# Laser Cutting of Electrodes for Advanced Batteries

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Lithium-ion batteries are at the forefront of current advanced battery technology development for applications in transportation, such as Hybrid-Electric (HEV), Plug-in (PHEV) and Electric Vehicles (EV). An important step in the manufacturing chain of Lithium-Ion batteries is the sizing of electrodes. Contact-free high speed laser cutting without tool wear can offer higher flexibility, increased quality, cost and throughput benefits to the electrode sizing operation. Challenges include the composite electrode material and high demands on edge quality. This paper presents results on laser cutting of cathodes and anodes for Lithium-Ion batteries. Different approaches using a pulsed solid state laser and a single mode fiber laser in combination with fixed optics and 2D scanning optics are discussed. The presentation focuses on the achievable cutting speed and cut quality for the investigated laser systems.

**Keywords:** Lithium-ion batteries, hybrid vehicles, electrodes, laser cutting

## 1. Introduction

Hybridization of gasoline and diesel powertrains for vehicles has become a rapidly expanding global market, because it combines the benefits of higher fuel economy and lower emissions with the power, range, and convenience of traditional gasoline and diesel powered vehicles. According to a report by The Boston Consulting Group [1], an estimated 14 million electric and hybrid cars may be sold in 2020 in the world's four largest automotive markets - Western Europe, North America, Japan, and China - compared to 480,000 in 2008.

A variety of systems such as hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV) are either on the market or currently under development. One of the enabling factors for the development of new hybrid systems for vehicles are significant advancements in new battery technology [2]. Today, Nickel-Metal-Hydride (NiMH) batteries are used in most HEVs offering higher capacity compared to conventional lead acid or NiCd cells. NiMH technology is proven to be safe and very reliable.

Future PHEVs and EVs will require even lighter, more compact, and higher-capacity batteries to achieve the targeted driving range. Most developers believe that the Lithium-Ion battery technology can address these challenges as they can store twice as much energy per liter of volume compared to NiMH-batteries, which can lead to substantial space and weight savings [3]. In addition to reliability and safety [4], battery cost will play a very important factor for a broad market acceptance of HEVs utilizing Lithium-Ion technology.

Battery pricing is significantly impacted by material cost and manufacturing cost in mass production. Today, at least 50% of the cost of battery packs is determined by the battery cells due to the multitude of operations and the precision and throughput required making the use of highly efficient manufacturing methods a first priority to lower cost. Laser processing is proven in industry as a highly efficient and reliable manufacturing method that can potentially contribute to significant cost savings a variety of manufacturing and assembly steps with sizing of electrodes being one of them.

## 2. Background

Electrodes for Lithium-Ion batteries are a composites consisting of the active electrode material that is coated onto a metallic foil serving as current collector. Active electrode powder material is mixed with a polymeric binder and solvent to a slurry. A thin film of the slurry is spread onto both sides of a wide metal foil and subsequently cured in a drying oven. Different materials are used for cathodes and anodes. The most common cathode materials include Lithium-Metal-Oxides, such as LiCoO2, Lithium-Iron-Phosphate and Lithium-Manganese-Oxide (spinel). Aluminum foil serves as current collector for the cathode. Graphite is widely used as anode material and the current collector is made of copper.

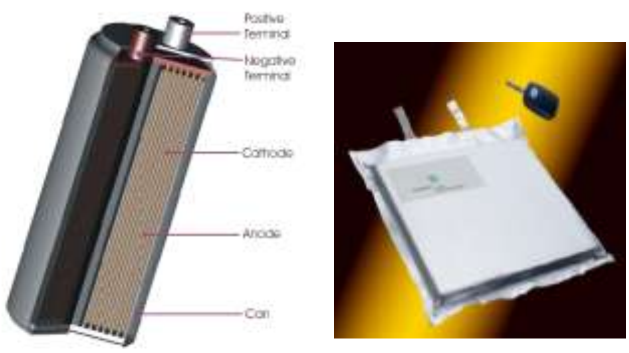
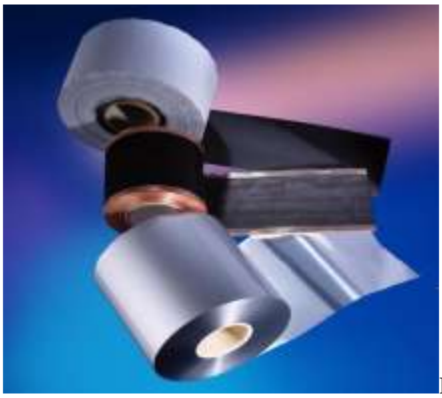



Figure 1: Cell designs – cylindrical and prismatic

The electrode thicknesses can range from 0.05 mm to 0.2 mm depending on the electrode type (cathode or anode), the intended application of the battery (high capacity or high power) and the cell design (Figure1).

Cylindrical cells have a wound electrode package consisting of anode, separator and cathode and prismatic cells with stacked electrodes and separators are currently the predominant designs. Typical thicknesses of the current collector foils are between 0.015 mm and 0.025 mm.

The coated metal foils are subsequently cut to size using mechanical tools (Figure 2). Slitting machines cut the foil into narrower strips for different electrode sizes used in cylindrical cells. Die cutting is applied to size the electrodes used in prismatic cells. Each electrode size and shape requires a specific cutting tool.



Picture: Fh-ISIT

Figure 2: Electrode material for lithium-ion batteries

Both, slitting and die cutting require precise and relatively expensive tooling that wears over time resulting in process instabilities and poor cut quality (Figure 3). Specifically, slight bending of the cut edge, the formation of burrs and random micron sized material attachments can result in short circuits inside the battery cell and potentially to catastrophic failure of the entire module.

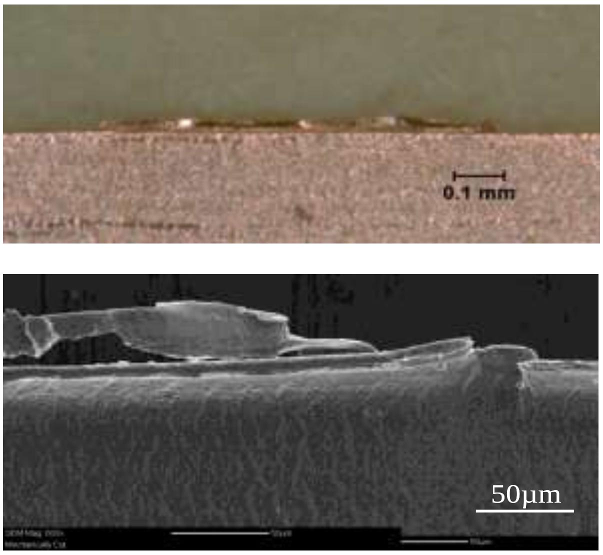



Figure 3: Edge defects in mechanical cutting

Furthermore, on coated material edge bending can lead to delamination between the electrode material and the current collector foil and the loose electrode material can break off. Therefore, frequent maintenance and tool replacement is required leading to machine downtime and increased manufacturing cost.

### 3. Laser cutting - Experimental set-up

Contact-free laser cutting of electrode materials has been investigated with the objective to determine the achievable cutting speed, cut quality and process robustness. Different laser sources, setups, and cutting schemes were applied for cutting uncoated and coated electrode material. A 500W cw single mode (SM) fiber laser and a 5W pulsed frequency tripled Nd:YAG laser ($\lambda$=355nm) were applied to investigate high speed laser slitting of current collector foil and cutting of coated electrode material. Both laser types provide highest beam quality that enable small spot sizes in the range of 0.01 to 0.02mm and high intensity levels, required to cut the highly reflective copper and aluminum foils (Figure 4).

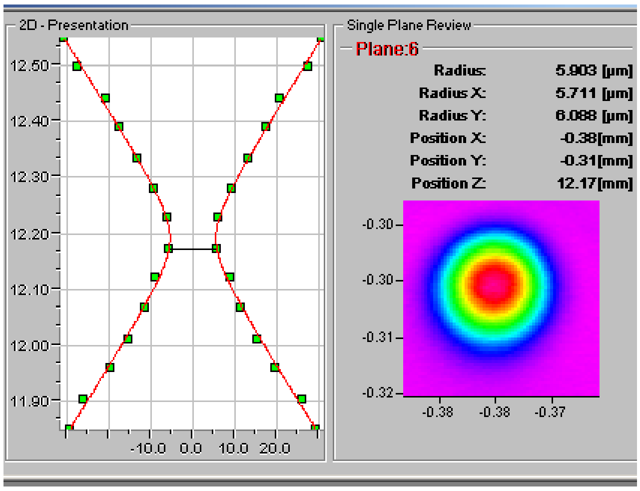



Figure 4: Spot size and caustic, SM fiber laser, fl=50mm

Either a fixed optic was used for beam delivery to the work piece or a galvanometric scanner moved the beam across the stationary electrode surface (Figure 5). Trials were performed using a cutting head with a focal length of 50mm and a galvanometer scanner with a focal length of 100mm for the 355nm wavelength and 80mm for the 1070nm wavelength. The test materials included uncoated copper and aluminum foil as well as Lithium-Ion Phosphate as cathode material and graphite as anode material.

A prototype web handling system was used to move the foil underneath the stationary cutting head from reel to reel for the slitting of current collector foil. The system is capable of handling a web with a width of up to 100mm at maximum speed of 30m/min. It was retrofitted with a special roller assembly to guide and support the web at the point of cutting. It also included an adjustable electronic brake on the decoiler to set the web tension during slitting. Vacuum fixture plates were used to hold the coated electrode material in place during cutting of prismatic electrodes. The laser parameter development focused on the variation of power, focal spot size, focal position, speed, nozzle diameter, nozzle stand-off, cutting gas type.

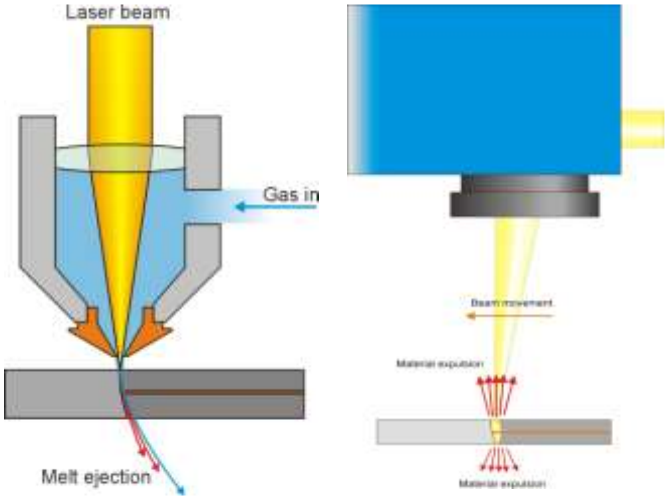



Figure 5: Cutting with fixed optic (left) and galvanometer scanner (right)

## 4. Results

### 4.1 Laser slitting of current collector foils

Cutting of copper and aluminum foils was investigated using the SM fiber laser and the prototype web handling system. The objective was to determine the optimum power level that establishes consistent cutting of the foil and minimize the width of the heat affected zone. Foil speeds between 10 and 25m/min were investigated. Typical speeds of current industrial coating lines are in the range of 10 to 15m/min. Laser slitting at speeds up to 25m/min provide the option for inline processing.

For the investigated speed range, consistent cutting of the copper current collector foil is achieved using laser power between 50 W and 150 W. Based on the small focal spot size, very narrow kerf widths in the range of 30 µm to 50 µm are observed. TEM analysis of the cut edge showed that the width of the heat affected zone (HAZ) is approximately 30 µm. Figure 6 shows a representative result for this set of trials.

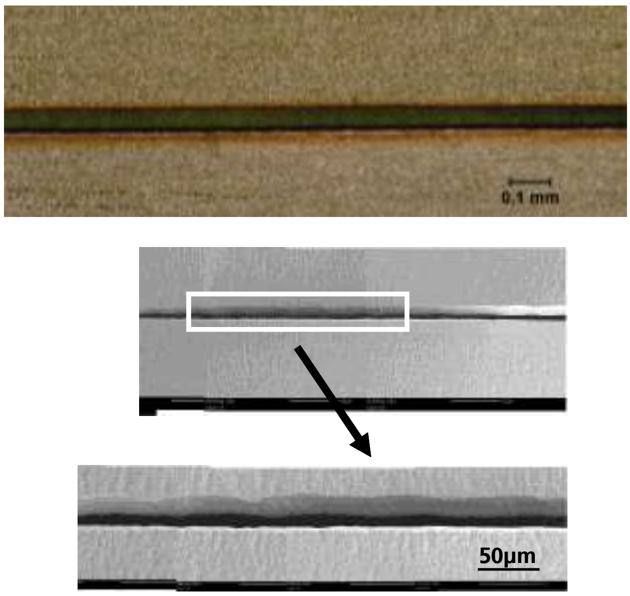



Figure 6: Results on laser cutting with fiber laser

The cut was performed at a speed of 25 m/min using laser power of less than less than 100 W. The gap shown does not represent the actual cut kerf width since the foil is completely separated and both sides of the cut are positioned at a random distance under the microscope. The surface picture taken with the optical microscope (Figure 6, top) show differences in the appearance of the cut edges. The upper edge (Figure 6) exhibits a very clean and consistent cut quality with a 15 µm wide discolored zone and no visible melt attachments. The lower edge has a melt film attached indicating that melt was not completely ejected from the kerf. Due to the residual melt the heat impact on this side is higher and a wider discolored zone with a width of approximately 25 µm can be observed. The attached melt film shows some sagging resulting in the formation of a burr after solidification. Burr sizes range between 5 and 15 µm depending on the processing conditions. However, due to the small size, well rounded shaped and firm bond of the attached melt film, no negative effects on the functionality of the electrode are expected. Similar results are achieved for cutting aluminum electrode material. Compared to copper, approximately 20% less laser power is required to cut the aluminum foil at the same speed.

A series of cutting trials were performed to determine the parameter sensitivity or the process parameter window and cut quality. The study included the effect of laser focal position on the cut quality of copper foil. It was found that changing the focal position of the laser spot more than 50µm from the nominal position results in poor cut quality and the process stops cutting if the variation is more than 125 µm from the nominal setting. This is due to the fact that the required laser intensity decreases rapidly with the increase in spot diameter and leads to insufficient intensity to cut the highly reflective copper foil. Due to the small depth of focus window (0.1mm), precise foil handling is very important. Therefore, special attention must be given to the foil position and guidance at the cut location during system design for industrial implementation of the cutting process.

Cutting trials on current collector foils were also performed with the 355nm diode pumped q-switched Nd:YAG laser to investigate the impact of the shorter wavelength and increased absorption on the cut quality. Especially on copper, the absorption of UV laser radiation is significantly higher (>50%) compared to the near NIR range (4%). In the case of aluminum the increase in absorption is only minor (2%). Trials were conducted at a repetitions rate of 50 kHz delivering maximum power of 3.98 W at the work piece surface. With the 10.2 ns pulse width the pulse energy was 80 µJ and the peak power approximately 7.8 kW.

The highest speed reached with copper under normal air atmosphere was 13.5 m/min and under an inert gas (argon) atmosphere 12.0 m/min were achieved. Overall, it was found that using an inert gas atmosphere leads to an approximately 10% decrease in cutting speed for the same power level; however the edge becomes smoother and cleaner using the inert gas. For aluminum a maximum speed of 4.2 m/min is achieved using power of 4.0 W. Micrographs were taken from the beam entrance and exit sides of the cuts and the width of the cut was measured. The width of the cut on the beam entrance (top) side in aluminum was approximately 20 µm and on the exit side 18 µm. Similar measurements were made to copper and they showed a 23 µm width on the entrance side and 16 µm on the exit side. The cut edge in aluminum did not show any signs of heat affected zones (HAZ) on either side of the foil. The cut edge in copper showed slight oxidation and a rounding of the edge, however overall thermal effects are very limited. In conclusion, UV-lasers even in the low power range are powerful tools for cutting thin foils. The cut quality is good and relatively high process speeds can be achieved.

### 4.2 Laser cutting of electrode material

Lithium-iron phosphate electrode material was cut using UV and fiber laser. For the anode, each side of the current collector has a 35 µm thick coating of active material resulting in a total electrode thickness of 85 µm including the current collector. The cathode has a total thickness of approximately 190 µm with the aluminum current collector being 25 µm thick.

Due to the difference in materials and thickness the maximum cutting speed varied significantly between anode and cathode. The anode is cut at 4.2 m/min using laser power 3.6 W. The cut quality is very good exhibiting no delamination between coating and current collector and minimum HAZ. Figure 7 shows a representative result of the cut surface.

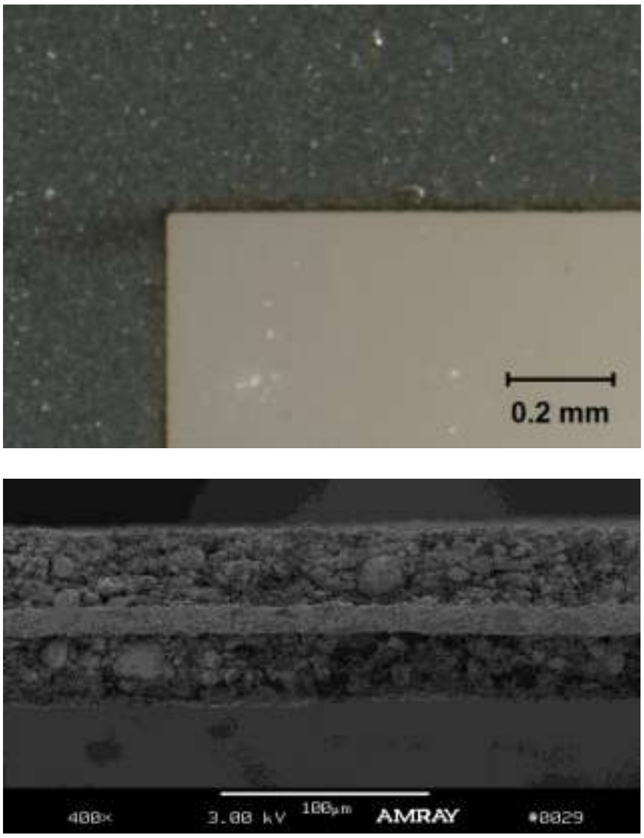



Figure 7: Anode cut with UV laser

Due to the higher thickness cutting speeds on cathode material are much lower. At the same power level (4W) only a speed of 180 mm/min is achieved. In addition, the cuts performed on cathode material exhibit some burr formation at the bottom edge. Increasing laser power directly coverts to higher cutting speeds. Trial performed with a pulsed UV laser at 17 W resulted in maximum cutting speeds of 12 m/min and 3 m/min respectively for the same anode and cathode materials.

While these cutting speeds will meet productivity goals in prototyping and low volume production, much higher speeds in excess of 20m/min are required to compete with die cutting technology in mass production. Therefore, high speed laser cutting using a single mode fiber laser and galvanometer scanner was investigated for straight and contoured cuts. At spot sizes of less than 20 µm the intensity exceeds $10^8$ W/cm$^2$. Similar to other cutting approaches the material is partially evaporated and melt is ejected from the cut kerf. The initial set of trials was focused on determining the maximum cutting speed in dependence of the laser power and the corresponding cut quality. All trials were performed under normal atmosphere without shield gas. Figure 8 shows the achievable cutting speed as a function of the laser power for anode and cathode materials.

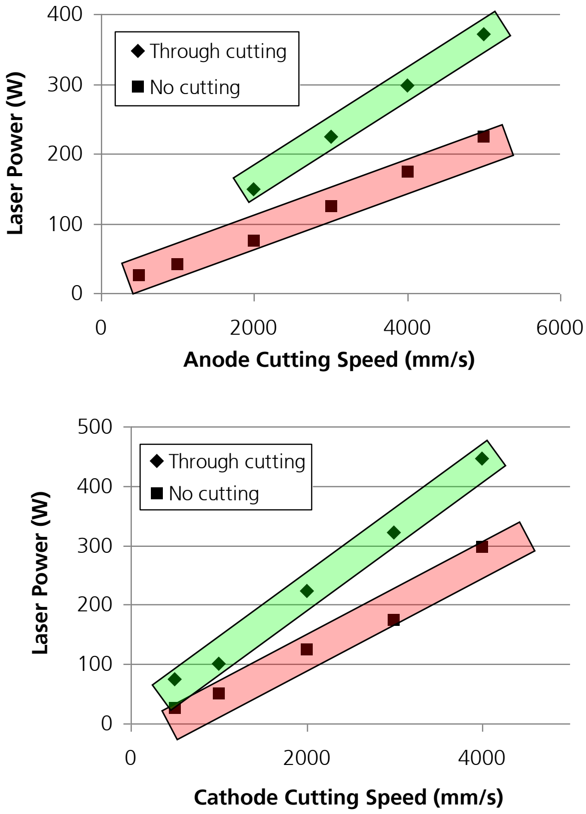
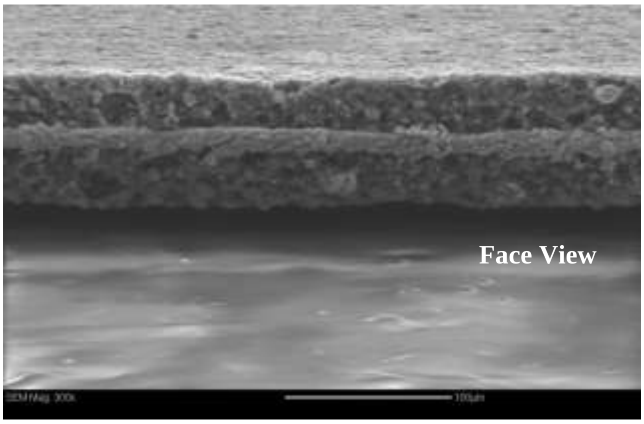



Figure 8: Cutting speeds for anode and cathode material

The required power level increases with raising cutting speed. The green bar represents the minimum power level required to achieve complete cuts. Parameter combinations between the green and the red bar (no cut) lead to incomplete cuts that are mostly characterized by small tabs that randomly occur and link the cut edges together. For the thinner anode material a speed of 300 m/min is achieved using laser power of 370W reaching the limit of the galvanometer scanner. The maximum speed for the cathode material is 240m/min using 450 W. An improvement in cut quality is observed with increasing speeds. At speeds below 2.0 m/s all cuts are incomplete independent of the applied laser power. Further analysis of the cut edge revealed a consistently good cut quality without noticeable delamination and a very narrow heat affected zone. Figure 9 shows the face view and the top view of a laser cut anode edge that was cut at 300 m/min. Further investigation of the edge quality is required to determine any degradation of the electrode material and its bond to the current collector that might impact the durability and functionality of the battery cell.



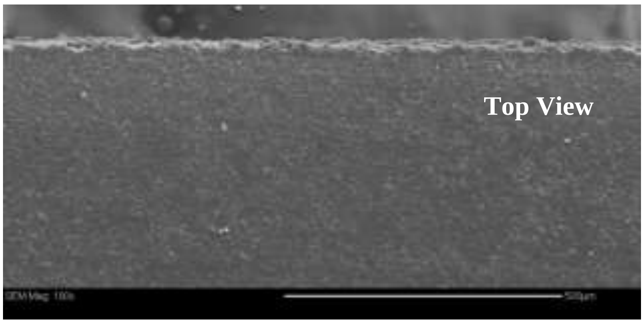




Figure 9: Laser cut anode material, Speed: 300m/min

## 5. Summary and Conclusions

Lithium-ion battery technology is considered as being the one best suited for meeting future HEV requirements regarding weight, capacity and energy density. However, high battery costs still play a critical factor in achieving broad market acceptance and highly efficient manufacturing methods are needed to further lower cost.

Different laser cutting processes using pulsed UV and fiber lasers were investigated regarding their capability for sizing of battery electrode materials. Processing capabilities with cutting speeds reaching up to 300 m/min were successfully demonstrated. The laser cut edges are of good and consistent quality in initial characterization. As a next step, battery cells will be assembled that will undergo extensive testing to further evaluate the quality and cycle life of laser cut electrodes.

**Acknowledgments**

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