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Pulsed Laser Influence on Temperature Distribution during Dual Beam Laser Metal Deposition

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Received: 4 May 2020; Accepted: 5 June 2020; Published: 9 June 2020

Abstract: Wire-based Laser Metal Deposition (LMD-w) is a suitable manufacturing technology for a wide range of applications such as repairing, coating, or additive manufacturing. Employing a pulsed wave (pw) laser additionally to the continuous wave (cw) process laser has several positive effects on the LMD process stability. The pw-plasma has an influence on the cw-absorption and thus the temperature distribution in the workpiece. In this article, several experiments are described aiming to characterize the heat input during dual beam LMD. In the first setup, small aluminum and steel disks are heated up either by only cw or by combined cw and pw radiation. The absorbed energy is then determined by dropping the samples into water at ambient temperature and measuring the water's temperature rise. In a second experiment, the temperature distribution in the deposition zone under real process conditions is examined by two-color pyrometer measurements. According to the results, the pw plasma leads to an increase of the effective absorption coefficient by more than 20%. The aim of this work is to achieve a deeper understanding of the physical phenomena acting during dual beam LMD and to deploy them selectively for a better and more flexible process control.

Keywords: laser metal deposition; dual beam; laser absorption

1. Introduction

Recently, various Additive Manufacturing (AM) processes exist. They can be classified either by the properties of the filler material (wire, powder, and flakes) or by the form of energy supply (e.g., electric arc, laser, and gas flame). Laser-based techniques are advantageous as they offer the possibility to combine high precision with a low thermal affection of the base material [1].

Since Laser Metal Deposition with wire (LMD-w) combines comparatively high deposition rates with a feedstock material which can be handled in a quick and safe way without contaminations, it is a suitable technology for a wide range of applications [2]. In particular, with regard to recent developments for the transformation towards industry 4.0, LMD offers different possibilities. LMD processes are suitable to be automated and can be accompanied by different sensor systems such as in-situ optical scanning of the welding bead surface or temperature monitoring. This allows the generation of data for the setup of a Digital Twin which helps to make production more transparent and reliable [3,4]. A special laser-based process is the dual beam process in which a continuous wave (cw) process laser is combined with an additional pulsed wave (pw) laser beam. The process is schematically represented in Figure 1. The employed pulsed laser powers are typically small in comparison to the cw power (approximately 5–10%). The process has initially been developed for fluxless laser brazing of aluminum [5], but recent results show that a transfer to LMD-w can be advantageous. First, the pulsed laser has an influence on the shape of the cladded bead because the pulsed laser-induced

evaporation creates a pressure acting on the melt pool. In addition, the thereby created plasma is assumed to improve the absorption conditions for the cw beam. Therefore, as the needed pw power is low compared to the cw power, but supposed to have a strong influence on absorption, it should be possible to reduce the total power required for the process by optimizing the applied pulsed laser parameters. This hypothesis is examined in this contribution.

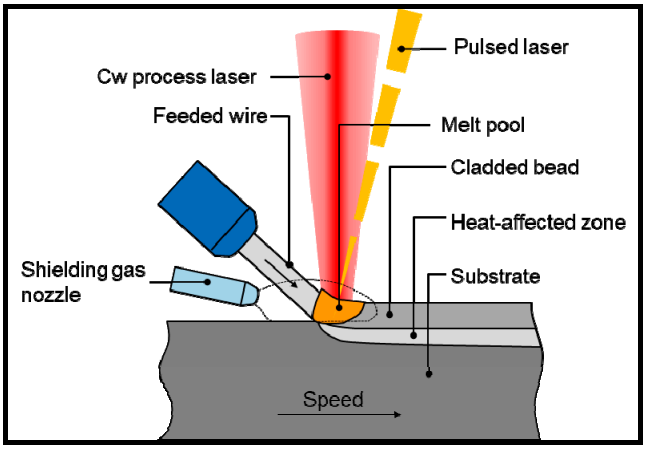


Figure 1. Process principle of dual beam Laser Metal Deposition with wire (LMD-w).

As the dual beam process is controlled by a coexistence of both effects, the quantification of the magnitude of the influences is crucial. In former works, the authors already demonstrated that the evaporation-induced forces acting on the melt pool are high in comparison to other relevant process forces (e.g., gravity) and strongly depend on the applied pulsed laser frequency and power [6].

The aim of the present article is therefore to quantify the change in the absorbed process energy and the temperature distribution in the workpiece caused by the pulsed laser plasma. Based on this knowledge, the choice of more suitable process parameters is possible.

In the literature, there exists little information regarding processes with a combination of different types of lasers, the physical phenomena related to their interaction, and the resulting impact on the material. The main reason is that in laser-based processing, typically either a pulsed or a continuous laser is employed. Exemplary processes for pulsed laser use are laser structuring and polishing, while continuous lasers are used for laser welding, Laser Metal Deposition (LMD) or laser alloying among others [7,8]. Adding a pulsed laser to a cw process laser, as it is done in the dual beam process, remains an exception and this is the reason why the physical effects have not been exhaustively investigated up to now. Concerning the interaction of lasers and plasmas, several studies have been carried out during the last decades. Baton et al. [9] examined the propagation of a laser beam in a preformed plasma (i.e., a plasma which exists independently of a laser-material interaction) and saw differences depending on the plasma density. Their most important result is that the higher the density of the plasma, the stronger are its interactions with the laser beam. In a denser plasma, the beam is much more deviated and its divergence decreases. In 2008, Rozman et al. [10] published another theoretical work, in which they modeled the absorption of a laser beam in plasmas taking into account several physical absorption mechanisms. Among others, Cui et al. [11] also investigated those effects, especially the transition zones between them by numerical and experimental methods, in 2013. The two main absorption regimes to be considered are collisions in the plasma for low laser intensities and collision-less absorption going along with hot electron (solid electrons with higher energy than the equilibrium energy at the given temperature) formation for higher intensities. In this case, collisional absorption signifies that a laser photon is absorbed by a plasma electron. Its kinetic energy is thereby increased. In contrast, collision-free absorption mechanisms can be related to resonance oscillations of the plasma electrons and ponderomotive forces, i.e., the electric field of the light acting on the charge carriers of the plasma. Those last two effects are accompanied by hot electron emission by the used target. From a

process-related point of view, the works of Miller et al. [12] and Semak et al. [13] reported interesting results regarding the influence of the plasma plume during laser welding. Cristoforetti [14] described a shielding effect at high plasma frequencies during the ablation of aluminum targets, for example. It has to be noticed that in all three cases, the examined plasma is induced by the process laser itself, but not by a second laser as it is the case in the two-beam process. In conclusion, the literature sources can deliver some elements for the explanation of the effects occurring during the dual beam process, but due to the complex interaction of both lasers with the workpiece, only special experimental studies can give reliable results.

2. Materials and Methods

In order to measure the change in absorption of the continuous laser beam by the pw plasma and thus the influence on the workpiece temperature, two experimental setups have been employed.

For both of them, the same optical system is applied thanks to which the pw and cw beams can be superposed. The cw spot is circular with a diameter of 2 mm and the pw spot rectangular with a length of 2.5 mm and a width of 50 µm. A diode laser from Laserline GmbH, Mülheim-Kärlich, Germany (model LDF 5000-40) provides the continuous beam with a maximum power of 5 kW and wavelengths of 910, 940, and 980 nm. A diode slab laser from EdgeWave GmbH, Würselen, Germany (model IS20I-ET) generates the pulsed beam with 1064 nm wavelength and pulse lengths between 9 and 32 ns, fixed by the system and depending on the applied diode current and frequency [15]. The examined materials are S355 J0 steel and EN AW 7075 (AlZn5.5MgCu) aluminum alloy as substrates and a tool steel wire (commercial name QuFe13 from Quada) for the deposition experiments. The respective nominal compositions are given in Table 1.

Table 1. Overview of the employed pulsed laser parameter sets.

Wt.%	C	Si	Mn	Mg	Cr	Cu	Mo	Ti	Ni	Zn	Fe	Al
S355 J0	0.2	0.55	1.6	-	-	0.55	-	-	0.01	-	Bal.	-
QuFe13 (Quada)	0.25	0.5	0.7	-	5.0	-	4.0	0.6	-	-	Bal.	-
EN AW 7075	-	0.4	0.3	2.5	0.23	1.5	-	0.2	-	5.5	0.5	Bal.

The first setup is a basic research test stand aiming to quantify the change in absorbed energy at different pulsed laser parameters. A schematic of this test stand is shown in Figure 2. The principle of the setup is similar to a calorimeter. A round sample with a diameter of 30 mm and a thickness of 5 mm is clamped in a holder which is situated above an isolating vessel filled with 600 mL of water at 21 °C. The sample is then processed for 41 s at 400 W continuous laser power and different sets of pulsed laser powers and frequencies.

The values are shown in Table 2. Due to the internal laser configuration, the range of applicable diode currents and thereby power is smaller at 5000 W. All the used parameter sets lead to a formation of a pw-induced surface plasma on the substrate. For some of the used pulsed laser parameter sets, the impact of a variation of the cw power is also studied.

Table 2. Overview of the employed pulsed laser parameter sets.

Frequency (Hz)	Diode Current (A)	Corresponding Power (W)
5000	40, 41, 42	45, 53, 58
7500	40, 42, 44, 46, 48, 50, 51	48, 62, 74, 81, 88, 93, 97
10,000	40, 42, 44, 46, 48, 50, 51	49, 63, 77, 86, 93, 105, 110

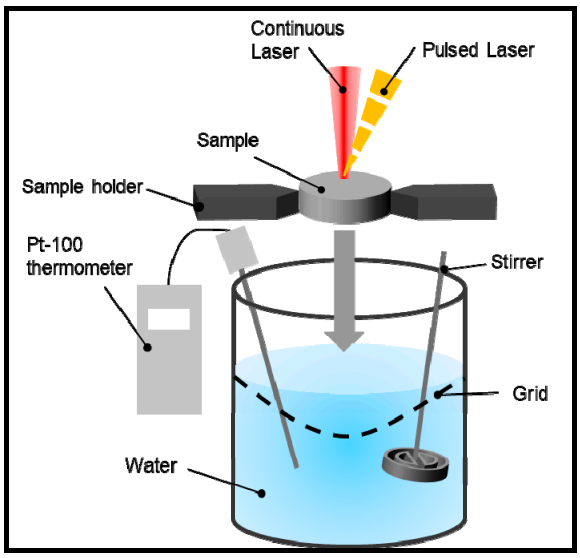


Figure 2. Schematic of the test stand for absorption measurements.

After laser treatment, by opening the sample clamping system by a compressed air valve, the sample is dropped into the water where it is held at mid-level by a coarse metallic grid. Directly afterwards, the vessel is closed with a polystyrene cover and a Pt-100 thermometer (TC Mess- und Regeltechnik GmbH, Mönchengladbach, Germany) is inserted into the water. While stirring the water, the temperature raise is measured until a stagnation is observed. The certainty of the used Pt-100 thermometer was evaluated by calibration in an accredited laboratory. In the considered temperature range, the measurement deviation is −0.3 K. As only temperature differences are examined, this deviation can be neglected in the following calculations. The error to be included is therefore the inaccuracy of the display which is ±0.1 K.

For every measurement, a new sample and fresh water are used to ensure identic initial conditions. Every experiment with a given parameter set is carried out two times. The measurements are realized for S355 steel and EN AW 7075 aluminum samples. In the following, the measured temperatures can be employed to calculate the thermal energy absorbed by the sample by the equation:

$$E_A = m_L c_L (T_E - T_{0,L}) + m_S c_S (T_E - T_{0,S}) \quad (1)$$

where m_L and m_S are the masses of the liquid and the sample, respectively, c_L and c_s the corresponding specific heat capacities, $T_{0,L}$ and $T_{0,S}$ the initial temperatures of the liquid and the sample, and T_E the final measured temperature of the water. The material constants have been defined according to [16,17]. At the same time, as E_A is transferred to the sample by the laser, it is in relation with the absorption coefficient α, the laser power P_L and the time t_A during which the sample is exposed to the radiation via the following equation:

$$E_A = \alpha P_L t_A \quad (2)$$

If P_L is considered to be the total laser power of pulsed and continuous radiation, the measured temperature can then be used to determine an effective absorption coefficient. As all other parameters are kept constant, variations of α_{eff} can be explained by the pw-induced plasma dynamics. It has to be mentioned that this approach is only valid if energy losses due to evaporation effects and thermal conduction to the surroundings are neglected. In the range of the measured temperatures and the duration of each measurement, differences in thermal conduction (for example to the vessel) are not significant. To exclude an evaporation influence, the respective masses of the samples and of the water were determined before and after the experiments. Significant differences as a function of the applied

pulsed laser parameters could not be found, so that evaporation-induced losses can be ignored. Thus, the measured temperatures and related calculated values are comparable among each other.

The second setup is dedicated to evaluate the influence of the pulsed laser on the real dual beam LMD-w process. Welding trials with single welding tracks are realized with a 1.2 mm tool steel wire (commercial name QuFe13 from Quada [18]) on S355 steel plates. The plate dimensions are $250 \times 80 \times 15$ mm^3. The different sample size has been selected as a deposition on the small disks would lead to welding tracks with too short length for the evaluation of process stability. In addition, the process reproducibility can be studied by depositing several welding beads next to each other on the same plate. The parameters are at first selected in such a way that the process works in a stable way with the cw laser only. This is the case at 2500 W continuous laser power, 1000 mm/min machine feed rate, and 1800 mm/min wire velocity for a back feeding setup.

In the following, the change in surface temperature of the workpiece when the pulsed laser is added to the process is studied by means of a two-color pyrometer (Dr. Mergenthaler GmbH & Co. KG, Neu-Ulm, Germany, model LASCON V3.76). The used pw parameters are the same as in the first experiment. The temperature is measured on the cladded bead just behind the deposition zone and the mean temperature during the process is determined for each welding trial. The induced temperature difference as a comparable value is calculated based on the surface temperature recorded before each start of the process.

A final experiment aims to verify the hypothesis of process energy saving thanks to the pulsed laser. Therefore, a pulsed laser beam with a frequency of 7500 Hz and a power of 81 W is added to the continuous laser. Then, the cw power is gradually decreased from 2500 W until the power becomes too low to enable a deposition. The same series is then repeated at continuous laser use only and the threshold values of critical power are compared.

3. Results

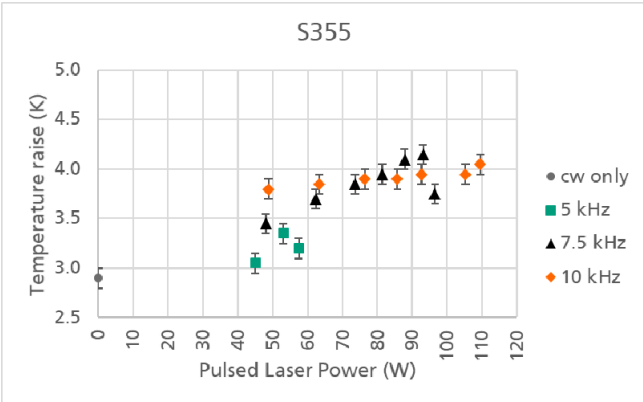
3.1. Absorption Measurements

The realized experiments reveal significant results. For the absorption measurements on small steel and aluminum samples, the mean temperature raise of the water is plotted as a function of applied pulsed laser power in Figure 3. First of all, it can be seen that from a global point of view, the temperature raise becomes higher for increasing pulsed laser powers. It can also be observed that most of the curves corresponding to different used pw frequencies show a decrease of the gradient of the temperature raise at higher powers. For EN AW 7075, a local minimum occurs at intermediate powers.

As the continuous laser power is kept constant, the global raise in temperature with applied pw power is easily explainable by the increase in total added energy which leads to a stronger warming of the water. The more unexpected observation is related to the gradient of the temperature raise. For the S355, but especially for the EN AW 7075 samples, the slope of the measured temperature difference decreases at pulsed laser powers above 50 W at 5000 Hz pulse frequency and above approximately 90 W at 7500 and 10,000 Hz. It is possible to explain this phenomenon by the density of the plasma and its related oscillation frequency. At higher pw powers at a given pulse frequency, more material is ablated, which leads to a higher plasma density. Therefore, a higher amount of the still incoming energy is absorbed by the electrons, ions and atoms forming the plasma, which results into a comparatively smaller increase of the temperature. The fact that this effect occurs at lower pw powers for the 5 kHz pulse frequency can be explained by the higher power of the single pulses in this case [15], resulting in stronger evaporation.

Figure 4 shows the calculated corresponding effective absorption coefficients depending on the pulsed laser power. The curve progression is qualitatively similar to the results of temperature raise measurement. A global raise of the absorption coefficient, a flattening of the curves for higher pw powers and a local minimum for the aluminum samples are evidenced. As for the temperature measurements, the results are clearer for the aluminum samples, but the same tendencies can be

observed for steel samples. The most important observation is that the effective absorption coefficient (i.e., the coefficient calculated by considering the total energy applied by both lasers) during the two-beam process is higher than the one determined at cw laser use only. For frequencies of 7500 and 10,000 Hz and powers around 90 W, an α_{eff} of almost 0.55 is obtained, which corresponds to an increase of more than 20%. This means that the plasma has a favourable impact on the absorption from a general point of view. A more detailed look on the curves reveals though that there are some plasma conditions which seem to be more suitable for the enhancement of absorption. For the three used frequencies, a decrease of the effective absorption coefficient is evidenced when the pulsed laser power approaches the upper limit of the powers which are possible for the respective frequencies. This can once again be explained by the stronger absorption in the plasma if it comes to higher plasma densities. In addition, for the aluminum samples, a local minimum of the curves can be identified at power levels around 60 W. This finding is in good agreement with the results of Cui et al. [10] who justify a high laser dissipation in the plasma at low laser intensities by collision-based effects and at high intensities by collision-free absorption going along with the occurrence of hot electrons.



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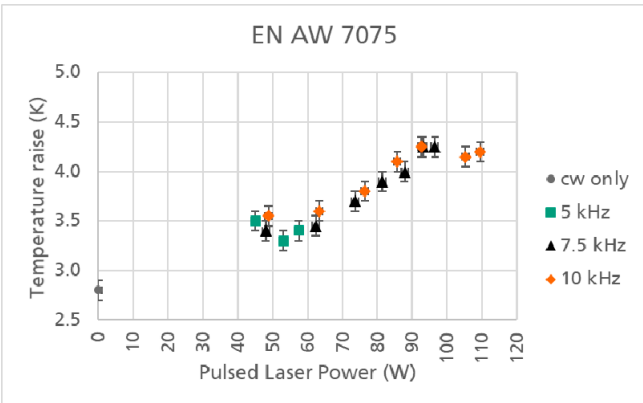
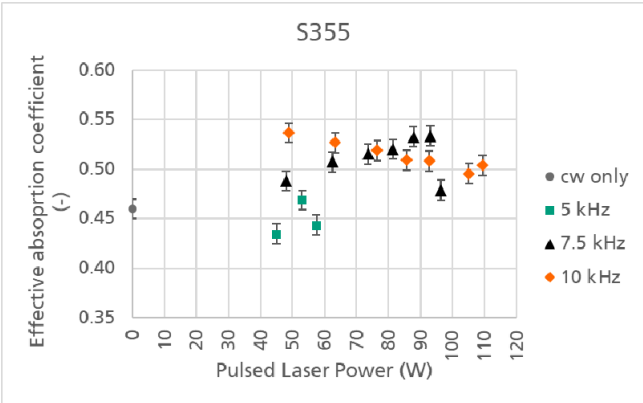


(**b**)

Figure 3. Graphic representation of the temperature raise of the water caused by the S355 (**a**) and EN AW 7075 (AlZn5.5MgCu) (**b**) samples previously processed at 400 W continuous laser power and different pulsed laser frequencies and powers.



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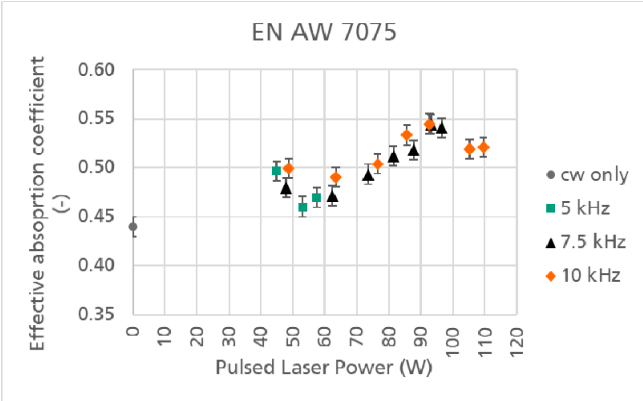


(**b**)

Figure 4. Graphic representation of the calculated effective absorption coefficients for the S355 (**a**) and EN AW 7075 (**b**) samples processed at 400 W continuous laser power and different pulsed laser frequencies and powers.

Another important observation is that the chosen pulsed laser frequency does not seem to have a significant influence on thermal absorption effects. Only for the steel samples, a bigger difference between the absorption coefficients at different frequencies can be seen at high and low applied laser powers (below 60 and above 100 W). This finding is in contrast to the results the authors obtained regarding the analysis of evaporation-induced forces acting on the workpiece during pw processing. Here, at higher frequencies, a shielding effect leading to the reduction of the induced forces is observed [6].

In a further series with the same experimental setup and for steel samples, the continuous power is raised to 700 and 1000 W under employment of the same pulsed laser parameters in order to verify whether the effective absorption coefficients are power-dependent. The corresponding results are shown in Figure 5. It is evident that for higher cw powers, the absorption coefficients decrease from approximately 0.5 at 400 W continuous power to values between 0.35 and 0.4 at 1000 W. This result is justified by Cui et al.'s finding that at high intensities and temperatures, the collision-free absorption and hot electron emission become significant. This leads to the fact that less thermal energy is transmitted into the workpiece.

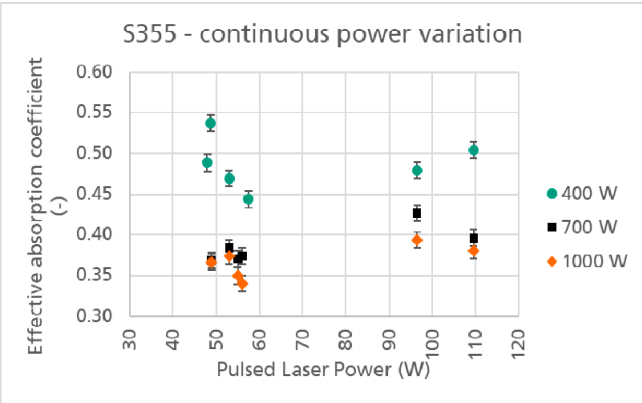


Figure 5. Comparison of the calculated effective absorption coefficients on S355 samples for different continuous wave powers combined with the same pulsed laser parameter sets.

3.2. Evolution of Process Temperature

The results achieved by the pyrometer-based measurements of the welding track surface temperature during wire-based LMD of QuFe13 wire on S355 substrates with the dual beam process qualitatively confirm the before-obtained observations. They are visualized in Figure 6. There is a minimum in the temperature increase at intermediate pulsed laser powers, corresponding to the higher absorption in the plasma in this region, as well as a flattening of the curves at higher powers. However, there exists a bigger difference between the temperatures measured at different frequencies, which is not in agreement with the results of the first experimental setup and not fully explainable. One aspect to be considered is the presence of the wire (respectively, the welding bead), which changes the interaction between the plasma and the substrate.

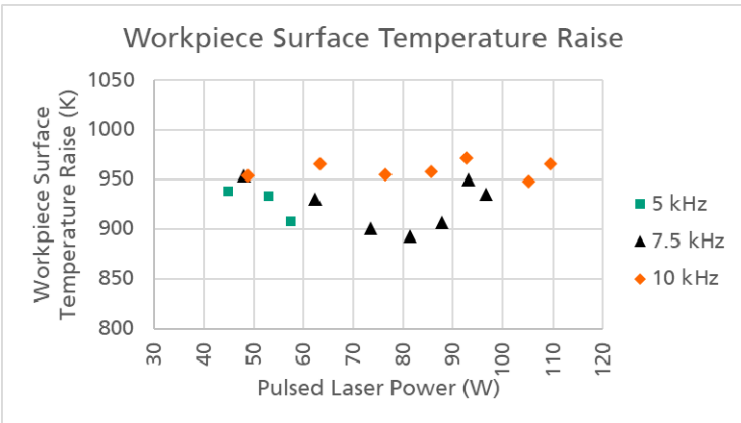
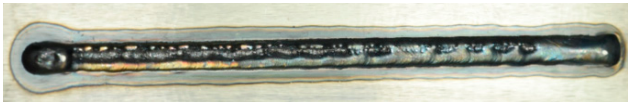


Figure 6. Surface temperature raise during LMD-w of QuFe13 wire on S355 substrates with the dual beam process. 2500 W cw, 1000 mm/min machine feed rate and 1800 mm/min wire feed rate with back feeding and different pulsed laser parameter sets.

In a last experiment, the threshold values regarding continuous power for a working LMD-w process of QuFe13 tool steel on S355 have been determined. It was found that at cw use only, the critical power which still enables melting the wire properly is 1900 W at 1000 mm/min machine feed rate and 1800 mm/min wire feed rate. However, if only 81 W average pw power at 7500 Hz is added, the threshold is decreased to 1300 W. This means that the necessary energy input can highly be reduced thanks to the enhanced effective absorption coefficient generated by the pulsed laser-induced plasma. Figure 7 shows the comparison between a welding bead at 1700 W cw only and at 1700 W cw combined with 81 W pw power at 7500 Hz. It is visible that without pulsed laser (see Figure 7a), the wire

is not completely molten and scratches trough the melt pool. The surface quality is not satisfying. The process result obtained at combined continuous and pulsed radiation (see Figure 7b) is similar to the one achieved at 2500 W cw employment only. The enabled reduction of total process power from 2500 W to 1781 W corresponds to a decrease of approximately 29%. This is a strong change compared to the corresponding increase of the absorption coefficient of only 13% according to Figure 4. As a consequence, the enhancement of absorption is not the only relevant effect. It is known from previous studies that the improvement of the welding track surface quality by the pw laser is also related to evaporation-induced forces acting on the melt pool [6] and smoothing its surface. In conclusion, the here-obtained results prove that the improvement of welding bead surface quality by pulsed laser employment is based on two mechanisms which are enhanced energy input in the plasma and pressure-induced melt pool shaping. Together, they enable the melting of the wire and the substrate at lower total process power.



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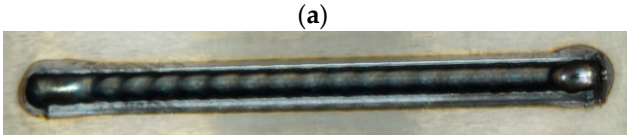

(**b**)

Figure 7. Comparison between welding beads realized at 1700 W cw power only (**a**) and at 1700 W cw combined with 81 W pw power at 7500 Hz (**b**). For cw use only, the power is not sufficient to completely melt the wire.

4. Discussion

In summary, the obtained findings prove the pulsed laser to cause remarkable changes in the process temperature of dual-beam LMD-w.

The effective absorption coefficients were determined by laser processing of small metallic samples which were subsequently dropped into water at ambient temperature. The measurement of the water's temperature raise allows the calculation of the energy absorbed by the sample and thereby the absorption coefficient. After constant duration of laser radiation, the temperature raise of the water was stronger for the samples processed at combined pw and cw radiation. The determined absorption coefficient is significantly higher for the dual beam process than for the single continuous beam process. If the absorption coefficient is plotted as a function of added pulsed laser power, a minimum at lower laser powers and a flattening of the curves at higher powers are evidenced. Thanks to literature, these two phenomena can be assigned to absorption mechanisms in the plasma. Based on temperature measurement errors, an uncertainty of ±0.01 is calculated for the effective absorption coefficients.

These results are quantitatively confirmed by in situ pyrometer measurements during dual beam Laser Metal Deposition of a tool steel wire. The curves of workpiece surface temperature raise during the process as a function of pulsed laser power show a minimum at intermediate powers and a decrease of the gradient at higher powers. This finding is in good agreement with the corresponding evolution of the absorption coefficient.

In addition, the range of process powers enabling a stable process is enlarged in dual beam LMD-w. An optical comparison of the resulting welding tracks reveals that the total necessary process power for a stably running process can be decreased by several hundred Watts if the pulsed laser is added. This reduction is proportionally higher than the corresponding increase of the absorption

coefficient by the pw laser. This leads to the conclusion that the effect is caused by at least two different pw-related phenomena, which are enhanced absorption and pressure-induced melt pool shaping.

Altogether, the results presented in this work provide new important knowledge for the understanding of the physical effects taking place during dual beam Laser Metal Deposition on steel and aluminum substrates. In the absorption experiments, some influences such as the heating-up of the vessel and the grid as well as evaporation-related energy consumption (by the water and the sample itself) could not be considered. Thus, the measured temperatures can be compared to each other, but the determined physical data are less exact than they would be in a real calorimeter measurement, where perfect isolation conditions exist. Because of this reason, the obtained results do not allow fundamental material characterization. The differences between measured values are though strong enough to reveal global tendencies of the pulsed laser influence on the dual beam process. The comparability of the measured values is ensured due to identical experimental conditions. The order of magnitude of the induced change is quantified and proves the significant influence of the pw laser on process temperature.

5. Conclusions

The present work reveals important results concerning the impact of the pulsed laser-induced plasma on the absorption of process energy and therefore the workpiece temperature during two-beam wire-based Laser Metal Deposition (LMD-w). The realized experiments are absorption measurements on a calorimeter-like test stand as well as pyrometer measurements under real process conditions. The main conclusion is that the absorption is globally increased thanks to the employment of a pulsed laser in addition to the continuous wave laser. The effective absorption coefficients calculated based on temperature measurement data rise by up to 20%. The local minimum and gradient changes of the curves can be interpreted by absorption phenomena in the plasma. For the present laser system, it can be concluded that for an enhanced cw absorption, the used pulsed laser parameters should be pulse frequencies between 7500 and 10,000 Hz and pw powers around 90 W. In addition, it was shown that the dual beam process even allows a reduction of the necessary process energy. At 1700 W cw power combined with 81 W pw power at 7500 Hz pulse frequency, a comparable welding bead quality as at 2500 W cw laser power without pulsed laser was achieved. Thus, energy can be economized and the heat affection of the substrate can be reduced.

To conclude, the magnitude of influence of the pulsed laser-controlled absorption during two-beam LMD-w is proven to be significant for the process. The pulsed laser-controlled plasma allows a melt pool temperature and geometry manipulation due to the increased absorption and evaporation-induced forces. As described, the two-beam LMD-w will further improve the process stability and flexibility of LMD-w additive manufacturing.

In a next step, the influence of sample size on the absorption and temperature has to be studied. In larger samples, the heat conduction to colder zones of the substrate is important and can therefore decrease the pulsed laser influence on the measured temperature. This will be examined by simulations as well as by other methods of temperature measurement. Measurements with higher resolution should be possible by an IR camera or by optical backscattering reflectometry with fibers attached on the bottom of the substrate.

Author Contributions: Conceptualization, M.G., K.A. and T.B.; Data curation, M.G.; Formal analysis, J.R.; Investigation, M.G.; Methodology, M.G. and J.R.; Visualization, M.G.; Writing—original draft, M.G.; Writing—review & editing, J.R., K.A. and T.B.; Supervision, K.A. and T.B.; Project administration, M.G. and J.R.; Funding acquisition, K.A. and T.B. All authors have read and agreed to the published version of the manuscript.

Funding: Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)—370349951. The authors thank the DFG for the provided support.

Conflicts of Interest: The authors declare no conflict of interest.

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