Process Monitoring at Laser Welding of Thermoplastics

3D-scanner with integrated pyrometer enables online temperature monitoring at quasi-simultaneous laser transmission welding

Anton Schmailzl, Sebastian Steger and Stefan Hierl

A pyrometer, integrated into a 3D-scanner, offers the possibility to measure the weld seam temperature at quasi-simultaneous laser transmission welding. Experimental studies have shown that gaps located in the joining zone can be identified by a temperature rise even at a high scanning velocity. This enables the implementation of algorithms for observation and control strategies.

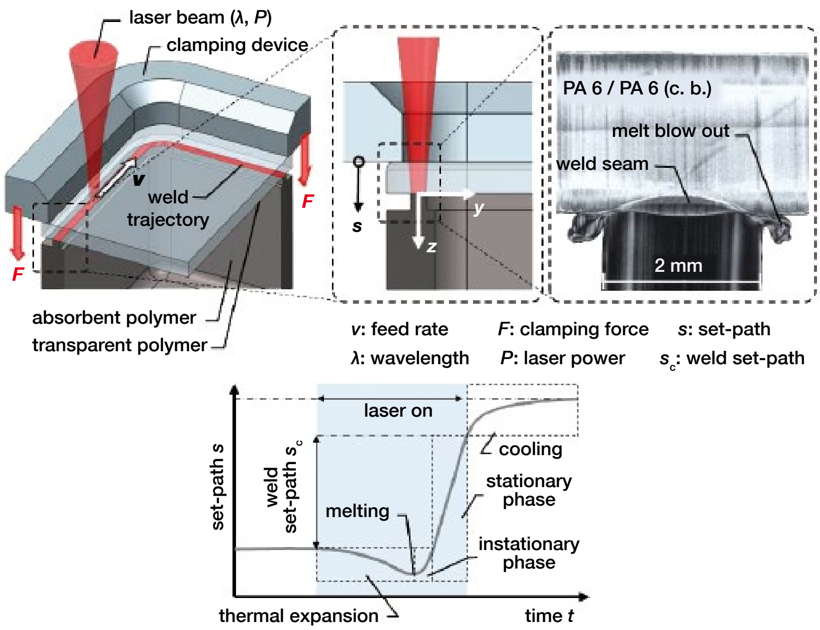

Fig. 1 Process principle of quasi-simultaneous laser transmission welding (left hand, top), a typical weld seam of PA 6 (right hand, top) and a sketch of the measured set-path *s* during welding (bottom).

Laser transmission welding is a well-known joining technique for thermoplastics and often used in the automotive or medical industry and for consumer applications. A transparent polymer is positioned above an absorbent filled polymer and fixed by a clamping-device. At quasi-simultaneous welding, the laser beam, typically in the infrared spectrum, is guided several times along the weld trajectory, passes the transparent and heats the absorbent polymer close to the interface (see Fig. 1). The transparent polymer is mainly heated via heat conduction. After reaching the melting temperature in both polymers, a weld seam is formed. The high feed rate ($v >$ 1 m/s) in addition to the low heat conduction of the polymers causes a nearly simultaneous heating and melting of the entire weld trajectory. By this, the applied clamping force leads to a relative movement of the joining partner, which is referred to as set-path *s*, and melt is squeezed out of the joining zone (see Fig. 1) [1]. Usually, the so-called set-path monitoring is used, in which the laser emission is turned off as soon as a desired weld set-path is reached. Hence, a part-specific heating time is evident. The weld is specified as "good" if the heating time is within a defined confidence interval [2].

However, local gaps in the joining zone, which are mainly caused by warpage after injection molding, cannot be detected. A localized process monitoring system based on pyrometric temperature measurement is commercially available by using a 2D-scanner [3]. The integration of a pyrometer at a certain spectral range beside the used laser wavelength makes it necessary to use a color-corrected flat-field optic. The correction is needed in order to guarantee that laser- and detection-spot are coaxial at a desired working field [4, 5]. By using a 3D-scanner in addition with a pyrometer, laser- and detection-spot are basically coaxial; therefore a color-corrected flat-field optic is not needed. A scanner system without this special optic ensures that the heat radiation, which is fundamentally low, is not additionally reduced. Especially the use of a 3D-scanner offers the possibility to weld parts with a three-dimensional weld-trajectory.

Institute

Laser Material Processing Laboratory, OTH Regensburg
Regensburg, Germany

The laser material processing laboratory, which is part of the Faculty of Mechanical Engineering at the Ostbayerische Technische Hochschule Regensburg was founded in 2011 by Prof. Dr. Stefan Hierl. A team of young scientists conduct applied research and development in the field of laser plastics welding with the focus on process control and simulation.

www.oth-regensburg.de/fakultaeten/maschinenbau/labore/laser-materialbearbeitung.html
www.oth-regensburg.de/en

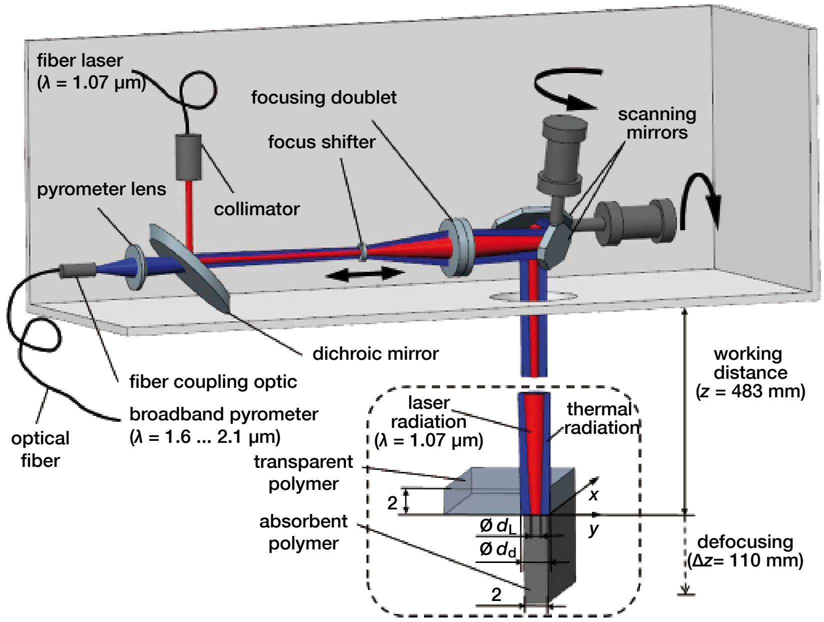

Fig. 2 Optical setup of a 3D-scanner with integrated broadband-pyrometer for online temperature measurement during quasi-simultaneous laser transmission welding of thermoplastics.

3D-scanner with integrated pyrometer

A 3D-scanner with integrated broadband-pyrometer is used to measure the temperature that is emitted from the joining zone. The heat radiation is separated by a dichroic mirror and afterwards analyzed by a fiber-coupled pyrometer (see Fig. 2).

In order to measure the temperature in the weld seam, the spectral range of the pyrometer has to be in a region where a sufficient transparency of the above placed polymer is given. Typically, a spectral range beneath 2 µm is used [6].

The focal length of the entire system of a 3D-scanner can be dynamically adjusted by a movable lens, a so-called focus-shifter. An adjustment of the laser beam is needed for processing in a 2D-field or even in 3D-space. Due to the high beam quality of the used fiber laser, the laser beam has to be defocused for welding plastics. Since the heat radiation is also guided by the focus-shifter, an adjustment implies that the diameter of the detection-spot varies, too. A variation of the detection-spot diameter affects the resolution of the temperature signal along the weld trajectory and causes a change in the magnitude of the signal itself. This effect is negligibly small, if the deflection of the laser beam and thus the adjustment of the focus-shifter are small-sized. In order to interpret the temperature signal in correlation to a position onto the sample, the tilt-angle of the mirrors is measured and converted into a position at the working field.

Temperature measurement at quasi-simultaneous laser transmission welding

Welding experiments are carried out for plates (PE-HD) in a t-joint (see Fig. 3, right hand, top). The surface of the absorbent polymer adjacent to the transparent is milled in order to provide good heat conduction between the joining partners. The scanner deflects laser- and detection-spot from Pos. I to Pos. II. The temperature is thereby measured while laser emission is on. Afterwards, the laser is turned off and the detection spot is deflected back to Pos. I by using the same feed rate (v = 4 m/s). Thus, the temperature signal within a single scan includes an irradiation- and a cooling-phase. The scanning procedure is repeated until the desired weld set-path s_c is reached. The reversal points are located at a distance of 0.5 mm outside of the samples. In order to prevent that direct reflected laser radiation is measured, the welding samples are placed in distance of 25 mm lateral to the center of the working field (see Fig. 3, right hand, top). The measured temperature signal within the irradiation- and the cooling-phase can be

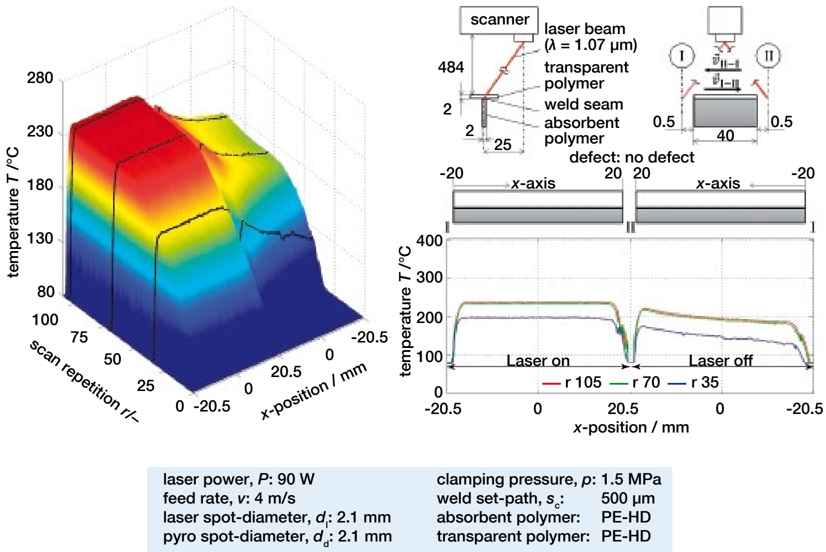

Fig. 3 Temperature signal at quasi-simultaneous laser transmission welding of plates in a t-joint (PE-HD, right hand, top), plotted for all scan repetitions (left hand) and for specific scans (right hand, bottom).

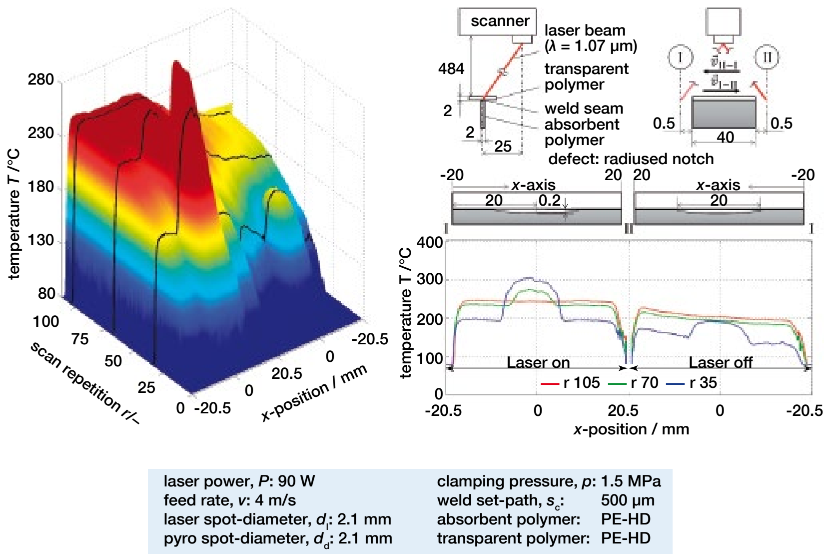

Fig. 4 Temperature signal at quasi-simultaneous laser transmission welding of plates in a t-joint (PE-HD) with a milled gap of t = 0.2 mm (right hand, top), plotted for all scan repetitions (left hand) and for specific scans (right hand, bottom).

interpreted for each scan repetition in a three-dimensional diagram (see Fig. 3, left hand).

By reaching the temperature threshold of the pyrometer ($T > 80$ °C) the magnitude of the temperature signal remains constant within the irradiation-phase for each scan. Afterwards, a reduction in the temperature signal in dependency to the elapsed time within the cooling-phase can be seen. The temperature increases with each scan until a plateau is reached. The time at which the plateau is reached is identical with the beginning of the stationary phase (see Fig. 1, bottom). In this process-phase, melted material is squeezed out of the joining zone. By this, a thermal equilibrium state is evident. The inserted thermal energy is divided into a plastification- and a blow-out-portion. As a result, the temperature signal remains constant and a stationary phase is given.

Fig. 4 shows a temperature measurement of a t-joint (PE-HD) with a milled gap of t = 0.2 mm. At the beginning of the welding process, the temperature signal at the milled gap shows a steep rise in the irradiation-phase as well as in the cooling-phase, because the joining partners do not stay in contact at the milled gap. Heat conduction is therefore disabled, so that only the absorbent polymer is heated. The temperature rises for each scan repetition until the gap is closed. At the time when the gap is closed, the heat balance at the gap-zone is abruptly changed. Due to the emerged contact between the joining partners, the thermal energy is transferred via heat conduction to adjacent zones or leaves the joining zone due to the beginning melt-flow. This constitution causes an immediate drop of the temperature signal at the gap-zone (see Fig. 4, left hand). For further scan repetitions, the temperature signal at the gap reaches the same level as in adjacent zones ($\Delta T < 2$ °C). The amount of scans with a low temperature-difference along the weld trajectory has to be sufficient in order to achieve an appropriate melt layer-thickness within the transparent polymer. Thus a good weld quality can be anticipated.

Potentials of the online temperature measurement

By analyzing the heating of the polymers, the temperature measurement offers a closer look into the process. Primarily, this helps to find suitable parameters for running the process. Thermal damage of the polymers, which can occur predominantly at complex formed weld trajectories like sharp corners, can be detected by the temperature measurement and hence prevented by adjusting the process. More innovative is the fact that an online measurement system can be used for dynamic optimization of the process. Local gaps, which are a result of varying warpage at injection molding, can be detected while running the process. This enables a dynamic adjustment of the process: One possibility is, for example, to enlarge the process-time by increasing the weld set-path in order to close all local gaps and hence to provide a hermetically sealed weld seam. Finally, parts with remaining gaps can be extracted from the process-chain. Subsequent weld seam tests like tightness-analysis can be reduced or omitted without replacement.

Conclusion

For process monitoring of quasi-simultaneous laser transmission welding, the measurement of the set-path is a com-

mon technique. However, the detection of local gaps is not possible. A localized process monitoring is possible by integrating a pyrometer into a 3D-scanner in order to measure the weld seam temperature while welding. Experimental studies on polyethylene (PE-HD) have shown that the temperature signal can be used to identify local gaps even at a high feed rate. Subsequent weld seam tests can be reduced or omitted without replacement. Different thermoplastic materials even with glass-fibers are part of further studies to evaluate the measurement system. In order to measure the temperature for parts with a large format or even with a three-dimensional trajectory, the optical setup will be improved. Furthermore, algorithms for an automatic detection of gaps while welding should be investigated.

*

Controlled 3D Laser-Transmission-Welding of Plastics is funded by Bayerisches Staatsministerium für Bildung und Kultus, Wissenschaft und Kunst. The laser material processing laboratory at Ostbayerische Technische Hochschule and the cooperation partner Bayerisches Laserzentrum, Arges and Inotech are doing research work in controlled laser transmission welding.

DOI: 10.1002/latj.201500029

[1] *S. Hierl:* Laser Transmission Welding of Plastics – Principles, Applications and Process Monitoring, in: Cemal Meran (Ed.), IMSP'2014: 15th International Materials Symposium, Denizli, 1084–1093.

[2] *J. Ackermann:* Prozesssicherung beim Laserdurchstrahlschweißen thermoplastischer Kunststoffe, Meisenbach, Bamberg, 2010.

[3] *S. Reinl:* Radial Welding of Polymer Parts under Closed Loop Process Control: Innovative solutions facilitate faster and controlled process, Laser Tech. J. (2015) 48–52.

[4] *V. Wippo, M. Devrient, M. Kern* et al.: Evaluation of a Pyrometric-based Temperature Measuring Process for the Laser Transmission Welding, Phys. Proc. **39** (2012) 128–136.

[5] *V. Wippo, R. Stähr, P. Jäschke* et al.: Pyrometrische Temperaturüberwachung für flexible scannerbasierte Laserdurchstrahlschweißprozesse, Joining Plastics **8** (2014) 39–45.

[6] *A. Hofmann, S. Hierl:* Methoden der Prozessüberwachung beim Laserdurchstrahlschweißen, in: *M. Geiger* (Ed.), LEF 2005: Laser in Elektronikproduktion & Feinwerktechnik, Meisenbach, Bamberg, (2005) 107–116.

Authors

Anton Schmailzl studied mechanical engineering at Ostbayerische Technische Hochschule Regensburg and received a bachelor and a master degree. In 2012, he received a diploma as international welding engineer from the Schweißtechnische Lehr- und Versuchsanstalt (slv) in Munich. Since 2012 he is research assistant in the field of laser plastics welding at laser material processing laboratory; especially finite element process-modelling, irradiation strategies and process monitoring are part of his research work.

Sebastian Steger studied at Ostbayerische Technische Hochschule Regensburg and received a bachelor and master degree in mechanical engineering. He is research assistant at laser material processing laboratory since 2012. Steger's research topics are in the field of laser plastics welding; especially measurement technology development, process monitoring and online process control are part of his research work.

Stefan Hierl studied production engineering at the universities in Erlangen and Copenhagen. After that, he worked as research assistant in the field of laser material processing at the university in Erlangen. From 2001 to 2006, he was one of the leading figures establishing LPKF's plastic welding division. Mid 2006, Hierl joined the Schaeffler-Group and was responsible for the corporate innovation management. In early 2010, he received a call to the Ostbayerische Technische Hochschule in Regensburg. His subject areas are engineering design and laser material processing. Furthermore, he is head of the laser material processing laboratory.

Anton Schmailzl, OTH Regensburg, Galgenbergstraße 30, 93053 Regensburg, Tel: 0941-943-9876, E-mail: anton2.schmailzl@hs-regensburg.de