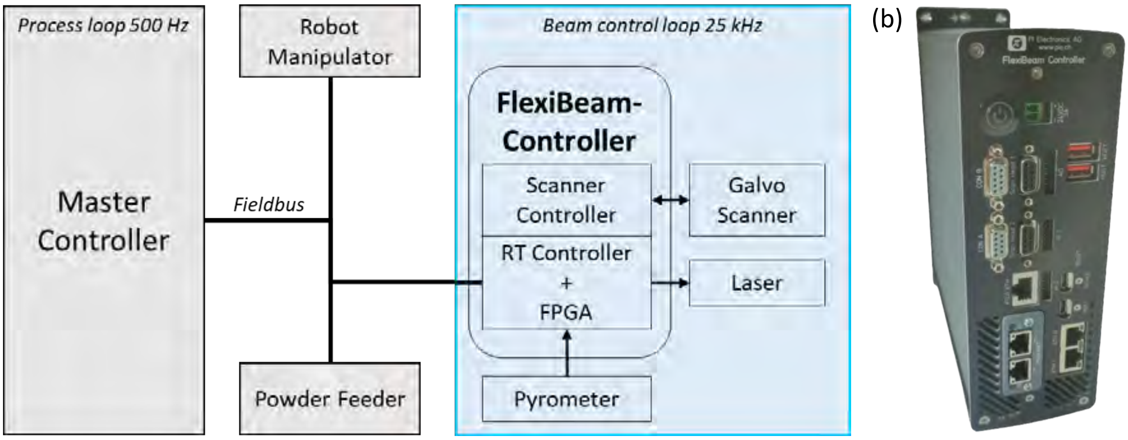


Fig. 2. (a) Simplified communication scheme between the FlexiBeam-Controller and system components; (b) Picture of the FlexiBeam-Controller

The FlexiBeam-Controller is a real-time controller with FPGA connection and dedicated interfaces to the excelliScan20, pyrometer and IRC5 and to the fiber laser. The combination of real-time system and FPGA allows an optimum split of the process control tasks. For maximum performance, temperature data acquisition and the algorithms for adjusting laser power are performed directly on the FPGA. Process data from the scanner is acquired via a fast serial interface at a clock rate of 40 µs. Up to 8 signals from the scanner can be transmitted sequentially through this interface, e.g., mirror positions and mirror temperatures. A fieldbus interface (PROFINET) for communication with the master controller (IRC5) is implemented directly on the FPGA.

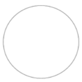
Relevant process data is transferred from the FPGA into a log file via direct memory access transfer at 25 kHz update rate. This data logging ensures traceability of the process for quality assurance. The FlexiBeam-Controller also receives profile parameters from the master controller, such as amplitude and frequency. It then calculates positioning commands for the scanner and synchronizes them with the laser output. The communication between FlexiBeam-Controller and scanner is transferred via Ethernet (UDP), whereas the laser power is modulated via an analogue signal.

3. Methodology

3.1. Flexible beam shaping

In contrast to fixed optical components (e.g., lenses, mirrors) in the beam path, our setup uses a galvo scanner for beam shaping. The scanner deflects the laser beam within a defined area on the working plane. Boundary limits are typically set by additional system components like the coaxial powder nozzle. By moving the laser spot at high velocities in recurring patterns across the part, the resulting intensity profiles approach characteristic shapes. A common way to achieve a desired intensity profile is the superposition of two orthogonal harmonic oscillations with defined frequencies and amplitudes. Depending on the phase shift between the oscillations, different Lissajous shapes can be generated (shown in Table 1). During these oscillations the robot moves forward, and the heat dissipates into the part smearing out intensity variations on sub-mm length scales. With a frequency ratio close to 1, a fine mesh can be realized.

Table 1. Four different Lissajous figures with different phase shift and frequency ratio

Visualisation				
Frequency X	100	100	200	270
Frequency Y	100	100	300	300
Frequency ratio	1:1	1:1	2:3	9:10
Phase shift	π/2	0	π/2	0

By letting the laser oscillate in such Lissajous patterns, different energy distributions of a quasi-donut, square or rectangular shape can be realized. The single path coverage increases and therefore less robot paths are necessary to process a given surface area. Thus, the efficiency of the LMD or laser hardening process improves. For additional flexibility, profiles can be stretched in both directions as the robot moves across a part. The FlexiBeam-Controller automatically adjusts the direction of the scanner oscillations along the robot path to keep them aligned with the trajectory.

However, care must be taken as the velocity of the laser beam along the oscillation path is never constant. This leads to energy (and therefore heat) accumulation at the reversal points of the oscillation, where the movement direction changes. It is inevitable to modulate the laser power quickly at those turning points. This in particular if larger amplitudes and frequencies are applied because the variation of the beam velocities along the oscillation trajectory increases.

We have measured the effect of 2D beam oscillations with a Cinogy FBP-1KF-CMOS laser beam profiler and analysed the results with the software RayCie (64bit V2.3.12). The beam is directed through an optical system to adjust the imaging ratio from 1:1 to 1:4, allowing to fit oscillations with up to 6 mm amplitude onto the detector chip. A 1D oscillation with 500 Hz and 4 mm amplitude shows a 45 % intensity reduction in the centre, compared to the reversal points of a cross section (Fig. 3 (a)). This effect would have been even more pronounced for a smaller laser spot.

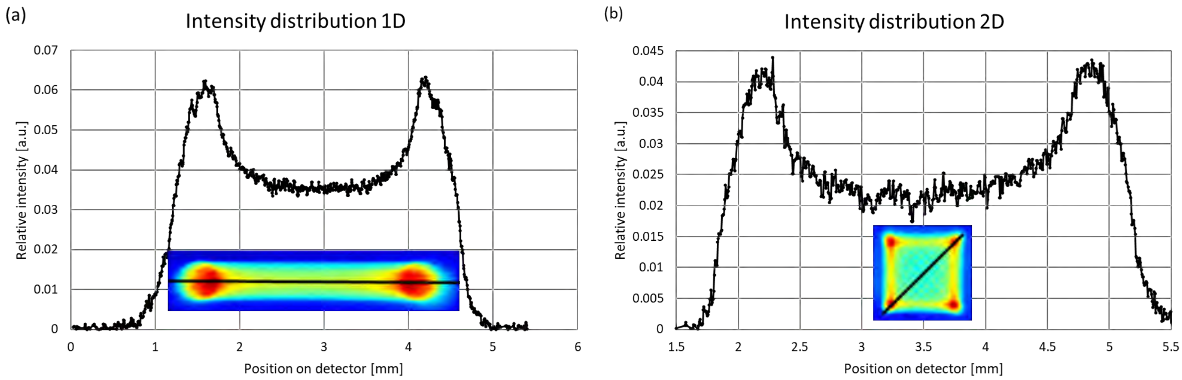


Fig. 3. Cross sections of measured intensity distribution with (a) 1D beam oscillation at 500 Hz; (b) 2D beam oscillation at 270 Hz (X) and 300 Hz (Y)

Figure 3 (b) indicates 50 % less intensity in the centre compared to the reversal points. It is obvious, that such excessive local heat input must be avoided to keep the process results within specifications. To homogenize the temperature field a measurement system would have to record the temperature at the laser spot position with an update rate of 5 kHz and process it in real time with a powerful controller.

3.2. Synchronized laser operation

For optimum results the parameters of the rapid scanner oscillations must be adapted to the thermo-physical properties of the part. The relevant quantities for the dissipation of the laser energy into the bulk of the substrate is the thermal diffusivity α (Lienhard and Lienhard, 2011)

$$\alpha = \frac{k}{\rho \cdot c} \qquad (1)$$

with k: thermal conductivity, ρ: density, c: specific heat capacity

The characteristic thermal diffusion length $\mu_t = 2\sqrt{\alpha \cdot \tau}$ describes the heat dissipation distance during a duration τ. Typical values of the thermal diffusivity for the widely used stainless steels 1.4307 and 1.4404 are from about 3 to 6 mm^2/s (Kim 1975). The corresponding thermal diffusion length range from about 0.1 mm to 0.5 mm for time scales between 2 ms and 50 ms. Oscillation frequencies between 20 Hz and 500 Hz are therefore adequate to homogenize the intensity variations between the laser paths of Lissajous patterns while keeping the heat input sufficiently well confined between the boundaries of a desired intensity pattern.

Oscillations with amplitudes of 4 mm and frequencies of 500 Hz can only be realized with highly dynamic scanners of the latest generation. The Scanlab excelliScan20 of our system provides an acceleration of 160’000 rad/s^2 and enables the realization of such rapid oscillation patterns (Scanlab GmbH, 2023). In the example above, the laser beam travels at a maximum speed of more than 12 m/s, which is 3 to 4 orders of magnitude faster than typical movements during laser hardening or LMD. With its RTC6 ScanAhead technology, the real trajectory is calculated during a fixed preview time of 1.2 ms and this temporal offset remains constant at all frequencies. This fixed delay and the response time of the laser source define the available time budget for the calculations and actions of the FPGA controller. Our FPGA controller updates the control signal output to the laser in less than 40 µs and then adds an appropriate output delay to synchronize its arrival exactly with the oscillation movement of the laser beam.

3.3. Complex laser intensity distributions

The controller enables a user to define a 3*3 matrix of zones with different laser intensities. The borders between the 9 zones and their intensity values can be adjusted as required by the user. The much more homogeneous energy input of the modulated input is evident in Fig. 4.

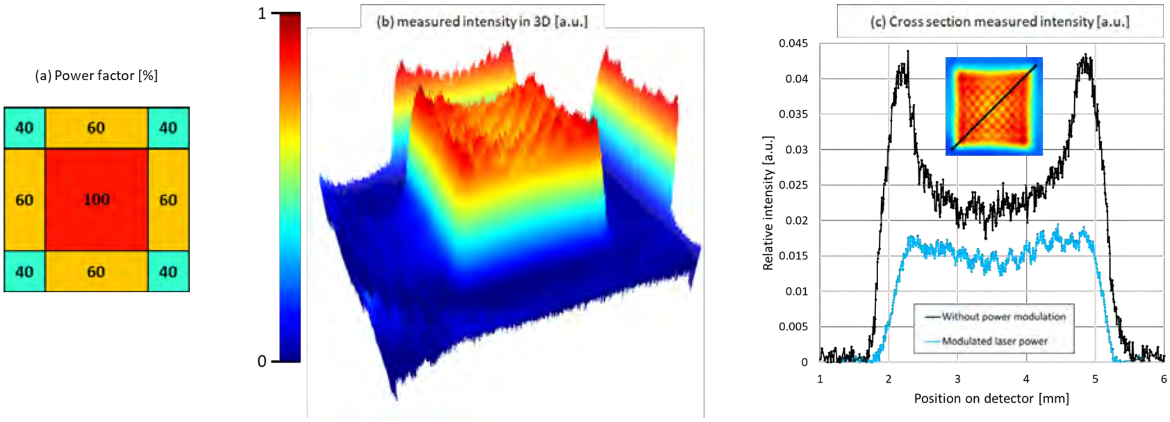


Fig. 4. (a) Selected power levels and zones; (b) Recorded intensity distribution with modulated 2D-oscillation (X:270 Hz, Y:300 Hz, 4 mm amplitude, 700 W); (c) comparison of cross sections though the same Lissajous pattern with and without power modulation

Even the complex 'armchair profile' suggested for optimum laser hardening can be realised in the same manner. Figure 5 shows a striking similarity with the laser intensity distributions proposed by Burger, 1988. For additional processing flexibility, such complex profiles can be stretched and rotated in real time as the robot moves along its programmed path.

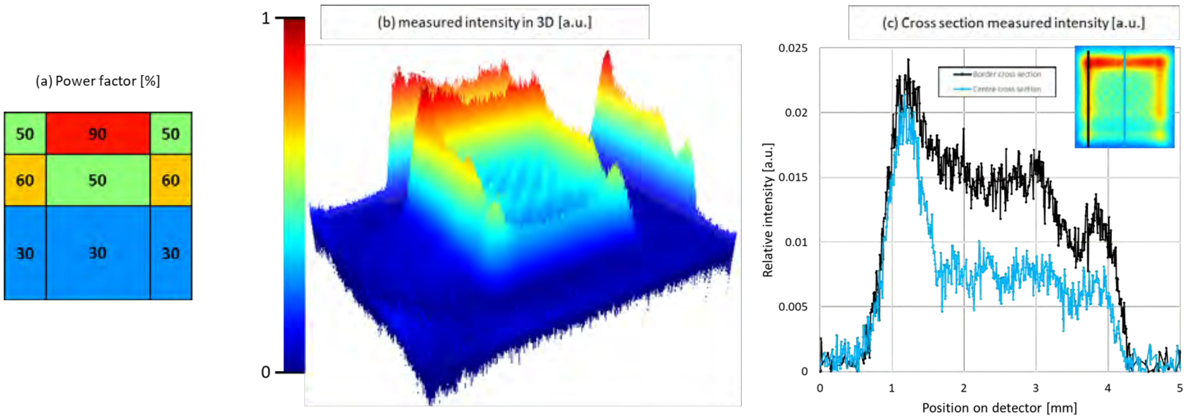


Fig. 5. (a) Selected power levels and zones; (b) Complex 'armchair' intensity profile realized with orthogonal 300 Hz and 270 Hz oscillations and adjusted power distribution; (c) cross sections of 'armchair' intensity profiles

4. Experimental Validation

4.1. Controller performance

A process with constant laser power is continuously heating up the sample, and the local temperature increase is difficult to predict. Hence an automatic feedback control loop for adjusting the laser output power is highly desirable. This capability is implemented in the FlexiBeam-Controller. Moving at a velocity of 8 mm/s on a milled surface of a steel 1.4404 sample without oscillation, the controller is able to stabilize the set temperature of 1300 °C within ±10 K.

With a 1D oscillation of 20 Hz perpendicular to the track direction and 2 mm amplitude, the controller is able to hold the temperature within ±30 K. Spikes indicate surface irregularities (scratches, local oxidation, dust, etc.). Nevertheless, the process quickly recovers and maintains the set temperature (Fig. 6 marked with red rectangle).

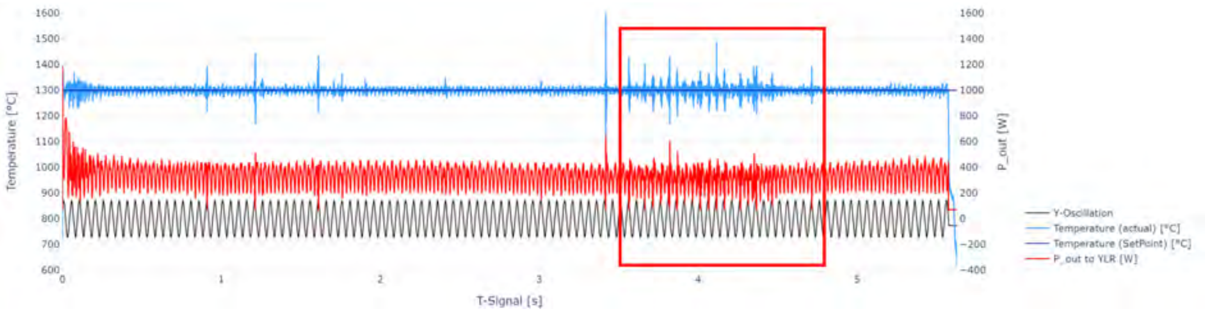


Fig. 6. Demonstration of process control along a 24 mm track with 20 Hz oscillation (steel 1.4404)

Even at a higher frequency of 100 Hz the temperature can be stabilized. However, the peak-to-peak variation increases to approx. ±60 K. At 500 Hz oscillation frequency the temperature remains within a similar temperature band. Increasing the oscillation frequency further to 700 Hz the controller action is no longer satisfactory. However, this is not due to a performance limitation of the FPGA controller, but rather due to the characteristic of the process. A zoom into Fig 7 (c) shows a thermal response of around 300 µs for steel 1.4404.

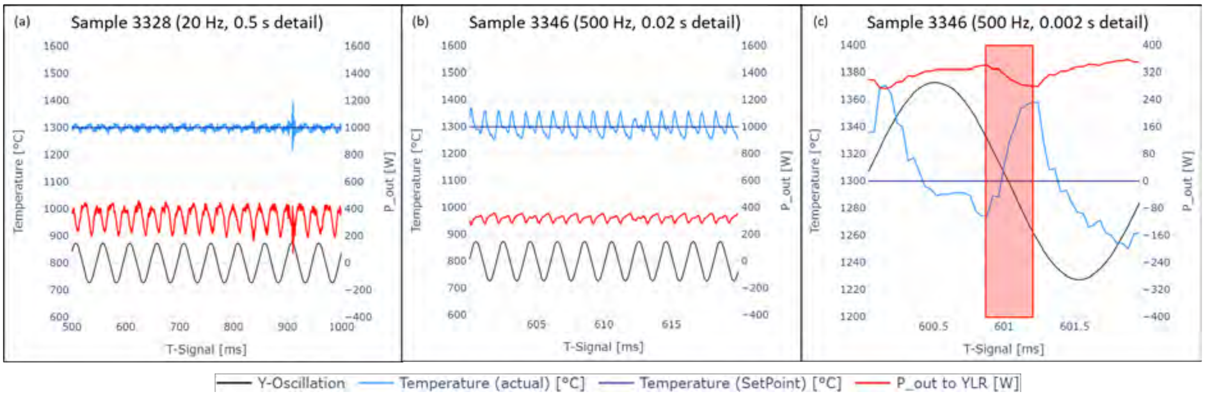


Fig. 7. Periods of 10 oscillations at (a) 20 Hz; (b) 500 Hz; (c) >300 µs thermal response (red box) observed during a 500 Hz oscillation

The higher the oscillation frequency, the more relevant becomes the thermal response time of the substrate. The controller action is therefore progressively getting out of phase with the oscillation movement. The result indicates, that at around 500 Hz and above, the thermal response time of the material becomes a critical factor. At such high oscillation frequencies, the adjustment of laser power on the oscillation trajectory is no longer well matched with the position of the laser spot. The delayed thermal response of the substrate material inhibits a closed loop process control.

4.2. Tailored 2D temperature profiles

The FlexiBeam-Controller allows to define 3*3 zones with different target temperatures. Instead of quickly modulating laser power, the controller works in a closed loop control mode and quickly adjusts the laser power in every zone to establish the local target temperature. Figure 8 shows that the desired temperature field is clearly visible in the recorded temperature data. Even without extensive parameter tuning, the controller was able to keep the temperatures in the 9 zones stable with a standard deviation of <40 K.

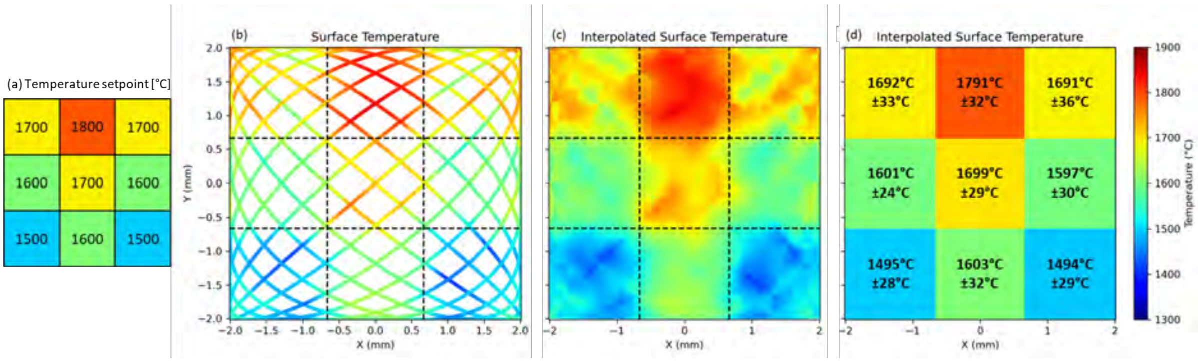


Fig. 8. Measured temperature of a steel 1.4404 sample with 3*3 temperature zones. (a) temperature setpoints; (b) temperature data along the oscillation path; (c) interpolated temperatures;(d) average temperatures with standard deviation

4.3. Laser Transformation Hardening (LTH)

Experiments with variable intensity profiles have been carried out on steel 1.1191 (C45E). Depending on the intensity profile, different hardening profiles were obtained. The larger the amplitude in longitudinal (track) direction, the longer the interaction time between laser and substrate. This results in a deeper hardening profile, however, at the cost of a reduction of the hardness improvement. With short longitudinal amplitudes, the sample can dissipate the accumulated heat faster and therefore hardness increases.

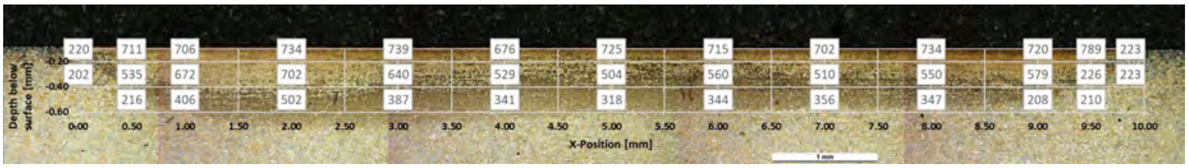


Fig. 9. Flat hardening profile with an oscillation of 500 Hz (X) and 300 Hz (Y). The robot moved at 4 mm/s and the controller held the temperature at 1400 °C.

The samples have been cut and polished in six steps. To make the grain boundaries and structures visible, the material 1.1191 has been etched with Nital 2% acid for 15s. Figure 9 shows hardness values according to $HV_{0.3}$. With the rapid two-dimensional oscillation, the laser spot of 1.44 mm diameter is increased to an effective rectangular profile of 9 mm by 2 mm size. Using this intensity profile for laser hardening, a thin, W-shaped hardening profile with a hardness of >650 $HV_{0.3}$ at 0.1 mm depth below the surface is obtained. At 0.3 mm depth, the hardness is >500 $HV_{0.3}$ and at 0.5 mm still >300 $HV_{0.3}$ compared to the base material with approx. 200 $HV_{0.3}$.

4.4. Laser Metal Deposition (LMD)

The LMD setup with the COAX14 powder nozzle and a laser spot of 1.44 mm diameter requires a good alignment (<0.05 mm tolerance) of the powder focus to the laser spot. When using a 2D oscillation, this mismatch becomes less relevant. Additionally, the LMD tracks are now significantly wider without increasing the melting depth of the substrate. The powder efficiency increases to values >85 %. In the example below, Hastelloy X powder was deposited on stainless steel 1.4404 (AISI 316L). The samples have been cut and polished in six steps. To make the material boundaries visible, the sample has been etched with V2A stain for 35s.

Fig. 10. Four LMD tracks with an oscillation of 1200 Hz (X) and 90 Hz (Y). The robot moved at 8 mm/s and the controller held the temperature at 1800°C.

To test a real-life situation, we purposely inserted defects (four shallow grooves on the top, three deep grooves on the back) on steel 1.4404 samples (see Fig. 11 (b)). The FlexiBeam-Controller is able to cope with these irregularities and maintains the target temperature even with superimposed oscillations of 1 mm amplitude perpendicular to the track direction.

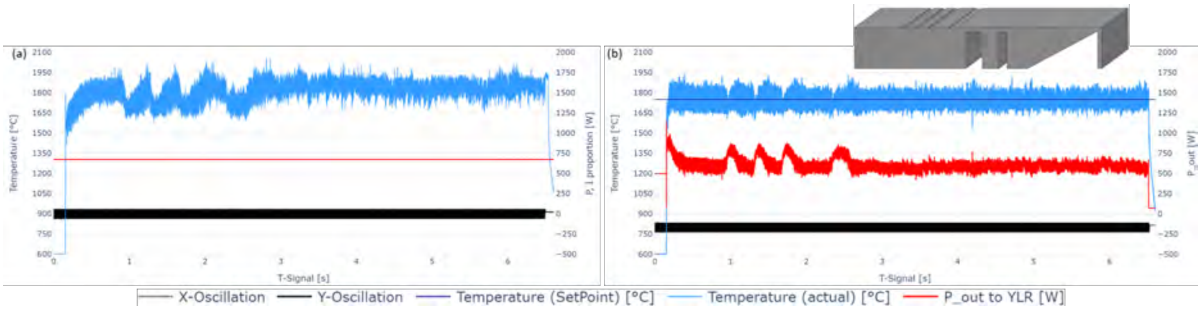


Fig. 11. LMD track with an oscillation of 100 Hz at 4 mm/s on surface with irregularities (a) with fixed 675 W power and (b) power controlled at 1750 °C.

5. Conclusion

We have demonstrated laser hardening and LMD with controlled energy input using fast 1D and 2D laser beam oscillations superimposed to the robot trajectory. The FlexiBeam-Controller is able to synchronize the modulation of the laser output power with the movement of the laser beam and thus avoids local overheating.

In automatic temperature control mode, defined 2D temperature distributions could be generated and maintained for oscillation frequencies up to 30 Hz. For uniform temperature setpoints the oscillation frequencies can be increased to several hundred Hz. In LMD applications large single pass coverage can be combined with minimum dilution of the substrate. In combination with a significantly increased powder efficiency this improves the process efficiency of commercial applications.

During the experiments we have seen that the thermal response of the substrate imposes a limitation to even higher oscillation frequencies. To overcome this limit, a hybrid control mode can be implemented. In this hybrid control mode, a synchronized and pre-defined modulation of the laser output power during the beam oscillations is combined with a slower automatic closed loop control of the average temperature of the interaction zone. Work on this topic is ongoing.

The FlexiBeam-Controller has the capability of creating defined two-dimensional temperature distributions and thermal gradients on a substrate and maintaining them during processing. This opens a new dimension for laser hardening and LMD.

Acknowledgements

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