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Laser cutting of pure lithium metal anodes

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Abstract

Aiming at a high performance lithium-ion battery, all process steps and materials have to be improved. Lithium metal is the most promising material for future anodes since their high theoretical capacity of 3860 mAh/g and their low density of 0.534g/cm^3. Apart from the current low cycle stability, challenges lay in the separation and the handling of lithium. Due to its toughness and adhesive properties, lithium metal anodes can not be separated by conventional processes (e.g. punching) within a high volume production. The most promising way to produce anodes with high-quality cutting edges in high numbers is laser cutting. The presented experiments show that in certain atmospheric conditions high-quality cutting edges can be produced with a pulsed fiber laser.

Keywords: Cutting; lithium; battery systems; electromobility

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1. Introduction

The future mobility development is characterized by a high demand towards resource-conserving, efficient, climate-friendly and environment-friendly technology. Mobility devices with an electrical drive system show the greatest potential to meet these requirements, so that the systematic expansion at the vehicle, infrastructure and battery level is promoted.

For efficient and ecological lithium-ion battery production, all production process steps have to be improved in terms of quality, performance and costs, or made more efficient by new technologies. The requirements profile of these technologies is defined by the geometry and structure of the cell as well as the product properties of the cell components, which differ for the different applied electrochemical system. Due to the high volumetric energy densities, pouch cells with alternately stacked anodes and cathodes are of

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particular interest for the ongoing mobile electrification. For such cell systems, it is necessary to separate single electrodes from the endless battery foil for the following stacking process. For this purpose, the punching process is mainly used due to high experience values from other application areas. For new systems with highly abrasive particles or lithium metal anodes, punching reaches its limits because high-quality cutting edges can no longer be produced reproducibly due to wear and contamination of the punching tool. As a further advanced technology, laser cutting is seen as a flexible and contactless as well as wear-free process for the high-reprocessing assembly of electrodes. In this case, laser cutting has the potential to achieve higher cutting qualities with longer service lives than with the previously established punching methods [Rahimze et al., 2015].

2. State of the art

2.1. Electrochemical system

Due to the increasing requirements on lithium-ion batteries, in terms of energy density, cycling stability and safety, established electrochemical systems must be improved and in addition, new systems must be developed. A promising cell system compared to the conventional liquid lithium ion cells, with lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA) or lithium iron Phosphate (LFP) cathodes and graphite anodes, are all-solid-state Li-ion batteries (ASLiBs). As a solid electrolyte, a ceramic or polymer is used which replaces the liquid light-flammable electrolyte. The high stability of the solid electrolyte allows the application of lithium metal anodes. In conventional lithium-ion systems with liquid electrolytes, lithium metal anodes are not stable because the electrolyte decompose the lithium metal anode. For that reason the advantages of lithium metal anodes can only be exhausted for future commercial applications in ASLiBs [Korthauer, 2013], [Wu et al., 2016], [Zhu et al., 2016].

Advantages of lithium metal anodes are the high theoretical capacity of 3860 mAh / g and their low density of 0.534g / cm^3, which is the lowest density of all solid elements. Due to the high capacity and low density, very thin and light anodes can be realized which enable cells with high energy densities. Because of high interfacial resistance between electrolyte and electrode there are still issues to exploit the high capacity which is expressed in form of limited power and charging performance [Zhu et al., 2016], [Zhang et al., 2017].

2.2. Laser cutting in lithium ion battery production

Remote Laser cutting of conventional lithium-ion battery foil (NMC, NCA, LFP cathodes or graphite anodes) is a method widely discussed in the scientific landscape for separation of electrodes [Lee et al., 2013],[Luetke et al., 2011 // 2014],[Reincke et al., 2015]. However, to date, the electrodes have mainly been punched, since the contamination of metal spatters and active material particles is not sufficiently investigated, and thus the contamination effects on a production line can not be predicted. With regard to the separation of lithium foil, there are currently no scientific investigations, since only a small number of lithium anodes are needed on the research level and the influence of the cutting edge is not focused in any investigations. Furthermore, the commercial application of ASLiBs with lithium anodes is in the long term, so that no further studies are available for efficient and ecological mass production.

For the separation of lithium Anodes, simple manual punching / cutting tools are used in the laboratories. These have to be cleaned up after only a few applications because the adhering lithium does not allow a reproducible cutting edge (figure 1.). Unfortunately, the separation and handling of lithium metal anodes must be carried out under certain operating conditions. Based on the high reactivity of the lithium with water to lithiumhydroxid and hydrogen cell manufacturing is only possible under protective atmosphere. Furthermore due to its toughness and adhesive properties, lithium metal anodes can not be separated by conventional processes (e.g. punching) in large numbers. This is due to the fact that the stamping tool is contaminated by adhering lithium and the cut is thereby impaired. As a contactless method, laser cutting is thus to be regarded as a key technology, which will enable a high automation and throughput speed.

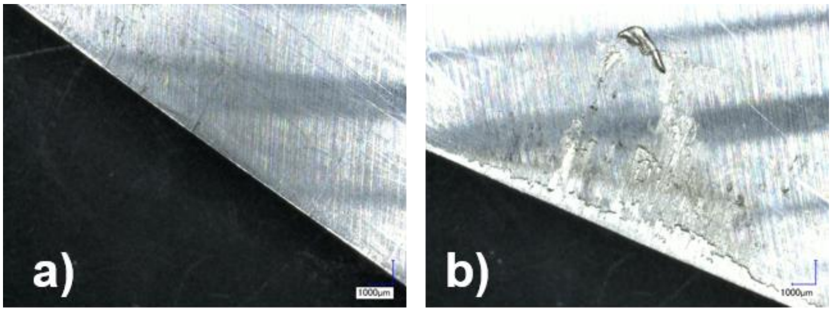

Fig. 1. a) Unused cutting tool; b) Contaminated cutting tool after 5 cuts

3. Experimental set-up

Within these studies, a fiber laser (1062nm) with an average power of 72 W and a peak pulse power of up to 13 kW (G4 Pulsed Fibre Laser, SPI Lasers UK Ltd, Southampton, United Kingdom) was applied to investigate the influence of the laser and process parameter on the cutting edge quality. The remote process is realized by means of two orthogonally arranged mirrors and a focus tracking. This allows traversing of contours with high accuracy and very high cutting speeds.

The experiments and measurements were carried out in an atmosphere with a dew point of -30 °C to minimize the lithiumhydroxid and hydrogen formation. Concerning safety issues laser cuts were only realized in small foil sheets with a size of 50 mm to 100 mm to minimize the explosive material in case of a uncontrolled reaction. The lithium sheets were placed on a flat sanded steel plate in focus level of the laser. In the cutting area the steel plate is grooved to avoid a reaction with respectively welding on the steel plate.

For the cutting experiments lithium metal foils (Rockwood Lithium) with a thickness of 50 µm were applied. The influence of cutting speed and pulse repetition rate on cutting edge quality were investigated considering the width and the superelevation of melt formation. The cuts were characterized using a light microscope (Keyence VHX 2000) and a laser scanning microscope (Keyence VK-X Series 3D Laser Scanning Confocal Microscope).

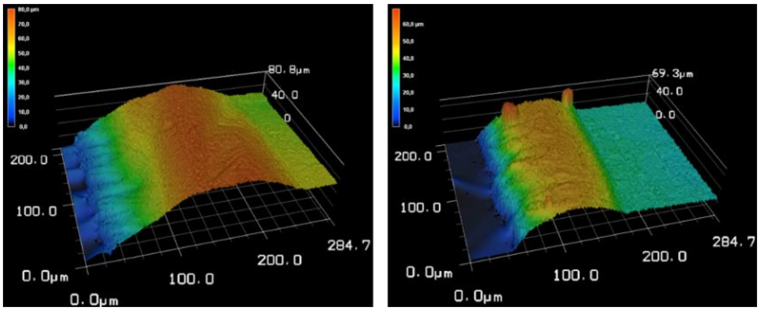

Fig. 2. Laser cut lithium foil; high melt superelevation and high melt formation width (left), low melt superelevation and low melt formation width (right)

The characteristics for the cutting edge quality evaluation are the melt superelevation and the melt formation width, in this case a good cutting edge is characterized by a low melt superelevation as well as small melt formation width (figure 2).

The main influencing parameters in this process are the pulse repetion frequency (PRF) and the cutting speed. Therefore, the PRF of 70 to 490 kHz and cutting speeds of 50 mm / s to 150 mm / s were varied and investigated in the presented experiments. The pulse overlap (PO) was used to compare the interactions between these parameters. It was examined if the pulse overlap has an influence on the cut result at constant line energy (ED). The pulse overlap and the line energy is defined as follows [Kreling, 2015]:

$$PO = \left(1 - \frac{v_c}{f_{pulse} \cdot d_{spot}}\right) \cdot 100 \quad \% \tag{1}$$

$$ED = \frac{P_{avg}}{v_c \cdot d_{spot}} \tag{2}$$

The pulse overlap is defined by the cutting speed v_c, the pulse repetion frequency f_{pulse} and the spot size d_{spot}. The line energy describes the energy entered in the separation zone by dividing the average power P_{avg} by the cutting speed and the spot size.

4. Results and discussion

In the following, the effects of the cutting speed on the melt formation width are shown at a constant frequency of 200 kHz and 72 W average power. The cutting speed was increased in four steps from 50 mm / s to 150 mm / s. The section a - d in figure 3 shows the laser cut lithium foil for different cutting speeds.

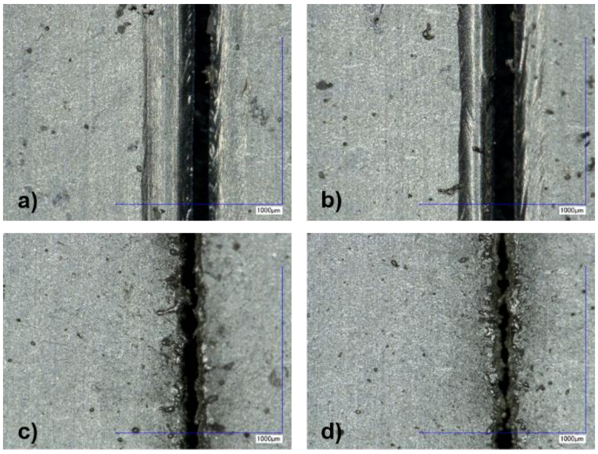

Fig. 3. Laser cut lithium foil, Parameters 200 kHz and 72W: (a) 50 mm/s, PO 99,72 %; (b) 75 mm/s, PO 99,58 %; (c) 100 mm/s, PO 99,44 %; (d) 150 mm/s, PO 99,17 %

As the speed increases from 75 mm/s to 100 mm/s, the shape of the cutting edge changes significantly. The melt bath formed in figure a) and b) can no longer be formed and the cutting edge becomes very inhomogeneous. The reason for this is a decreasing overlapping of the pulses (PO) respectively the laser-material interaction time at high speeds is no longer sufficient to produce a molten bath in the cutting edge area. Since the spot diameter d_{spot} is constant the cutting speed v_c and the pulse repetition frequency f_{pulse} are the influencing parameters. To verify that the pulse overlap is the crucial factor the frequency was elevated to assure a pulse overlap over 99,44 %. The results of these experiments are shown in figure 3.

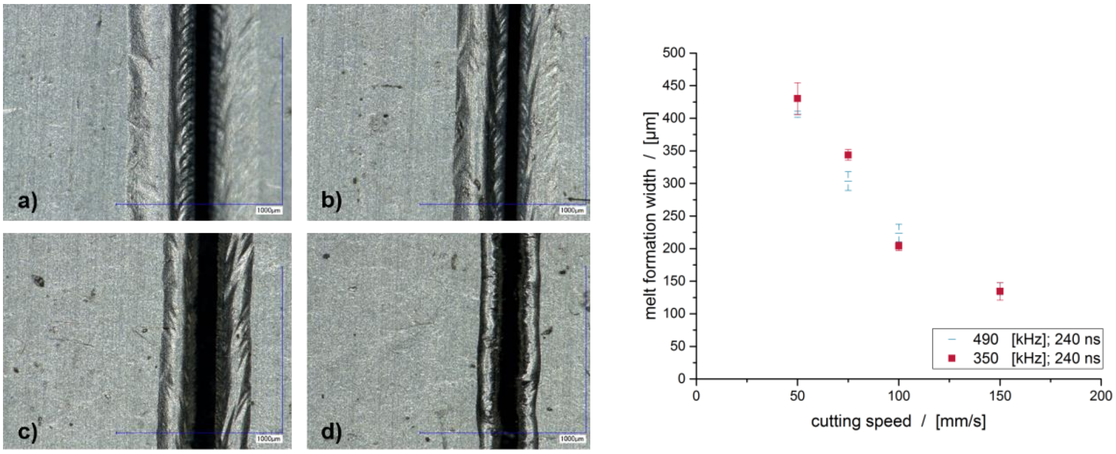

Fig. 4. Parameters 490 kHz and 72 W: (a) 50 mm/s, PO 99,89 %; (b) 75 mm/s, PO 99,83 %; (c) 100 mm/s, PO 99,77 %; (d) 150 mm/s, PO 99,66 %; Dependence of the melt formation width on the cutting speed (left diagram)

The laser-cut lithium foil in figure 4 section a - d was performed at the same speeds as in figure 3, but at an increased pulse repetion frequency of 490 kHz. It can clearly be seen that the homogeneous molten bath remains intact even at high cutting speeds. Furthermore, it can be observed that the width of the melt decreases with increasing cutting speed. The diagram in figure 4 also shows that the pulse repetion frequency has a minor impact on the width of the melt formation in the case of sufficient pulse overlap for the formation of molten bath. Both the cutting speed and the pulse repetion frequency have a significant influence on the geometry of the cutting edge.

The results allow us to conclude that a given pulse overlap is necessary for a given line energy to produce a homogeneous molten bath. Thus, a sufficient number of pulses must reach a segment in order to liquefy it and drive it out of the separating gap. It is therefore to be assumed that the material removal close to the cutting edge is mainly a photothermic effect which results in the cutting of the foil. At lower PRF at constant average power, the energy per pulse is higher so the material removal (figure 3 section c - d) in the separation zone is much more intensive. Due to the insufficient pulse overlap and the fact that the energy is not sufficient in the edge region, caused by the Gaussian beam profile, there is no clear cutting edge formed. The reduction of the melt width by an increase in velocity can be explained by the reduced energy input in the separation zone, which manifests itself in a lower line energy. Furthermore, this effect can be explained by the Gaussian intensity distribution of the laser beam, since the interaction time decreases at an increased speed, and higher intensities are needed for material removal.

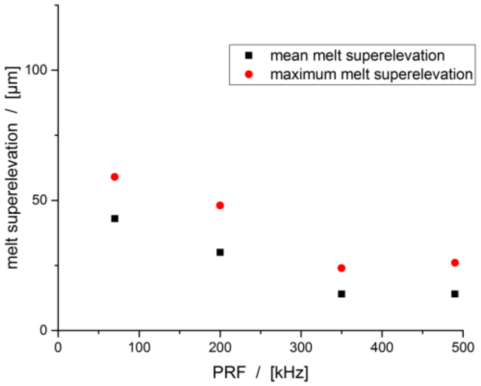

Fig. 5. Mean and maximum melt superelevation in dependance of pulse repetion frequency; 100 mm/s and 72 W

The graph in figure 5 shows that, as the PRF increases, the melt superelevation decreases and reaches a plateau. This is due to the fact that with increasing PRF the formation of a homogeneous molten bath is forced. Due to the increasing pulse overlap, the lithium is melted and the melt is displaced from the separation zone and driven forward as described above. At lower PRF, melt spatters arise and solidify next to the cutting Edge which lead to a substantial increase superelevation of the cutting edge. The melt splatters are formed because in parts the high energy of the individual pulses is not sufficient to remove the material by means of a photochemical removal, and the molten lithium is shoot out the gap with the following pulses.

5. Conclusions

The results of the present investigations show that it is possible to cut lithium foil by laser radiation at a dew point of -30 °C without causing an uncontrolled exothermic reaction of the lithium. Furthermore, it was seen that a minimum pulse overlap at a specific line energy is necessary to produce a homogeneous cutting edge. High PRF thus enable homogeneous cutting edges even at fast cutting speeds. It should also be noted that as the cutting speed increases, the width of the melt formation decreases and the melt superelevation decreases with increasing PRF. In further investigations, it should be examined whether by a decreased wavelength the photochemical ablation can be used to realize a clear cut edge without melt spatters and melt bath.

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