Lasers in Manufacturing Conference 2021

Open-loop control complex pulse shapes for laser beam welding

Marc Seibold[a,*], Klaus Schricker[a], Jean Piere Bergmann[a]

[a]Technische Universität Ilmenau, Production Technology Group, Gustav-Kirchhoff-Platz 2, 98693 Ilmenau, Germany

Abstract

Pulsed laser beam welding is of high importance in micro-welding applications and used for materials susceptible to hot cracking, e.g. 6xxx aluminum alloys. Pulse shapes are adjusted to prevent hot cracks by reducing solidification rates which is accompanied by decreased welding speeds. Numerical simulations are now used for optimizing the tradeoff between crack-free welds and highest possible welding speeds. This procedure requires small deviations between the nominal value of the laser beam power calculated by numerical simulations and the actual value in the experiment. A methodology is developed and validated for a fiber laser beam source (IPG YLM-450/4500-QCW) using different pulse shapes. The differences between nominal and actual values were identified by high-speed power measurements and reduced from 13 % down to 2 % for complex pulse shapes over time. This paper shows how to set up power compensation in order to emit an accurate complex pulse shape compared to numerical simulations.

Keywords: open loop control; pulsed laser beam welding

1. Introduction

Aspects of lightweight construction and electromobility have become much more important in recent years. At the same time, challenges for production of related components have also increased. Especially the use of alloys with beneficial mechanical properties challenges joining technologies, especially for aluminum alloys. Hot cracking is a common problem within 6xxx and 7xxx series of aluminum alloys. These hot cracks appear immediately during solidification of the weld and result in unsound welds and thus rejects [1]. To avoid hot cracks in pulsed laser welding, it has been shown that an adjusted pulse ramp prevents the formation of hot cracks [2]. These ramp forms have been experimentally determined so far that is accompanied by an increase of pulse energy. The pulse repetition rate decreases as the pulse energy increases due to the duty cycle. In order to continue to have a constant pulse overlap, the feed rate must be reduced. A reduction of the feed rate is highly unwanted as it reduces the economic efficiency. One way to avoid this is to adapt the pulse shape. From a simple ramp-down shape to a complex pulse shape that is adapted to the solidification rate of

---

* Corresponding author.
E-mail address: marc.seibold@tu-ilmenau.de .

the weld. The solidification rate is considered to be the main factor influencing hot cracking in thin sheet joining. [3,4]

For the determination of the complex pulse shapes a simulative approach is chosen. [5] It is particularly important that the determined pulse shapes can be reproduced as accurately as possible on the laser beam source.

In this publication, an open-loop control will be presented as power-dependent compensation between set and actual values and will be validated using a complex pulse shape from the numerical simulations performed by Technische Universität Chemnitz. The pulse shape does not represent an optimization of the welding process, but a possibility of implementation.

2. Experimental setup

A beam source with a fixed processing optic mounted on a three-axis gantry system were used during the experimental investigation. The power compensation was performed for two different beam sources. The first laser beam source is an Ytterbium fiber laser from IPG Laser GmbH. The Q-switched source, YLR-450/4500-QCW-MM-AC-Y14 has a maximum pulse power of 4500 W at a maximum pulse energy of 45 J. A nominal focal diameter of 470 µm was set. This beam source has a laser power supply with a cycle time of 10 µs. This means that the beam source readjusts the power up to 5 times faster than conventional laser beam sources [6].

The pulse power over time was measured by means of Coherent Power Max Pro HP. Pulses can be resolved in a time range of milliseconds due to the sampling rate of 20 000 Hz. The power linearity of the instrument is ± 2 % according to the manufacturer specification [7]. The last calibration by Coherent showed a power linearity of 0.54 % at a wavelength of 801 nm. To protect the measuring instrument from damage, the measurements were performed with the beam strongly defocused.

The power measurements were performed at different pulse lines in order to determine the difference between set values and actual values of power output. This also allows power-dependent deviations to be determined, i.e. if the difference between set and actual value depends on power levels. Square pulses with a pulse duration of 10 ms in power steps of 250 W were made over the power range of both laser beam sources. Fig. *1* presents some of the pulse shapes used.

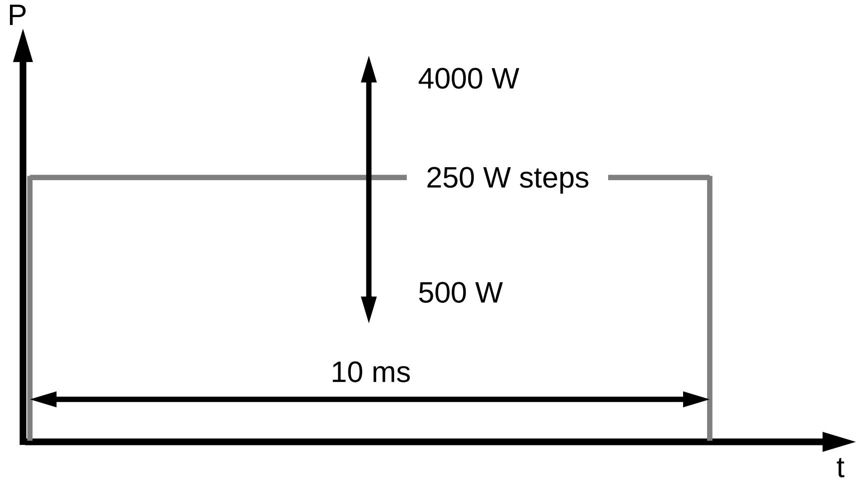

Fig. 1. Examples of different set laser powers

3. Results and discussion

In the following, the focus will be on the results of the IPG laser beam source. The laser power was measured 5 times in order to increase the number of samples for statistical purposes. Fig. *2* illustrates some of the measured powers. It can be seen that the actual power output is constant over time, independent of power levels. The power build-up from 0 to the maximum power happens with a low latency. The power build-up from 0 to 4,000 W takes about 0.1 ms for example. The very fast adjustment of the voltage in the laser power supply of the IPQ beam source leads to minimal fluctuations in the laser power. This shows that an internal power control takes place in the laser beam source.

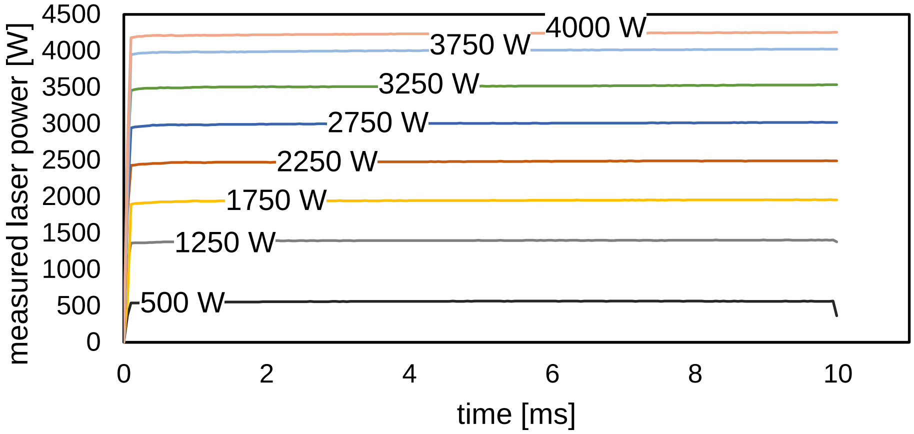

Fig. 2. Measured square pulses of several different power levels

Fig. 2 depicts the comparison between set values and actual values of laser beam. To consider small fluctuations of the power over time, average values after reaching the time step of 0,1 ms. In Figure 3, measured power values are plotted against the nominal power. The measured laser beam power increases linearly over set laser beam power. In all cases, the laser beam source emits more power than the set value. The laser beam source shows a high stability and reproducibility in terms of power level and deviation, e.g. the actual value reached approx. 4,250 W for a nominal value of 4,000 W, i.e. 6 %. With respect to a comparison between numerical simulation and experiment, however, this deviation shall be considered again in more detail.

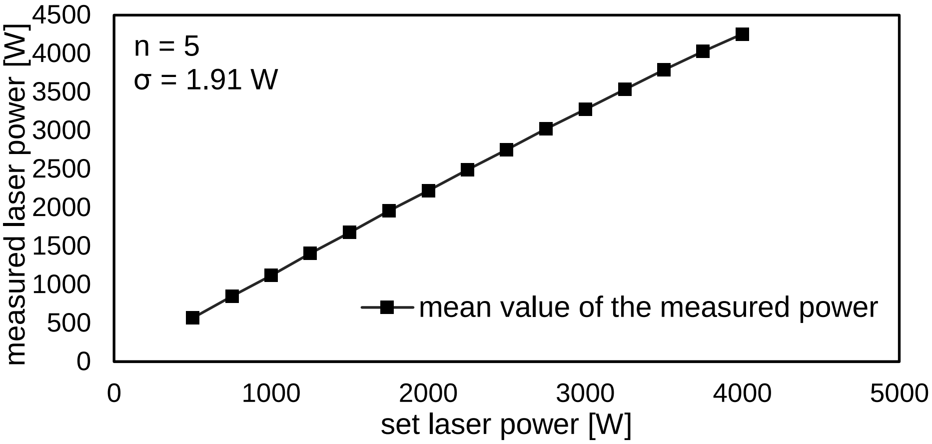

Fig. 3. Measured power plotted against set power (n = 5, standard deviation σ = 1.91 W)

In Fig. 3, the difference between set power and actual power is plotted for the data shown above (Fig. 2). This representation allows the deviations to be discussed more precisely. It becomes obvious, that the IPQ QCW laser beam source continuously provides higher output powers than required compared to set values. The deviation increases up to a set pulse power of 3,500 W and then it decreases again. This characteristic is due to the construction of the laser beam source and cannot be further influenced by the user.

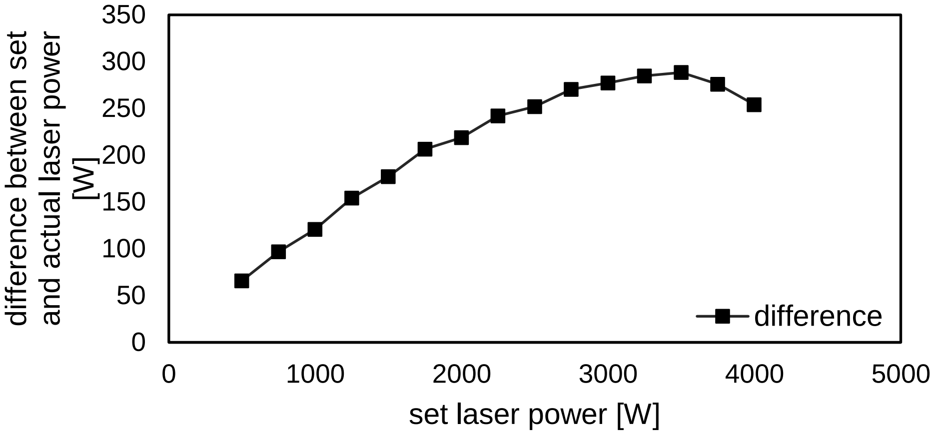

Fig. 4. Difference between measured and set power above

The results obtained show that the IPG QCW laser beam source has a high stability in power output, but a power compensation is purposeful regarding a comparison between simulation and experiment. The power compensation based on a fixed value is not effective since there is no constant offset between the nominal and actual value. Especially the power range from 500 W to 2,750 W shows a nearly linear course. In order to check whether a relative compensation sufficiently represents the deviation, the differences between nominal and actual values shown in Figure 4 are plotted over set laser powers (Fig. 5). In addition, a linear regression was carried out and reached a coefficient of determination of $R^2 = 0.97$. The regression line shows that the difference between nominal and actual power corresponds to a linear relationship. Also, the maximum deviation of the beam source from the specified power is approx. 13% that is reached for low beam powers.

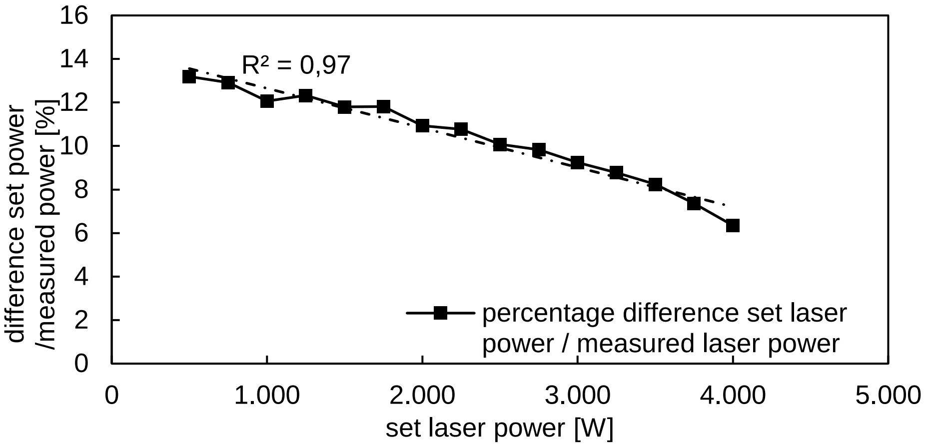

Fig 5: Plot of the percentage results from Fig. 4 as their linear regression lines.

The regression line can be approximated by the following equation (1).

$$\Delta P(P_{set}) = -0{,}0018\,\frac{\%}{W} \cdot P_{set} + 14{,}464\,\% \qquad (1)$$

In order to make the equation usable for open-loop control of power, the following condition in equation (2) is defined based on Fig 5.

$$P_{wanted} = P_{set} \cdot \frac{\Delta P(P_{set})}{100} \qquad (2)$$

This function has now been used to determine the difference between nominal and actual power of a complex pulse shape. A power-dependent correction factor can be applied to compensate the power deviation. For this purpose, a software based on Python has been developed which allows the generation of pulse programs in order to load them onto the beam source. In order to verify the power compensation, a complex pulse shape was determined in cooperation with Technische Universität Chemnitz. The pulse shape is not optimized with regard to the welding process but is intended to demonstrate the functioning of the power-dependent compensation by permanently changing the power. This can be used to show exactly how the open-loop control is implemented. The power curves are shown in Fig. 6. The black curve represents the target power curve, the dark orange the uncorrected power and the blue the power curve after the compensation has been applied. Due to the limited power range in the diagram from 800 W to 1,300 W, the difference between the two measured curves can be seen more clearly. What becomes very clear here is that the deviation of the corrected curve from the power setting is much smaller. A deviation of just 2 % is reached with regard to the nominal value which represents a highly accurate reproduction of the simulated pulse shape.

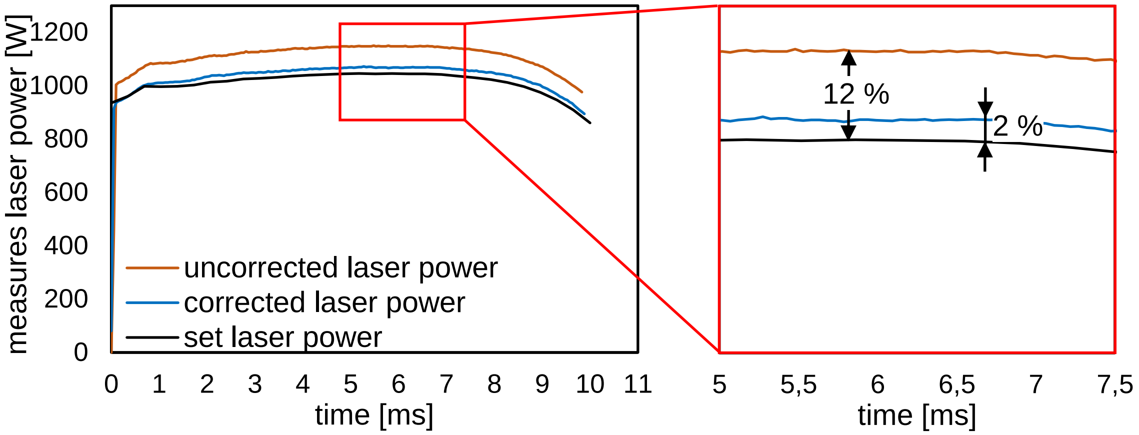

Fig. 6. Comparison between pulse setting, corrected and uncorrected laser power applied to a complex pulse shape.

4. Summary and outlook

In this paper, a methodology for power compensation of complex pulse shapes based on relative deviations from set to actual values was demonstrated. Beam sources that have a very reproducible power deconvolution nevertheless deviate between set and actual value depending on the power level. The developed compensation function was determined for the beam source used here and validated on a complex pulse shape. It could be shown that the compensation minimizes the deviation of output power to nominal value to approx. 2 %. In the next steps, the methodology of power compensation is transferred to other laser beam sources, e.g. Nd:YAG lasers, and welding results in the numerical simulation and experiments are compared based on the same pulse shapes regarding hot-cracking of aluminum.

Acknowledgements

The authors are grateful for financial support of the AiF Arbeitsgemeinschaft industrieller Forschungsvereinigungen in the frame of the research project 20.826 BR / DVS-Nr.: I2.3005 of the IGF Industrielle Gemeinschaftsforschung, entitled "Simulationsbasierte Optimierung der zweitabhängigen Pulsleistung beim Laserstrahlschweißen von Aluminiumlegierungen zur Vermeidung von Heißrissen". Furthermore, we would like to thank our colleagues from Technische Universität Chemnitz, Prof. Dr. Roland Herzog and M.Sc. Dmytro Strelnikov, for providing a complex pulse shape for validation.

References

[1] Katayama, S., Solidification phenomena of weld metals, Solidification cracking mechanism and cracking susceptibility (3rd report) Welding International15(8), 627-636, 2001

[2] Bielenin, M., Schmidt, L., Schricker, K., Bergmann. J. P., Prevention of solidification cracking by use of a diode laser superposition in pulsed laser beam welding, SPIE LASE, 2019

[3] Zhang, J., Weckmann, D. C., Zhou, Y., Effects of temporal pulse shapingon cracking susceptibility of 6061-T6 Aluminum Nd:YAG laser welds, WeldingJournal87(1), 18-30, 2008

[4] Bielenin, M., Prozessstrategien zur Vermeidung von Heißrissen beim Schweißen von Aluminium mit pulsmodulierbaren Laserstrahlquellen (german), Universitätsverlag Ilmenau, 2021

[5] Bergmann, J. P., Bielenin, M., Herzog, R., Hildebrand, J., Riedel, I., Schricker, K., Trunk, C., Worthmann, K., Prevention of solidification cracking during pulsed laser beam welding, PAMM, 2017

[6] IPG Photonics. SPECIFICATION YTTERBIUM FIBER LASER Model YLR-450/4500-QCW-MM-AC-Y14, datasheet, 2015

[7] Coherent Inc., PowerMax-Pro HP Sensor, datasheet, 2017