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Pulsed laser influence on two-beam laser metal deposition

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Abstract

While pulsed lasers are generally used to process solid materials, there are other technologies based on interaction between pulsed lasers and liquids. One example is the double-beam laser brazing where material is molten by a cw-laser and spread using a pw-laser. This technology can be transferred to enhance process stability during laser metal deposition by adjusting the force applied on the liquid surface. It is known that the liquid's dynamic is controlled by the pressure caused by vaporization and opposed influences such as surface tension and gravity, but the magnitude of the force applied on the surface by the pw-laser remains unknown. This study tries to quantify the mean value of this force over time by placing a metal ball into the laser beam. The whole system is mounted on a stage, which is gradually tilted during the experiment. When the gravity forces exceed the pulsed laser pressure, the ball rolls down. Thus, laser parameters can be correlated to acting forces.

Keywords: Dual-beam LMD; Laser induced forces

1. State of the Art

1.1. Introduction

During the last decades, laser-based manufacturing technologies have strongly gained in importance thanks to continuous research activities in this field and the related decrease of the costs of laser systems, which makes these processes affordable for a wide range of users. Nowadays, lasers can be used for various manufacturing processes such as cutting, surface structuring, microstructure adjusting by remelting or hardening and joining techniques (Hügel and Graf, 2009). This variety is based on the high flexibility of lasers (power and pulse rate can easily be tuned according to the material to be processed) and on the good automation suitability. Another laser-based technology, which becomes more and more important, is laser metal deposition (LMD). Here, the laser is utilized to melt and deposit a metal feedstock, e.g. powder or wire, onto a substrate. As this principle can be applied as an additive manufacturing (AM) technique, it is an object of a large amount of recent investigations (Kaierle et al., 2012). The advantage of wire-based LMD (LMD-w) in comparison to powder-based LMD-p is the uncomplicated handling of wire as a feedstock material with less potential hazards while high deposition rates can still be achieved (Syed et al., 2005).

However, despite the above-mentioned flexibility of laser processes, materials with a permanent oxide layer such as aluminium are difficult to process through LMD, as the high-temperature resistant oxides inhibit joining the feedstock material with the substrate or the above layers (Bargel and Schulze, 2008). Previous works have shown that in laser-based

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welding and brazing processes, this problem can be overcome by combining the typically employed continuous wave (cw) process laser with a second energy source. Literature reports for example a combination of cw-laser and plasma arc (Möller and Thomy, 2013). It is also possible to apply a dual beam laser process with a cw and a superposed pw-laser source (Chen and Molian, 2008; Donst, 2012). In addition, from a material-independent point of view, the bead geometry is often not fully controllable, which can result into disadvantages regarding additive manufacturing. The dual laser beam approach also addresses this geometrical problem (Donst et al., 2009b) and will be the focus of the present work.

1.2. Interaction of pulsed laser and meltpool

Several effects are assumed to occur during the process when the pw-laser is added. Firstly, the pulses exert a force on the melt pool and spreads it. Thus, the pw-laser has an influence on the geometry and the surface roughness of the welded bead. The force thereby can be induced due to the vaporized pressure or the thermal gradient on the melt pool, leading to Marangoni Convection. Secondly, it is assumed that the pulsed laser destroys the high-melting oxides by ablating them thanks to the high local intensity of the single pulses. Without oxide layer the material tends to spread easily. A third phenomenon consists of a surface modification of the substrate leading to better wetting conditions of the molten wire on the base material (Donst et al., 2009a; Donst, 2012).

As the real process is certainly characterized by a superposition of the three mentioned phenomena, it is crucial to explore which are the respective magnitudes of influence and whether there is a predominant one. This information will be helpful for further process developments, simulations and improved part quality based on simplified prediction models.

This work aims to quantify the forces appearing when the pw-laser interacts with metal surfaces. Also, the experimental procedure will identify whether the force is caused due to thermal gradient-induced convections or rather the vapor pressure. This will lead to a deeper understanding of the forces that act on the molten metal during LMD.

The interaction between a laser and a solid is based on an absorption of the laser light by the material, whereby the quantity of energy absorbed during a given period is depending on the material's absorption coefficient for the considered wavelength and the laser intensity. The absorption is principally controlled by the electronic properties (Ruf and Dausinger, 2004). Depending on the thermal conduction coefficient, the heat will quickly be distributed in the material or rather stay concentrated in a smaller region. In this time scope, convective heat transport mechanisms of a liquid material can be neglected. The decisive point is the form of energy introduction. On the one hand, if the intensity of energy is constant over time, the result is a rather homogeneous heat input, that can for example lead to the melting or vaporization of a larger volume of material if the intensity is high enough. This is typically used for laser deep-penetration welding and cutting, where the plasma capillary stabilizes the melt pool region (Reisgen et al., 2017). If the energy input is pulsed, the effects are different, even if the average intensity is the same as in the aforementioned case. Here, the single pulses have much higher intensity, which will result in a very short and localized heat input. In the affected zone, this input is quasi-instantaneous and instead of being subjected to a comparatively slow thermal expansion, the material cannot accommodate the energy input and will sublimate to form a vapour-plasma mixture. Depending on the pulse energy and length in comparison to the characteristic times of the material dependent electron-phonon coupling, the volume of sublimated material and of the adjacent molten zone is different (Chichkov et al., 1996). The volume expansion from a solid or liquid to a gaseous state goes along with the propagation of a shock wave which exerts a force on the remaining solid material. The ablation and so the induced forces should be influenced by the shielding of the generated plasma (Cristoforetti et al., 2009). Thereby, it is also not sure whether the laser energy of subsequent pulses is absorbed in the plasma. If so, this would mean that there is no effect of single pulses, but that the vaporization is indirectly caused by the temperature radiation of the plasma. In this case, the pressure should be constant over time.

In literature, there exist several studies reporting the measurement of laser ablation induced forces. The described setups cause a relatively high effort. For example, Shirsat implements a double aluminium foil setup (Shirsat et al., 1988), while Grun makes use of a ballistic pendula (Grun and Ripin, 1982). Peyre explores the pressure during laser shock processing using a piezoelectric gauge (Peyre and Fabbro, 1995). As the results were obtained under very specific conditions, a simple transfer to laser metal deposition seems difficult. Therefore, the aim of this work is to use two simple experiments to measure the laser induced forces for different sets of pulse laser parameters with regard to dual-beam LMD in order to understand to which extent this has an impact on the process. The employed setups have the advantage of being independent of plasma oscillations or other side effects, as methods to quantify the integrity of the present forces is used.

2. Experimental procedure

The experiments were conducted with a pulsed laser manufactured by Edgewave (Model IS20I-ET). The laser output is controlled by setting the parameters current and frequency. The frequency is generated by the internal generator of the laser controller. The pulse width dependency on the parameter set deviates in between 32 and 9 ns according to the data sheet. The mean laser power for different currents was measured with a Coherent LabMaster Ultima laser power measurement system for each frequency used. The results will be presented as a function of the mean laser power rather than a function of the current. The minimum mean laser power is 48 W. The maximum is about 114 W.

In the first experimental setup, the laser was placed on an inclinable stage in order to quantify the forces occurring during the interaction of the laser with a moveable object. The maximum inclination was 30°. A steel ball with a radius of 6 mm and a weight of 0.8796 grams was put into the beam. The standard deviation of a random sample of 10 balls was below 0.2 mg. Thereby, the weight difference of each ball can be neglected. To avoid friction, the guidance rail was made of silicon nitride.

Starting from a horizontal position, the stage was progressively tilted. The ball then rolls into the laser focal point and is repelled by the laser-induced force. As far as the laser induced forces on the ball are greater than the gravitation-induced downhill force growing with the increasing inclination, the ball is held in its position by the laser beam. At a certain inclination angle, the downhill force exceeds the laser pressure and the ball rolls down. The experiment is recorded with a camera. Later on, the frame where the gravity overcomes the laser force is identified. By the framerate, the inclination velocity and the force triangle, the laser power can be conducted. By this way, for different sets of pulse laser parameters, the corresponding maximum laser induced force can be determined.

Two series of this experiment were carried out. In the first series the frequencies were 5, 7.5 and 10 kHz and the laser power was of 50, 75 and 100 W. At the frequency of 5 kHz, the laser source provided a power of 50 W only. To assure reproducibility, each parameter set was repeated at least six times. The second series was performed at the frequencies of 7.5 and 10 kHz. In order to obtain a more precise correlation between measured forces and laser power, the current was set at eight different values between 45 and 54 A, which can be converted into corresponding power values by means of the calibration curve. In this series, each parameter set was only conducted twice.

The second setup consisted of the vertically mounted pulsed laser over a precision scale on a movable x-y-stage. Metal sheets of aluminium and steel were placed onto the scale, so that their surface was located in the focal point of the laser beam. When the laser is running, metal will evaporate. The shock wave caused by the evaporation results in a measurable force on the scale. During the experiment, the stage has to be moved to generate a force signal constant over time. Otherwise, in case of a constant x-y position, the current surface would fall out of the focal point due to the ongoing material consumption caused by laser-induced evaporation. To prove the reliability of the results obtained in the first experiment, the forces acting on the scale were measured for the same sets of laser parameters. The accuracy of the scale was 0.05 g.

3. Results

Table 1 shows the results of the determined force and the standard deviation for the first series of the first setup. Additionally, the pulse energy as mean laser power divided by the frequency is shown. Based on the standard deviation, the dependency of the process from the parameters is proved. An analysis of variance (ANOVA) indicates that both parameters have an impact while the impacts are not separated from each other. The setup thereby enables measuring the forces on a curved steel surface due to the interaction with laser pulses.

Table 1. Results of the measurement on the inclinable stage.

Frequency (kHz)	Laser power (W)	Measured Force (mN)	Standard deviation (mN)	Pulse energy (mJ)
5	50	2.17	0.11	10
7.5	50	1.27	0.16	6.7
7.5	75	3.45	0.11	10
7.5	100	4.12	0.1	13.3
10	50	0.74	0.36	5
10	75	2.89	0.1	7.5
10	100	3.85	0.36	10

Figure 1 (left) illustrates that the force increases with increasing mean laser power while it decreases with the frequency. This phenomenon is contra intuitive at first site. At higher frequency, the number of pulses increases and therefore the force on the part. The observed results confirm a shielding effect, which occurs at higher frequencies. Alternatively, the induced force can also be shown as a function of the pulse energy as it is done in figure 1 (right). If the effect is discussed for a constant average laser power of e.g. 50 W, the energy per pulse increases from 5 to 10 mJ and the measured force increases from 0.74 to 2.17 mN. Therefore, it cannot be concluded whether higher frequencies or the related lower pulse energy is dominating the process. Also, the laser pulse width will have an impact on the measureable force, but is not controllable for the laser employed in this study.

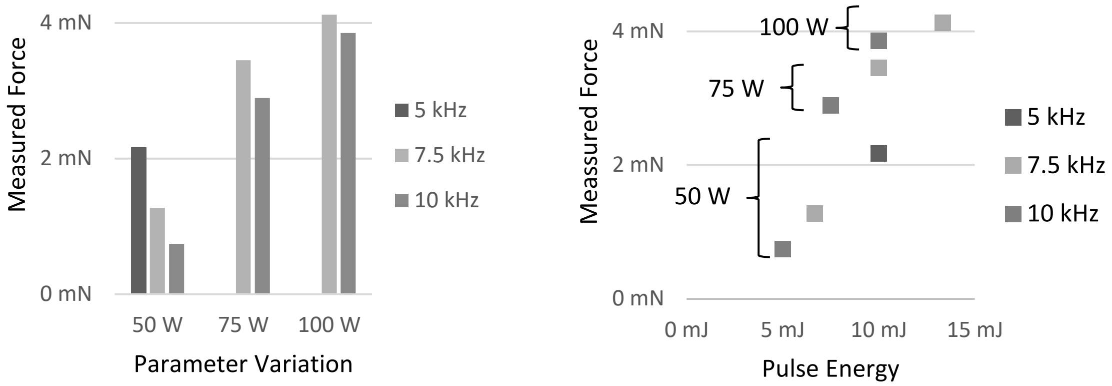

Fig. 1. Results of the first measurements on the inclinable stage. (a) Measured Force as a function of mean laser power and frequency ;
(b) Measured force as a function of pulse energy.

The results of the second experimental series with setup 1 are shown in figure 2. With increasing mean laser power, the measured force rises steadily until it reaches a maximum value of about 4 mN. These results are plausible with the shielding effect phenomena of the plasma. At a frequency of 7.5 kHz, the system reached the maximum tilting angle.

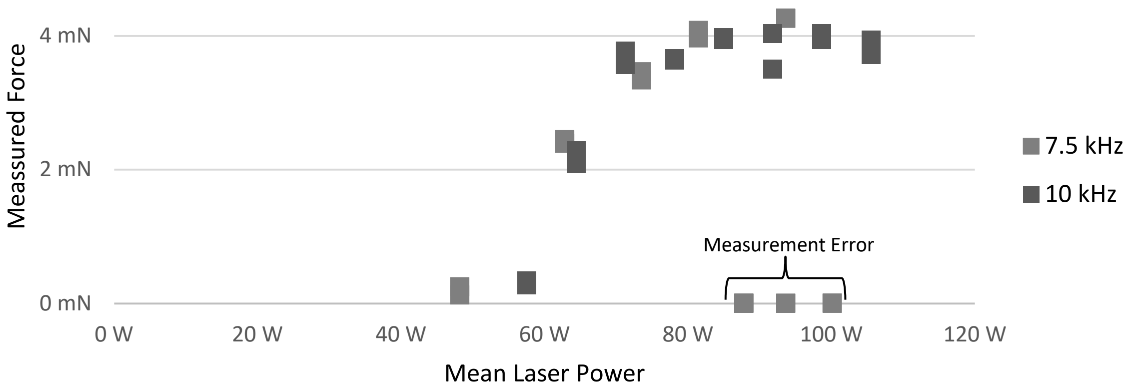

Fig. 3. Results of the second measurements on the inclinable stage. Measured Force as a function of mean laser power and frequency.

For the second experiment on the scale, every measurement was repeated at least three times on aluminium and steel sheets. The main observed problem was the accuracy of the scale. As the maximum measured weight was 0.3 g the accuracy of 0.05 g has a non-neglectable influence. The results are summed up in table 2 and figure 4. A significant difference between the measured forces on steel and aluminium could not be detected. It was checked that the moving of the stage itself does not lead to a signal of the scale. Thus, the measured values can clearly be related to the laser-induced evaporation.

Table 2. Results of the measurements using a scale.

Frequency (kHz)	Laser power (W)	Measured average weight (g)	Corresponding force (mN)
5	50	0.13	1.3
7.5	50	0.1	1
7.5	75	0.2	2
7.5	100	0.3	3
10	50	0.08	0.8
10	75	0.18	1.8
10	100	0.25	2.5

These results confirm those obtained with the inclinable setup. Higher laser powers lead to higher forces, whereas the forces decrease when the frequency is raised. This is also visualized in figure 4.

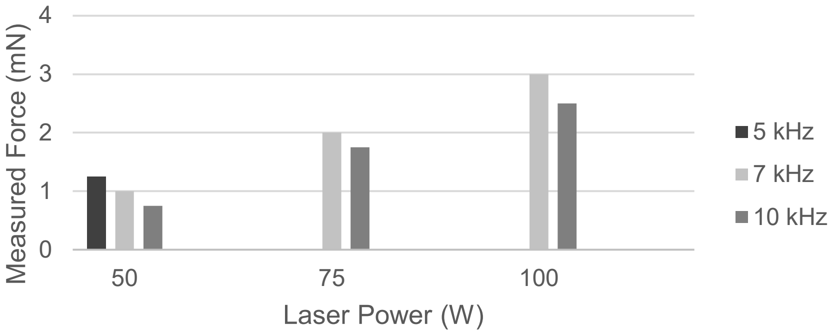

Fig. 4. Forces determined with the scale experiment as a function of mean laser power and frequency.

Even if the magnitudes determined with the second setup are not very precise due to the scale accuracy, they confirm the tendency and the order of magnitude determined with the ball experiment. A scale with higher precision would lead to more reliable results.

4. Discussion

To get an idea whether the force of 0.74 to 3.85 mN has an impact on the welding process, the following approximation will be made. The main forces acting on the melt pool without the pulse laser are gas pressure, surface tensions, acceleration forces due to thermal and chemical gradients and the gravity. While most of these forces cannot be measured directly, the gravity can be quantified rather easily. For most materials, deposition welding in overhead position is not possible due to the influence of the gravity. This shows that the gravity force is in the same order of magnitude as the other forces. As an exemplary geometry, a half sphere with a diameter of 1.5 mm can be considered. The density may be equal to the one of steel. Then, the gravity force can be calculated to 0.5 mN, which is significantly less than the lowest value of the measured force. This means that the studied pulsed laser-induced forces have a significant influence on the process. Thereby, the hypothesis that the force is induced due to very high thermal gradients seems unlikely.

5. Conclusion

Double-beam laser processing allows to manufacture aluminium-steel-joints and manipulate the shape of the beads. There have been several theories presented by Donst (Donst et al., 2009a; Donst, 2012) on how this effect is achieved. The present work indicates that the dominant effect is the force which is generated by the pressure of the vaporized material. This force is much higher than other forces appearing in the process. Combined with the removal of the oxide film on the surface, it should be the decisive factor leading to a weldability of aluminium. This can also be applied to additive manufacturing, where the pulsed laser leads to a process stabilization and a more controllable bead geometry.

Another aspect to be considered is the influence of the state of matter interacting with the pulsed laser. Currently, it is not clear how the above-mentioned forces vary during a change from a solid to a liquid substrate as it occurs during welding. Also, further experiments have to be conducted to identify the influences of pulse width, pulse energy and frequency.

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