Ultrafast laser structuring of electrodes to boost electrochemical performance of lithium-ion batteries

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Immense global efforts are currently being directed toward significantly increasing the demand for lithium-ion battery (LIB) manufacturing. In Europe alone, gigafactories with a total annual production capacity of around 2 terawatt-hours are planned. To map next generation batteries, novel processes must be developed and modularly coupled with battery manufacturing equipment. Within this scope, laser technology possesses the potential to prove itself as a key technology. Especially the ultrafast laser structuring of composite electrodes is attracting increasing attention across research and industry [1]. The advantages of this approach cover increased production reliability, improved battery safety, and enhanced electrochemical cell performance. Regarding the latter, battery lifetime, fast-charging capability, and high-power battery usage can be improved. Subsequently to the coating process in electrode production, laser structuring is used to apply the three-dimensional (3D) battery concept to thick-film electrodes. For the first time, high-energy density LIBs can be designed which simultaneously maintain high-power performances. Thus, the so far commonly known trade-off between energy and power density in LIB technology is resolved. For creating 3D electrode architectures, either hole, line, or grid patterns are feasible. Hereby, the micro-structuring of the coating down to the current collector (Fig. 1a) provides the highest benefit. However, the material loss due to structuring must be kept minimal, especially regarding the cathode which significantly contributes to the overall battery material costs. Therefore, generating high-aspect ratio features are aimed at which requires the use of ultrafast laser radiation (Fig. 1a). Using fs or ps laser ablation enables a damage-free structuring process with suppressed debris formation. At the Karlsruhe Institute of Technology (KIT) pioneering work in the field of laser structuring of electrodes for LIBs is performed. Thereby, it was shown, that line patterns with pitch distances of several hundred micrometers make electrodes superwicking for the liquid electrolyte. As a result, inhomogeneous wetting with dry electrode areas is avoided which can initiate electrochemical degradation and cell failure. Due to the novel 3D electrode architectures, new diffusion pathways in the liquid electrolyte are activated at high charging and discharging rates. The tortuosity of the electrode is reduced, the diffusion kinetics of lithium-ions significantly increased, and overpotentials can be decreased. In addition, lithium plating can be delayed or even avoided enabling a tremendous improvement in battery operation at high currents and low temperatures. The transition of the 3D battery concept to large scale battery production requires advanced laser and optical concepts. Roll-to-roll processing of electrodes coupled with multibeam laser processing using diffractive optical elements is essential to meet the high throughput (Fig. 1b) [2]. At TRL 6, a laser machining system is established at KIT with which large-format demonstrator pouch cells were successfully manufactured possessing the aforementioned beneficial performance characteristics.

(a) (b)

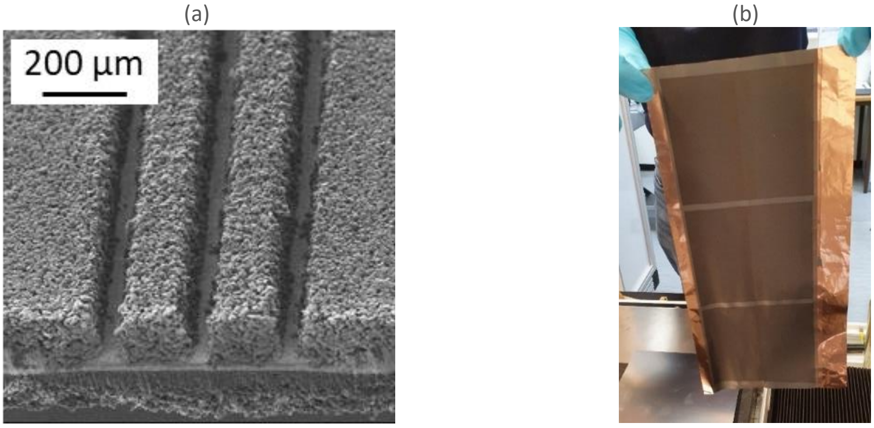

Figure 1 (a) SEM image of fs laser-structured composite anode with flake-like graphite as active material and (b) photograph of a large-area fs laser-structured electrode sheet.

[1] W. Pfleging, Recent progress in laser texturing of battery materials: a review of tuning electrochemical performances, related material development, and prospects for large-scale manufacturing, Int. J. Extrem. Manuf, 3., pp. 1-20, (2021)
[2] A. Meyer, Y. Sterzl, U. Rädel, S. Xiao, M. Zenz, D. Schwab, W. Pfleging, "Laser structuring of electrodes in roll-to-roll environment using multi-beam processing: process upscaling and its perspective, Proc. of SPIE, 12409, pp. 0J-1 - 0J-9, (2023)