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Solutions of laser material processing for electric mobility – evaluation of the Technology Readiness Level

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Abstract

Battery technology and lightweight design are central fields of research and development when it comes to making electric mobility technically and economically attractive for producers and customers. In this context, laser material processing will be a driver to enable innovations in future product generations. For this reason, the publication addresses the most relevant laser-based production technologies that are currently being researched or about to be transferred to applications in electric mobility. In order to give a structured and uniform overview, the advantages of individual processes are mentioned and the technology-specific state of the art is quantitatively presented based on a methodical procedure for the evaluation of the Technology Readiness Levels. Upon this, the challenges for the deployment in industrial production are specified, which is the basis to describe the need for adaption and further development in laser material processing.

Keywords: Technology Readiness Level; e-mobility; lightweight design; battery technology; laser material processing

1. Laser material processing for electric mobility

The transformation of the mobility sector from fossil fuel powered towards electrified vehicles is a necessary step to reduce CO_2 emissions. Higher prices, slower charging capabilities and smaller driving ranges

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are still the main drawbacks of electric compared to fossil-based vehicles. Consequently, research is focused on mass reduction by lightweight designs and on the development of high-performance batteries such as lithium-ion batteries (LIBs) or all-solid-state batteries (ASSBs) to advance zero-emission mobility solutions. New materials, miniaturization, and individualization of components require new manufacturing processes in series production. Laser material processing (LMP) can essentially contribute to reduce production costs or enable new designs and manufacturing potentials due to its high level of flexibility, productivity, and wear-free operation.

LMP can be used, for instance, for advancing lightweight constructions with high mass-specific properties. Conventional metallic structures are partly hybridized using fiber reinforced plastics, whereby the joining of the dissimilar materials and the individualization and sustainable manufacturing of metallic components are in the focus of research. Laser-based surface pre-treatment (LSP) (Roesner, 2014), laser metal deposition (LMD) (Kelbassa et al., 2019) and laser beam welding (LBW) (Das et al., 2018) are related technologies.

In battery production, LMP can speed up charging when modifying cell-internal components of LIBs (Habedank et al., 2019a) and can be used for productively contacting battery cells (Kick et al., 2020) in a flexible and rapid adaptable process. Quality assurance methods like an inline weld depth measurement can be used to ensure high process stability during LBW (Schmoeller et al., 2019). Moreover, LMP advances new battery types such as ASSBs as laser cutting of very brittle solid electrolytes (Schnell et al., 2018) or adhesive lithium metal (Konwitschny et al., 2019) is advantageous compared to conventional technologies.

Within this contribution, relevant laser technologies, which are currently being researched, are evaluated and the Technology Readiness Levels (TRL) is methodically determined. The TRL is intended to enable companies to determine at what point LMP is ready for the use in an industrial environment.

2. Evaluation of the Technology Readiness Level

The systematic analysis of production technologies supports manufacturing companies to identify threats and opportunities as well as technology needs (Greitemann et al., 2016). The structured management of production technologies ensures market competitiveness, especially in emerging fields of application, e.g., battery production (Michaelis et al., 2018). In this context, the term ‘technology’ refers to all manufacturing processes and techniques required for the production of a specific product (DIN 8580). Within this work, to evaluate the maturity of technologies, the method introduced by Reinhart et al., 2011 is used which is based on the concept of the TRL (Mankins, 2009). In this approach, seven TRLs are used to create a maturity profile that determines the required expenditure for research and development along a maturity scale. This scale includes basic research activities (TRL 1), feasibility studies (TRL 2), technology development (TRL 3) and demonstration (TRL 4), integration in production resources (TRL 5) and in environments (TRL 6) as well as the application in serial production (TRL 7) (Reinhart et al., 2011). A detailed description of the individual stages can be found in Schindler, 2015. Company-specific maturity limits need to be assured before integration in the production environment. In the scope of this work, expert elicitations were used to evaluate the maturity of processes, means of production, and sensors used for LMP. Each technology presented hereafter was evaluated in an expert workshop with at least three participants with years of experience in the field of laser manufacturing technology. To account for vagueness in the expert responses, the level of uncertainty was documented, processed by a Monte Carlo simulation, and modeled as a Gaussian standard deviation, represented as error bars in the maturity profiles. The results of the evaluation of relevant technologies from the field of LMP in electric mobility, which are currently addressed in research, are presented in the following in a profile-like manner. In summary, by applying a methodical technology assessment approach, this publication identifies necessary research and development directions and contributes to the industrialization of laser technologies.

3. Additive manufacturing using laser metal deposition with coaxial wire feeding

Additive manufacturing of metals is currently the subject of intensive research and development in both industry and science. Moreover, new areas of application are still emerging through specialized additive manufacturing processes such as wire-based coaxial LMD. In LMD processes, powder or wire is continuously and locally fed to a substrate into a laser-induced molten pool, as shown in figure 1a. The process is commonly used to apply protective coatings, to additively build up complex structures, and to repair worn or damaged components. Powder-based LMD processes are disadvantageous because of the low degree of material utilization and the hazardous effects of metal dust on the operator, the machine and the environment (Teichmann et al., 2021). The use of wire as feedstock, in contrast, enables a material utilization of 100 %, while the effort required to protect the operator and the environment is significantly reduced. A relevant step towards the industrial relevance of wire-based LMD is represented by recent developments in laser optics that enable coaxial wire feeding in the center of an annular laser beam profile (Govekar et al., 2018; Motta et al., 2018; Kelbassa et al., 2019). In the following, the TRL of the *LMD process using optics with coaxial wire feeding* will be evaluated.

As shown in figure 1b, the theoretical foundations like the laser beam propagation through the optical system and the interaction between the laser beam and the wire have been investigated in depth, along with feasibility studies of the process (levels 1 and 2). There is still the need for further investigations and developments (TRL 3) to increase the process reliability as needed for production-related applications. So far, the technological demonstrators (TRL 4) are mainly restricted to parts built for academic purposes. However, successful approaches to the integration into production facilities (TRL 5) have already been demonstrated. The substantial increase in the maturity from TRL 4 to 5 can be explained by the fact that the basic technical systems that are used in this process are already qualified for industrial applications (laser, wire feed unit, etc.). Currently, there is still a low degree of automation of LMD and most processes lack reliability, so further qualification is needed before a standardized industrial use is possible (levels 6 and 7).

One of the main challenges of the process is that the implementation of a new system as well as changes in influencing parameters, e.g., through the use of a different material, require extensive parameter studies to achieve a stable process. For this reason, suitable closed-loop control approaches are currently an important part of research and development in LMD processes (Wang et al., 2020). In this context, the qualification of sensor technology for the real-time monitoring of process variables is crucial. This enables an inline quality assurance, which eliminates the need for expensive subsequent inspections of the built parts. Thus, these efforts contribute to accelerate the qualification of the LMD process with coaxial wire feeding for industrial series production.

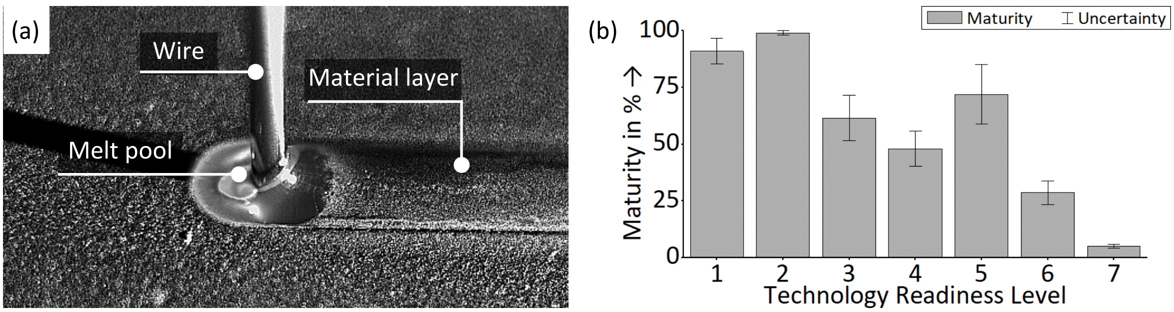

Fig. 1. (a) High-speed camera image of laser metal deposition using coaxial wire feeding and (b) quantitative evaluation of the Technology Readiness Levels for laser metal deposition using coaxial wire feeding

4. Laser-based surface pre-treatment for joining metals and (reinforced) plastics

LMP has already been providing support for several years by *pretreating the metallic surface to improve the bonding properties to polymers*, such as strength (Wunderling et al., 2020) or tightness (Heckert et al., 2016), as shown in figure 2a. In literature, explanations often base on geometric (Schricker et al., 2020) and chemical modifications of the surface (Heckert, 2019) that positively influence the adhesive bonding properties. Correspondingly, a wide variety of LSP methods has been explored, including a (sub-)microscopic ablation of material, the creation of surface structures by rearranging molten metal (Heckert and Zaeh, 2014) and additive manufacturing processes (Chueh et al., 2019). The following quantitative evaluation of the technological readiness is oriented towards a subtractive modification using pulsed and continuous-wave (cw) laser radiation as the dominant area of research.

LSP has already reached a high overall maturity level of 69 %. In figure 2b, showing the sequential development levels, a typical maturity profile is represented, indicating thorough and structured research into theoretical fundamentals (levels 1 and 2) up to the demonstration of the technological implementation (levels 3 and 4). Especially in scientific environments, comprehensive knowledge has been gained about the interaction of the laser radiation and the material, the resulting material removal and the interaction of topography design as well as the properties of the joint, especially strength. Within the investigations, different types of environmental and mechanical testing were carried out focussing on the tensile shear strength. The technical implementation mainly bases on commercially available system components. Thus, the integration of the technology into an operating device (TRL 5) can be classified as sufficiently qualified. In contrast, the qualification of the technology (TRL 6) based on industrial requirements for serial applications and the further optimization (TRL 7) show a sharp drop in the profile of technology readiness.

The TRLs 6 and 7 indicate that the technology has not yet been widely established in industrial use. In addition to financial aspects, it is not sufficiently qualified towards the partly industry-specific, technical requirements – the productivity of the processing, the complexity of the defined geometry or the quality of the joint. For this reason, a combination of process acceleration and high-performance systems will be necessary to process at higher area rates. At the same time, the geometric constraints for processing surfaces must be expanded and as investigated by Wunderling et al., 2019 the thermal distortion as a consequence of the pre-treatment has to be considered. In order to ensure the surface quality under the industrial manufacturing conditions, an efficient quality assurance for the pre-treatment and the joining process is necessary. Integrable measuring systems, whose inline measurement enables process control, are an elegant approach in this case. Finally, to qualify the technology for series applications the range of mechanical test methods has to be expanded with regard to different load cases and test conditions. Furthermore, the use of non-destructive methods, which has not yet been considered in detail, can be a chance for inline quality assurance.

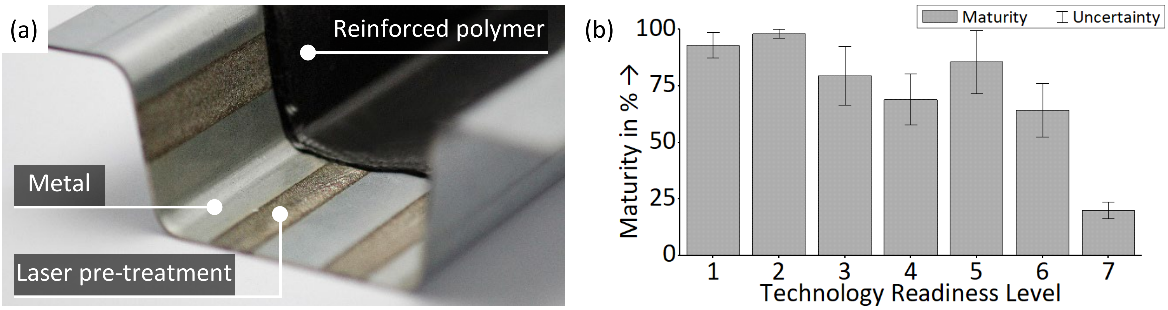

Fig. 2. (a) Technology demonstration of metal-plastic hybrids with applied laser pre-treatment and (b) quantitative evaluation of the Technology Readiness Levels for laser-based surface pre-treatment

5. Digital laser beam welding

In the following, *digital laser beam welding (DLBW)* is referred to as a process using a system for the inline acquisition of process variables, based on which quality characteristics relevant for the individual application can be derived and utilized at the runtime of the process. To a large extent, optical methods are used for process monitoring during welding (Purtonen et al., 2014). The high intensities prevailing in the process zone, however, impede the direct detection of process variables. The use of low coherence interferometry allows dimensional quantities to be recorded to a large extent independently of process emissions. This enables precise and temporally highly resolved geometric measurements to be conducted to assess the surface topography (Stadter et al., 2019) and the capillary depth (Schmoeller et al., 2019). It was shown that the surface quality can be predicted based on the measured weld depth profile, demonstrating the suitability for a comprehensive assessment of quality-relevant process variables during LBW (Stadter et al., 2020). However, to be able to derive adequate and reliable operating variables from the complex signal structure of inline data, a holistic investigation of the necessary data processing pipeline, as outlined in figure 3a (based on VDMA, 2020), is required.

The analysis of already demonstrated approaches and systems in terms of DLBW showed an advanced level of development, which suggests an industrial application in the near future. As can be seen from the technology readiness profile in figure 3b, the theoretical fundamentals (TRLs 1 and 2), which include the sensory recording of relevant process variables and data processing methods, have already been covered to a sufficient depth. In level 4, there is a clear drop in the maturity level. This can be attributed in particular to the need for further research into the evaluation of available systems for the entire process window and the fact that prototypes have not yet been used in a real production environment. While the integration into a production facility, assessed in level 5, can be classified as sufficient, there is still a clear need for action in the qualification of the technology for series use in level 6 (production structure), which is the basis for a subsequent optimization in series use (TRL 7).

An overall maturity level of 58 % (with a scatter of about 6 % around the mean value, which can be regarded as an ordinary uncertainty in the TRL evaluation) shows that a near-series maturity level has already been reached and indicates that the concept of DLBW can be transferred to series application. Further development is required in particular in level 4, the technology demonstrator, and in level 7, the optimization for series production. Based on a technology demonstrator, the evaluation for the full spectrum of possible process and environmental boundary conditions has to be conducted in series production facilities. Based on the process model outlined in figure 3a (based on VDMA, 2020), there is a broad understanding of the steps 1 to 4, incorporating business and data understanding, data preparation and modeling. To ensure reliable operation, however, action is required in the subsequent steps of field testing (step 5), product deployment (step 6), continuous data collection (step 7) and maintenance over the entire service life.

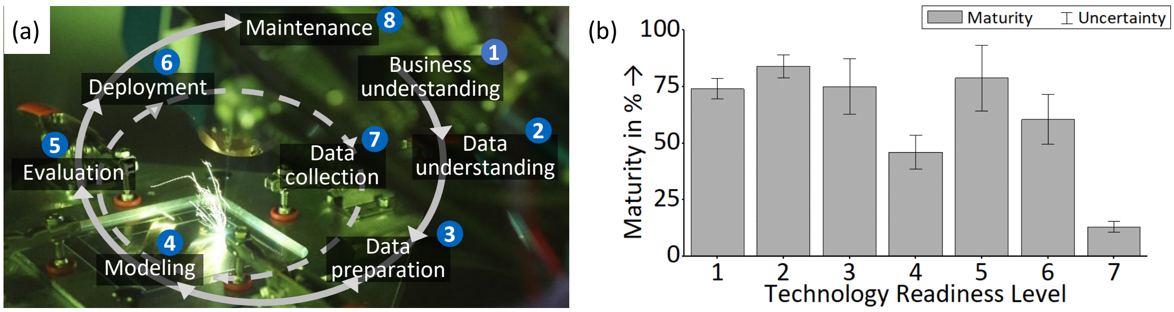

Fig. 3. (a) Process model for the implementation of the concept of digital laser beam welding throughout the entire service life (based on VDMA, 2020) and (b) quantitative evaluation of the Technology Readiness Levels

6. Laser beam welding for the production of power electronics

Power electronics are used for the transformation of electrical energy and play an important role in the powertrain of electric vehicles. Inverters, for example, transform the direct current provided by the battery storage system into an alternating current that is required for the electric motor (Afonso et al., 2020). A copper-plated ceramic tile can be used as the carrier for the integrated circuits and connections of the power electronic module. Ceramics (e.g., Al_2O_3, AlN) are characterized by a low coefficient of thermal expansion and provide a good durability for high-temperature operating conditions of up to 200 °C (Tuan et al., 2014). The demand for compact modules leads to an increase in power density and poses a challenge to manufacturers. Due to its high flexibility and precision, LBW opens up new possibilities for the design and manufacturing of power electronics. In early studies, a laser beam source and scanning optics were successfully integrated into a conventional ribbon bonding machine. The copper ribbon was held in position by a clamping device and joined using LBW on a metalized ceramic substrate (Mehlmann et al., 2014) and a silicon carbide semiconductor (Pavliček & Mohn, 2020). To avoid thermally induced damage to sensitive substrates, Laser Impulse Metal Bonding (LIMBO) was developed as an alternative method. For this process, the joining partners are arranged in an overlap configuration and thermally decoupled from each other by a predefined gap. Temporal power modulation is used to bridge the gap and achieve a bond with the substrate (Britten, 2017). Copper has an increased absorptivity for radiation in the visible wavelength range compared to infrared radiation. New laser beam sources designed to exploit this property have been developed in recent years and enable the joining of copper with high process efficiency (Haubold et al., 2018). Figure 4a shows a metallographic cross-section of a copper joint on a ceramic substrate using green laser radiation at a wavelength of 515 nm.

The evaluation of the current technological maturity level for *LBW in the production of power electronics* provides an outlook on future actions in research and development. The TRL profile in figure 4b shows that the highest maturity level is reached in level 1. Although there are continuous technological advances concerning the laser beam sources, the fundamental aspects of LBW are well known. The decrease in maturity in levels 2 and 3 indicates that further experimental investigations are necessary with consideration to the characteristics of the workpiece, such as the properties of the substrate and the metalized semiconductor. In TRL 5 an increase in maturity compared to TRL 4 can be observed. Since the joining partners are thin and, in the case of the substrate, even brittle, a suitable and thorough positioning of the workpiece is required. The already mentioned modification of industrial bonding machines is an easy way to implement the process. However, further adaptations are necessary to be able to join complex geometries. To achieve a sufficient degree of maturity in levels 6 and 7 and thus a successful industrialization, suitable methods for automatic inline quality assurance must be developed. This ensures that the high productivity of LBW can be fully exploited to reduce manufacturing costs and enable innovative products in the future.

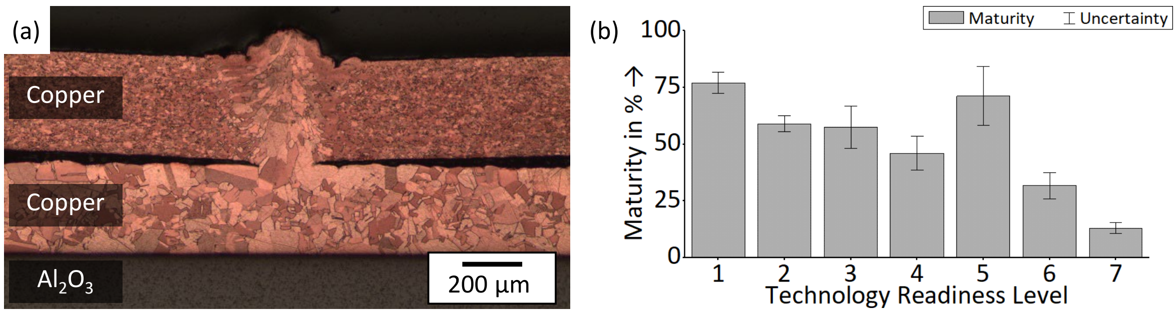

Fig. 4. (a) Metallographic cross-section of a joint made with continuous-wave laser beam radiation and (b) quantitative evaluation of the Technology Readiness Levels of laser beam welding for the production of power electronics

7. Laser beam welding for the contacting of lithium-ion batteries

In lithium-ion cell-based battery storages, up to several thousand electrical contacts have to be manufactured (Brand et al., 2015). As a feasible joining process, LBW is characterized by a high degree of automation, a low cycle time, and a precise local energy input (Das et al., 2018). Challenges arise in the processing of highly electrically and thermally conductive materials, such as aluminum and copper (Kick et al., 2020). Especially copper and its high reflectivity in terms of near-infrared wavelengths were issued in several publications as well as the advantages of the use of visible laser beams (Kaiser et al., 2015; Kick et al., 2017), as shown in figure 5a. The investigation described in the following assessed the TRL and provides an overview in figure 5b. It refers to the *LBW for the contacting of LIBs* without any special emphasis on laser beam sources and materials.

Laser beam sources as a tool for material processing, especially welding, have been investigated for years and are well established. Therefore, the theoretical fundamentals (level 1 and level 2) are estimated with an almost full coverage, so that the TRL 1 and 2 for this process have already been reached. Specifically in terms of the contacting of LIBs, numerous studies examined the welding process with respect to various material combinations of the cell terminal and its accompanying connector using different laser beam sources. Therefore, the mean of the maturity for the technology development of this process application is estimated with a lower but still sufficient value for TRL 3 than for TRL 2. As not every system technology and process window are fully investigated, the technology demonstrator level of stage 4 attains a lower coverage than the previous levels. For experimental investigations on LBW for contacting, it is necessary to build an experimental setup. As the beam deflection unit and the safety periphery must be of industrial standard for laser material processing, the integration into operating devices in level 5 is automatically mostly covered. The step from laboratory experiments to industrial applications has already been done in a few battery module production lines, which results in the high and sufficient coverage for TRL 6. As only a small amount of companies uses the LBW for the cell-external contacting, a lack of industrial optimization can be assumed. Hence, the technology maturity of the level 7 shows only a minimal estimated coverage and, therefore, a need for further development. In summary, an overall maturity of this technology of 74 % with an uncertainty of 6 % was estimated in the scope of this investigation.

From the TRL overview in figure 5b, it can be seen that LBW for the joining of LIBs and cell connectors is about to achieve the technological maturity to enter serial or mass production. A need for action can be identified in level 4 and level 7 as these values do not reach a sufficient maturity for the corresponding TRLs. In terms of level 4, the process windows for potentially advantageous, novel beam sources as well as for challenging material combinations have to be investigated more deeply. To increase the sustainability in serial production, an inline quality assurance is inevitable. Such systems provide a high potential for cost savings in production, as they precisely localize defects which can be reworked. The information acquired by the sensor can also be used for a (closed-loop) process control.

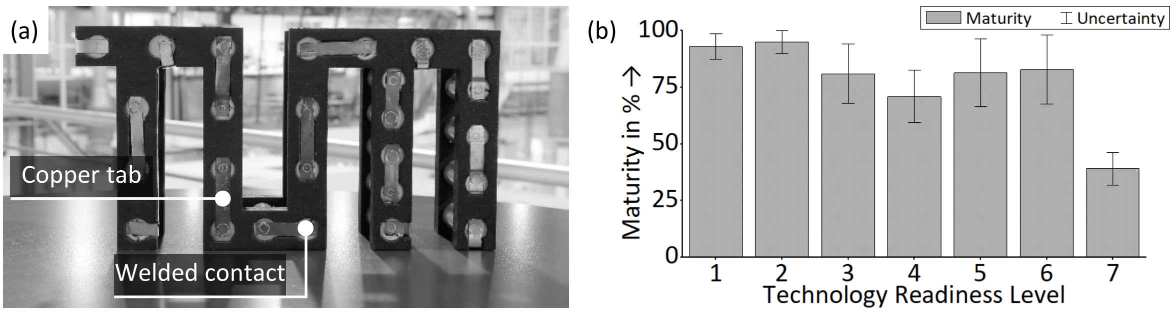

Fig. 5. (a) Welded battery pack demonstrator using green laser radiation and (b) quantitative evaluation of the Technology Readiness Levels for cell-external contacting of busbars in lithium-ion battery production by laser beam welding

8. Cell-internal contacting of lithium-ion batteries

Laser processes are promising with repect to the *cell-internal contacting of LIBs* (Das et al., 2018). In this production step, the uncoated parts of the metallic current collector foils of the electrodes are welded to an arrester tab and, thus, mechanically and electrically connected, as shown in figure 6a. Commonly, ultrasonic welding is used for joining the electrodes. Compared to this contacting process, laser welding improves the seam properties and enables novel product designs by higher geometric flexibility (Schedwey et al., 2011). The high reachable welding speeds using laser technologies contribute to an industrially scalable process. Besides laser beam sources emitting in the infrared and visible wavelength spectrum, different welding strategies, e.g., cw and pulsed welding, were investigated (Mohseni et al., 2019; Grabmann et al., 2020).

In the context of cell-internal contacting, the evaluation of the TRLs included the design of the process, approaches for quality monitoring, and the construction of feasible clamping devices for the contacting of aluminum and copper foil stacks. Figure 6b shows the determined TRLs. In-depth investigations have already been carried out on LBW of aluminum (Oladimeji et al., 2016) and copper (Leitz, 2015) materials, contributing to high values at level 1 and level 2. The theoretical fundamentals of micro-welding processes have been studied (Schmitt, 2012). Previous research has proven the suitability of laser welding processes for joining metal foils (Patschger, 2016; Standfuss et al., 2010). The limited knowledge about the relevance of some input parameters, e.g., the number of foils, and a research gap in modeling the electrical seam properties, leads to lacking fulfillments in TRL 3 and TRL 4. Furthermore, there is a need to reduce process irregularities. For example, cracks occurring in the seam adjacent zone, when joining aluminum foils, have to be minimized. In evaluating the technology readiness at level 4, the missing validation of the technology in large-format batteries was included. The influence of the contacting process on battery properties, such as the power density, has to be evaluated experimentally. Level 5 is classified as advanced compared to levels 3 and 4. The high degree of readiness at level 5 can be explained by the strong application orientation of the assessed technology. The laser welding process has to be investiged in an environment similar to production, and other processes in the manufacturing chain for LIBs have to be considered. An evident decline in the technology readiness was seen at TRL 6 and TRL 7, as the technology has neither been qualified so far nor optimized within an industrial serial production.

To increase the maturity at the levels 3 and 4, further investigations on suitable process parameters for a varied number of foils and the analysis of the thermal cell load during joining have to be carried out. In addition, the technology has to be verified on large-format LIBs. Using cell tests at high current to simulate rapid charging, the influence of the laser-based contacting on the electrical resistances can be validated. The transfer to an industrial production facility (level 6) is necessary to reflect industrial conditions and to increase the overall maturity of the TRLs. Here, the development of an automated clamping system and the consideration of connections to up- and downstream processes are seen as essential tasks.

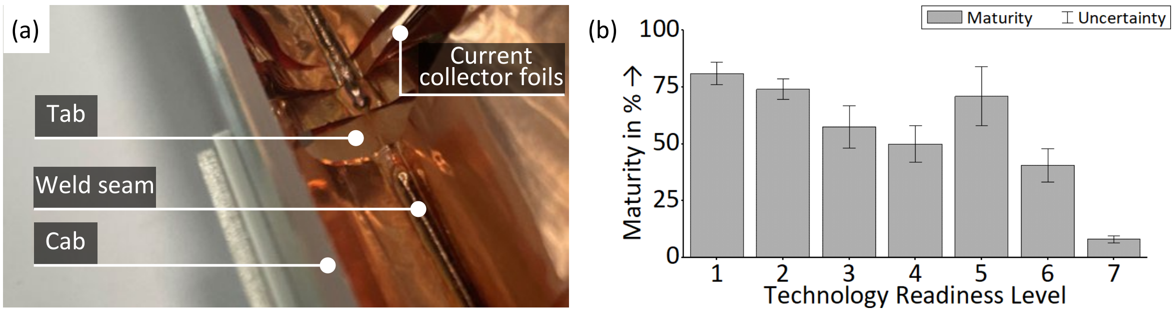

Fig. 6. (a) Laser-contacted cell-cap of a lithium-ion battery and (b) quantitative evaluation of the Technology Readiness Levels for cell-internal contacting of lithium-ion batteries using laser beam welding

9. Laser structuring of battery electrodes

Thick and highly compressed electrode coatings, which increase the proportionate share of active materials in comparison to passive materials such as the casing, enhance the energy density of a LIB. They, however, suffer from a decreased fast-charging ability caused by diffusion limitations in the electrodes. This conflict can be addressed by the introduction of microscopic holes in the electrode coatings as shown in figure 7a. Short-pulsed laser beams are a versatile tool for the creation of such structures with micrometer precision (Habedank et al., 2018a). Besides the enhancements of the charging and discharging performance of batteries with structured electrodes (Habedank et al., 2019a), an increase in the lifetime could be shown in empirical studies (Chen et al., 2020). Furthermore, a facilitated wetting with electrolyte was achieved through laser structuring of electrodes (Pfleging & Proell, 2014; Habedank et al., 2019b).

The assessment of the TRL of the *laser structuring process for battery electrodes* yielded an overall maturity of 54 % ± 4 %. The TRLs 1 and 2 show high maturities, as can be seen in figure 7b, reflecting the general feasibility and electrochemical benefits of electrode structuring. These fundamental insights were obtained through extensive empirical studies (Habedank et al., 2019a) and electrochemical simulations (Habedank et al., 2018b; Kraft et al., 2020). A decline can be observed for the TRLs 3 and 4 due to a limited knowledge about product process correlations and potential interdependencies with adjacent processes in battery production. The integration into a functional demonstrator, as assessed in TRL 5, can be classified as sufficiently given, which explains the increase in the maturity from TRL 4 to TRL 5. In the further qualification of the technology in TRL 6 (production structure) and particularly in TRL 7 (optimization in series application), a clear decline in the maturity can be seen. This is due to the fact that no prototype has been integrated into an industrial production environment so far.

Although the maturity in the field of fundamental investigations (TRLs 1 and 2) is already comparatively high, there is a need for deepened insights regarding the impact of electrode structuring on varying substrate materials and cell chemistries. In addition, providing an understanding of process-to-product correlations and the underlying thermophysical ablation phenomena is still due. From the pronounced decline of the maturity in the TRLs 6 and 7, various fields for further research and development can be deduced. In order to meet the throughputs of electrode manufacturing in battery production, a strong increase in the process speed of laser structuring is required. It can be achieved by novel scanning technologies such as polygon scanners (Habedank et al., 2020) or multi-beam approaches based on diffractive optical elements. A further challenge lies in the coupling of the laser structuring process with the continuous roll-to-roll processes in electrode production. In order to address these challenges and optimize the involved system technology, an integration of laser structuring into an industrial battery production line with continuous electrode manufacturing is required. To meet industrial quality standards, process observation methods need to be identified and implemented. Ultimately, the economical impact of laser electrode structuring on the overall manufacturing costs of LIBs needs to be quantified.

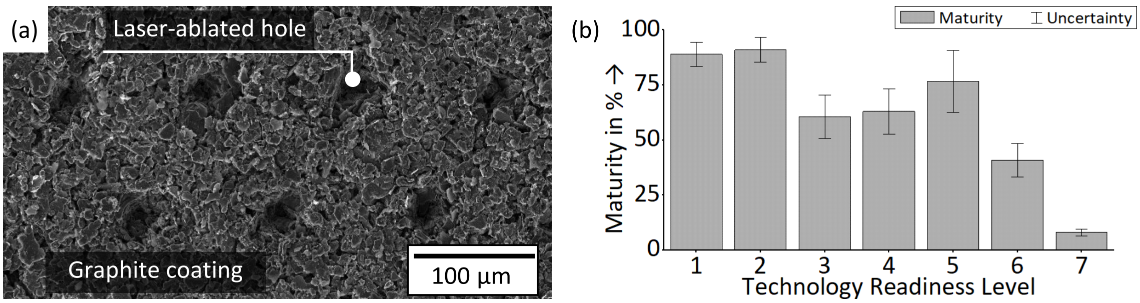

Fig. 7. (a) Scanning electron microscopy image of a laser-structured graphite anode and (b) quantitative evaluation of the Technology Readiness Levels for laser structuring of battery electrodes

10. Laser micro-cutting in the production of all-solid-state batteries

Due to appealing performance characteristics, e.g., the high energy density, the ASSB is seen as a promising battery technology (Zhao et al., 2020). Although market availability of ASSBs is expected within the next years (Varzi et al., 2020), no production routines have been established so far. However, in any case, cutting processes are expected to be part of the process chain (Schnell et al., 2018). Due to the high quality requirements, laser micro-cutting is investigated, which is also increasingly established as the state-of-the-art separation process in LIB production (VDMA, 2020). For an introduction into ASSBs, the electrodes and the solid electrolyte layers must be cut to shape, as shown in figure 8a. The solid electrolytes can be polymeric, ceramic, or glass-ceramic materials (Janek & Zeier, 2016). Depending on the respective material group, the laser system technology and the process parameters must be adapted. Furthermore, in ASSBs, the highly reactive lithium metal is used as anode material (Cheng et al., 2019), which requires the integration of the production equipment into an inert gas atmosphere. While for LIBs cause-effect relationships between the cutting process and quality characteristics of the cutting edge, e.g., the formation of a burr and the heat-affected zone, have been studied experimentally (Kriegler et al., 2021) and by simulation (Lee et al., 2013), only a few investigations are known for the ASSB materials.

For the evaluation of the TRLs of *laser micro-cutting in the production of ASSBs*, the process design, the product-side requirements, and the production-related boundary conditions were considered. As visible in figure 8b, a high maturity accounts for comprehensive basic studies on the beam-matter interaction of cw and pulsed laser radiation with polymers, metals, ceramics, and glasses. Due to the novelty of the ASSB materials, neither process windows nor system technologies were defined yet, which leads to a low maturity in TRL 2. The development of feasible processes for the respective materials, taking into account product-side requirements (TRL 3) and an in-depth analysis of system interrelations, e.g., between the cutting process and the obtained quality features (TRL 4), are still required. As the integration of the technology in functional demonstrators is addressed in scientific and industrial R&D projects, e.g., by equipment manufacturers, the maturity of TRL 5 is comparatively high. Due to special production requirements like an argon-atmosphere in ASSB production, technology demonstrators will enable the further evaluation of process-to-product interdependencies. The low maturities at TRL 6 and 7 account for the lack of industrial production of ASSBs.

To establish laser cutting in the mass production of ASSBs, a knowledge transfer from the processing of thin-film materials is needed. Parameter studies must be performed and laser-cut material layers must be integrated into ASSBs to quantify quality measures (TRL 2). The material diversity can be managed by deducing suitable system technology from similar industries (TRL 3) and by identifying interactions between the production equipment, the process, and the product (TRL 4). The integration of system technology into production demonstrators enables in-depth investigations under near-series production conditions. Once upstream process steps in ASSB manufacturing are defined, the integration into pilot and industrial-scale equipment considering the periphery and quality monitor systems should be initiated (TRLs 6 and 7).

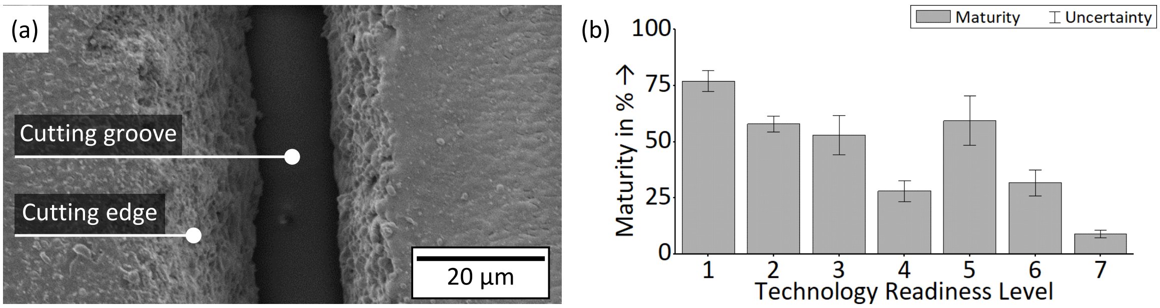

Fig. 8. (a) Laser-cut edge of a ceramic solid electrolyte processed with a picosecond pulsed laser system and (b) quantitative evaluation of the Technology Readiness Levels for laser micro-cutting in the production of all-solid-state batteries

11. Potential of laser material processing

The presented use of LMP in the field of electric mobility contributes to a significant improvement in a lot of applications. They include enabling fast charging through the cell-internal contacting of current collector foils, the introduction of microscopic structures, and the additive manufacturing of structural components. Besides enabling enhanced functionalities, laser-based manufacturing processes also reduce costs due to their high processing speed and wear-free operation. In addition, robust and reliable processes significantly improve the sustainability of the manufactured components. From a consideration of the various applications of laser radiation, four major trends can be identified: new fields of application, sustainable production, cheaper beam sources, and digitization.

In electric mobility, LMP is indispensable. This could also be conceivable in the long term for the production of fuel cells since processes for cutting, surface modification, and joining are also needed in this field – even for new materials. Further challenges arise in the processing of glass and other brittle materials as they are difficult or impossible to machine with conventional mechanical procedures.

In addition to stable and reliable manufacturing techniques to avoid scrap, other processes, such as rework or disassembly, will also be required for a sustainable production. Laser processes allow for rework due to their high flexibility. Due to the high precision of the beam positioning, it is possible to separate components without harming the surrounding environment. This can allow for a disassembly process for products that cannot be disassembled otherwise. As a result, laser-based applications promote the circular economy.

According to Gefvert et al., 2020, laser technology is experiencing a steady sales growth. In this context, low-cost diode lasers not only exhibit growth in sales but also in beam quality. For fiber and disk lasers to be economically competitive in the long term, a price decline can be expected.

Digitization effects all the fields already mentioned above. For safety-critical products, such as battery storages or fuel cells, a 100 % quality assurance is essential. To be economically competitive, this can only be done by inline process monitoring and suitable evaluation algorithms. Rework of products is a highly individual task. Therefore, possible defects have to be detected by suitable sensor technologies, and an individual rework strategy has to be planned by approaches of Artificial Intelligence. For the beam sources, digitization offers the opportunity to extend their availability through predictive maintenance and to increase the throughput through data-based optimization.

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