# INVESTIGATION OF DIFFERENT LASER CUTTING STRATEGIES FOR SIZING OF LI-ION BATTERY ELECTRODES

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Rahul Patwa[1], Hans Herfurth[1], Stefan Heinemann[1], Jyoti Mazumder[2], Dongkyoung Lee[2]

[1] Fraunhofer Center for Laser Technology, 46025 Port Street, Plymouth, 48170, MI
[2]University of Michigan, College of Engineering, Ann Arbor, MI

## Abstract

Lithium-ion batteries are currently considered to be the most promising advanced battery technology for electric vehicles that require high energy capacity. A lot of research and development activities have been focused on their development to achieve efficient mass production capabilities and to successfully commercialize the technology. This paper discusses the laser cutting process for coated anode/cathode and uncoated copper/aluminum tabs for both cylindrical and prismatic Li-ion cell designs. A number of different cutting strategies have been investigated using IR (fiber/disc) and UV laser sources in pulsed/cw configurations. An in-depth development study has been performed to understand the effect of different processing parameters on the maximum cutting speed, cut edge quality and overall energy efficiency of the process. Results show that excellent cut quality can be achieved using optimal processing parameters with cutting speeds ranging from several m/min up to 300 m/min depending on the processing requirements and the corresponding cutting approach.

## Introduction

Lithium-ion battery technology is currently considered the best suited technology for meeting the future hybrid and electric vehicle requirements regarding weight, capacity and energy density. However, in order to achieve broader market acceptance, highly efficient manufacturing processes are required to lower cost. One such manufacturing step is the cutting of electrodes to size. The electrodes demand high cut edge quality in terms of minimum burr formation, no-edge bending, no-delamination, low debris particles and minimum burnback. Conventional, mechanical slitting and die cutting are currently used for this production step, however there is a growing interest to pursue other competing technologies that can provide improved quality along with high throughput.

We have investigated laser cutting as an alternative production process and addressed the issues and concerns pertaining to this process. Our prior development efforts were directed towards developing specific laser cutting solutions for individual applications [1, 2, 3]. Consequently, we have developed a number of different cutting strategies for a variety of Li-ion cell electrode designs and material compositions using different laser sources and beam steering concepts. This paper provides an overview of cutting strategies and compares various aspects of their suitability in regard to quality, productivity and system requirements.

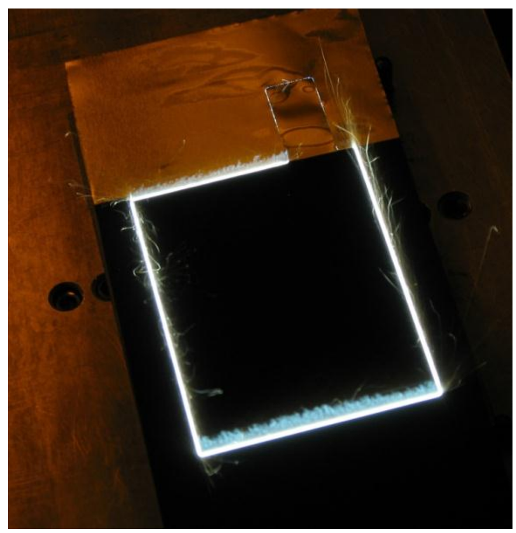


Figure 1 Laser cutting of electrode

### Electrodes for Prismatic versus Cylindrical cells

Lithium-ion battery electrodes are made from active material coated on both sides of aluminum and copper foils that serve as current collectors. Foil thicknesses can range from 0.01 mm (uncoated) to 0.2 mm (coated) depending on the cell design and the electrode type (cathode or anode). In this work, cathode coating composition included lithium-metal-oxides such as LiCoX, LiFeX and LiMnX, where X represents specific oxide. Graphite was investigated as anode material.

The most common Li-ion cell designs are cylindrical wound cells, flat wound cells, and prismatic cells with planar electrodes [4]. Lengths of electrode foils are interleaved with a separator and wound around either a circular mandrel or flat mandrel to produce cylindrical or flat wound cells. In prismatic cells, planar rectangular electrodes are cut to the required shape and then stacked with separators and other components to form a cell. The prismatic cell design provides more design flexibility and can therefore be easier customized for specific applications. Laser cutting was developed on current collector foils for cylindrical cells and on both, coated and uncoated section of planar electrodes for prismatic cells.

### Conventional, Pulsed and Remote Cutting

In conventional fusion cutting, the cutting head includes fixed beam delivery optics, cutting gas delivery system and other options as required by specific cutting processes. The nozzle placed at the end of the cutting head has a very small opening to supply assist gas that ejects the melt from the cut kerf. Cutting is performed by moving either the electrode or the cutting head or both in synchronized motion.

In pulsed cutting, high peak power pulses melt and partially vaporize the material which is removed incrementally with each laser pulse.

In remote cutting, a high brightness continuous wave (cw) laser is used. The material is cut using a combination of very high energy densities and high speed beam movement >0.5m/s. Cutting gas is not required, as the melt in the cut kerf is partially vaporized and partially ejected by very high vapor pressure under extreme conditions of temperature and melt pool dynamics [5].

In pulsed and remote cutting, the laser beam is steered using a galvo scanner, while the flat electrode material is held stationary and therefore, high accuracies and repeatability can be achieved. Despite the fact that scanner can provide efficient and flexible beam motion, its use limits the field size and the working distance, which is directly proportional to its focal length. To generate larger field size, a longer focal length is required which in turn requires higher beam quality to generate small spot sizes. If the electrode size is larger than the image field size then electrode or scanning system or both must be moved relative to each other (on-the-fly cutting). Accuracies and repeatability can be impacted using this approach. Compared to remote cutting, the achievable cutting speed in pulsed cutting is significantly lower due to limitations in the available power and the maximum pulse repetition rate.

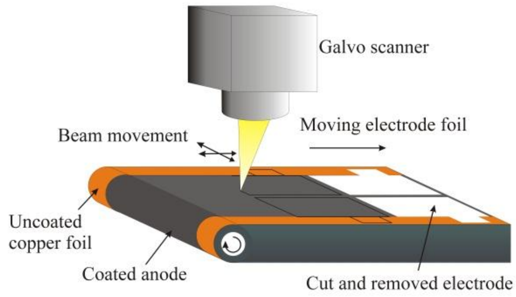
### Cut Quality Characterization

To evaluate the achieved cut edge quality, a common set of quality criteria was defined and used for measurements to compare different cutting processes.

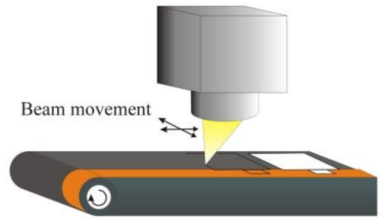
- Burnback is the distance from the outermost current collector edge to the edge of the coated electrode material. It signifies the amount of coating that is removed at the edges which exposes the current collector foil.
- HAZ is the heat affected zone and is visible as dark color on the coating close to the edge. It is important to minimize this because delamination of coating could occur in areas of excessive HAZ.
- Delamination between the coating and the current collector foil can lead to separation or loss of larger coating pieces close to the edge.
- Burrs are present on the cut edge as random micron sized attachments that can cause puncturing of delicate separators or result in short circuits inside the battery cell and potentially to catastrophic failure of the entire module.
- Debris is the dust and loose particles that are generated during the cutting process and settles on the electrode surface close to the cut edge.

## Cutting Strategies

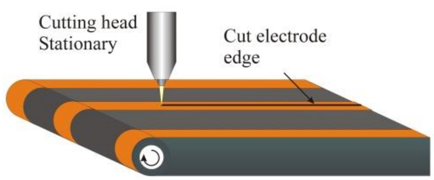
Table 1 summarizes the cutting processes, laser sources, beam delivery, process parameters, cut quality, laser cost and electrode size for different cutting processes investigated for electrodes. It provides a good comparison of many key factors that help to determine suitable cutting process based on specific requirements and goals. Since the intent is to provide an overview of different cutting processes, detailed information on a specific dataset is omitted to maintain clarity. Figure 2 shows schematic illustration of different laser cutting strategies. Although, it shows how different cutting processes would compare in roll-to-roll processing, there could be a number of other possible cutting combinations including special optics and motion systems, all of which are not discussed here. Nevertheless, the cutting strategies presented here are representative of many such system configurations.



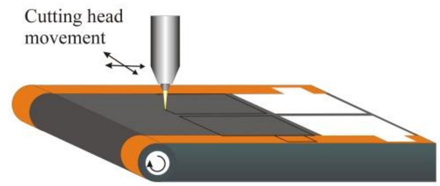

Pulsed cutting




Remote cutting




Conventional cutting
(cylindrical cell electrode)




Conventional cutting
(prismatic cell electrode)

Figure 2 Schematic illustration of different laser cutting strategies

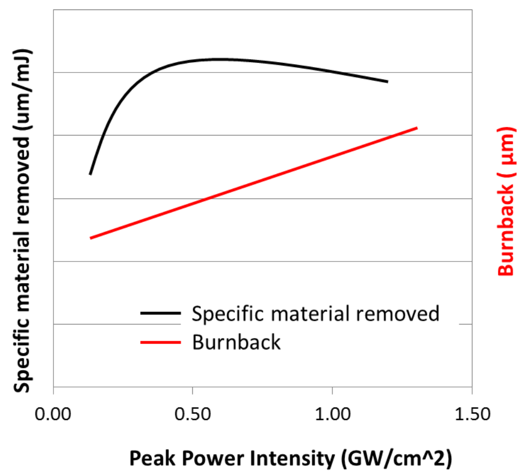
Table 1 Comparison of different laser cutting processes for sizing of Li-ion cell electrodes

| **Cutting Process** | | Pulsed cutting IR | | Remote cutting | | Pulsed cutting UV | | Conventional cutting | |
|---|---|---|---|---|---|---|---|---|---|
| **Cell Type** | | Prismatic | | | | | | | Cylindrical |
| **Laser Source** | | | | | | | | | |
| Wavelength | µm | ~ 1 | | ~ 1 | | ~ 0.35 | | ~ 1 | ~ 1 |
| Operation | | pulsed | | cw | | pulsed | | cw | cw |
| **Beam delivery** | | scanner | | scanner | | scanner | | cutting head | cutting head |
| **Process Parameters** | | Electrode | Tab | Electrode | Tab | Electrode | Tab | Electrode | Tab |
| Average power | W | 30 [28-32] | 35 [32-38] | 410 [370-450] | 350 [320-370] | 13 | 13 | 215 [130-300] | 60 |
| Specific material removed | µm/mJ | 11 [6-16] | 7 [6-7] | 11 [9-13] | 14 [13-15] | 10 [9-11] | 30 | 3 [2-4] | 7 |
| Peak intensity | GW/cm$^2$ | 0.24 [0.12-0.36] | 0.26 [0.12-0.40] | 0.52 [0.47-0.56] | 0.44 [0.41-0.47] | 1.15 | 1.15 | 0.27 [.16-0.38] | 0.03 |
| Max cutting speed | m/min | 20 [12-27] | 16 [12-27] | 270 [240-300] | 300 | 8 [7-9] | 24 | 30 | 25 |
| Process gas | | none | | none | | none | | $N_2$, $O_2$ | Ar, $O_2$ |
| **Cut quality** | | med-high | med | med | | med-high | high | low | low-med |
| Burnback | µm | < 50 | < 40 | > 50 | | < 50 | < 20 | > 80 | < 80 |
| **Electrode size** | inch | < 6 | | < 3 | | < 3 | | > 10 | continuous |
| **Laser cost*** | | low-med | | low-med | | med-high | | med | |

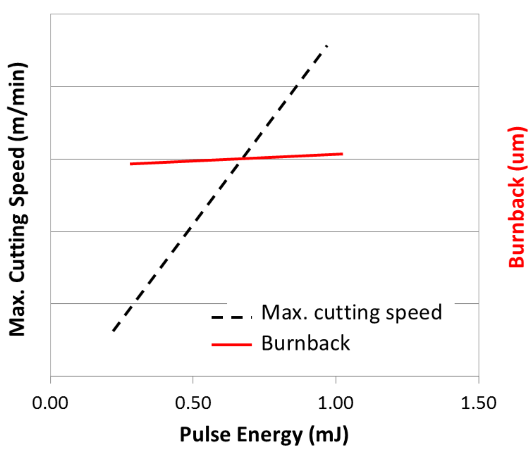
Thickness: Electrode -- 75-180 µm; Current collector -- 10-15 µm
* Estimated ‘high’ figure > $100 k and ‘low’ figure < $50 k

## Pulsed Cutting with IR laser

A Jenoptik pulsed disk laser (IR70) was used for pulsed laser cutting of prismatic cell electrodes. The disk laser emits at 1030 nm wavelength and can provide maximum average power of 65 W. In most cases, the pulse length (200-1100 ns) could be set independently of the repetition rate (8 kHz – 100 kHz) allowing high flexibility in parameter selection. During cutting, the flat electrode foil was kept stationary while the laser spot of Ø30 µm was moved using a 2-axis scanner with a 163 mm f-theta lens.




**(a)**




**(b)**

Figure 3 Process charts for pulsed cutting with IR lasers. (a) SMR and burnback versus PPI, (b) Max cutting speed and burnback versus pulse energy

To understand the key primary and secondary process parameters that led to high cutting speed and higher cut quality, a detailed experimental test matrix was created where effects of average laser power, pulse energy, pulse length, rep rate, peak power, spot size and cutting speed were investigated. Laser cutting tests were performed on anode, cathode and tab and those results were related back to the specific change in processing conditions. These results of individual parametric studies were analysed and then combined by normalizing those parameters. This way, the effects of changes in pulse length, rep rate, pulse energy, peak power and speed were summarised and represented by only two key process parameters: peak power intensity (PPI) and specific material removed (SMR).

PPI is calculated by averaging the peak power over the laser spot area. SMR is the ratio of cutting speed and laser power and is defined as the linear distance of material removed per mJ of applied laser energy. In other words, it defines how efficiently the material is removed in each laser pulse. To achieve higher cutting speeds, specific material removed should be maximized.

Figure 3(a) shows the relationship between the PPI, SMR and burnback. Note that specific data points are replaced by smoothened trendlines. Although both pulse length and rep rate were varied to achieve different PPI values, according to the plot, both SMR and burnback is dependant only on the PPI and independent of pulse length or rep rate. Below the threshold PPI (0.08 GW/cm$^2$), no cutting takes place and therefore the SMR is zero. At lower PPI, SMR is low. SMR increases rapidly with increase in PPI and reaches maximum at PPI of about 0.4 GW/cm$^2$. Further increase in PPI causes slight gradual lowering in SMR. This suggests that there is a maximum value of SMR which is only achieved at optimal PPI and selecting proper laser parameters is key to achieve high SMR, which translates directly to higher cutting speed and higher process efficiency. It was also found that burnback increased linearly with PPI and is directly proportional to it. Lower burnback corresponds to high cut quality. Therefore, to achieve high quality, PPI must be kept around lower threshold level while to achieve higher cutting speed, PPI has to be kept at higher (optimal) PPI level. In other words, both highest quality and highest productivity do not correspond to one PPI value and a trade-off PPI is required to achieve processing goals of productivity and quality.

Figure 3(b) shows the plot of maximum cutting speed and burnback as a function of pulse energy. Here the rep rate was kept constant at 50 kHz and pulse length was increased to achieve higher pulse energy. Clearly, maximum cutting speed increases linearly with pulse energy (PPI – constant). Moreover, it was found that the cutting speed had no direct impact on the burnback.

The absolute values of SMR, max cutting speed and burnback would depend on the specific material albeit similar trends are expected. Table 1 lists the parameter optimised for medium to high quality cut edge over a large speed range of 12-27 m/min for the coated electrode and 12-20 m/min for the electrode tab.

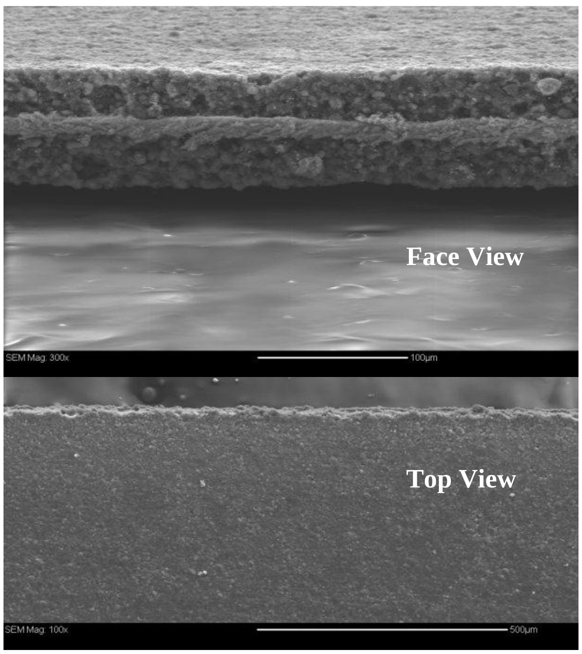



Figure 4 Pulsed IR laser cut edge of anode

Figure 4 shows the cut edge from pulsed IR cutting process. It shows high cut quality exhibiting no delamination between the current collector foil (center) and the coating. The top view shows that only a very small part of the current collector is exposed and no burrs are formed.

In summary, pulsed IR cutting is the most flexible cutting process that allows cutting process to be optimized based on specific productivity and quality requirements.

## Pulsed Cutting with UV laser

A pulsed UV laser (Spectra-Physics Hippo) was used for cutting prismatic cell electrodes. The laser emits at 1070 nm wavelength which is then frequency tripled to a wavelength of 355 nm. The maximum output power of the laser was >20 W @ 355 nm but due to limiting optical components, average power at the electrode was 13 W. This maximum average power was achieved at 100 kHz at a pulse length of 23 ns and resulted in peak power of 5.6 kW. A 2-axis scanner was fitted with a 100 mm f-theta lens that resulted in an estimated spot size of 25-30 μm.

Both copper and aluminum have high laser absorption at UV wavelength which resulted in very high SMR and consequently high speed for tab cutting. Best cut quality is achieved for the tab using this cutting approach. Nevertheless, the cutting speed achieved for electrode is low due to (a) limited average power of UV laser sources compared to IR laser sources and also, (b) since the laser had a fixed pulse length at high average power, only high PPI value could be selected. Although the edge quality of pulsed UV cut electrode is one of the best, a UV laser cost is much higher. Moreover, the electrode size is limited.

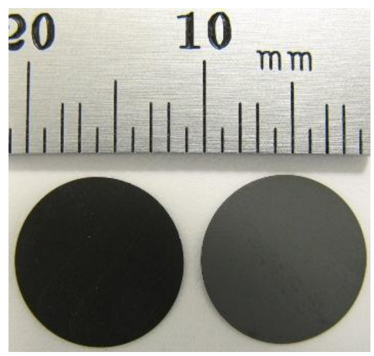



Figure 5 Pulsed UV laser cut button cell electrodes

## Remote Cutting

A single mode cw fiber laser (IPG) was used for remote cutting of prismatic cell electrodes. This laser emits at 1070 nm and has maximum power of 500 W. A 2-axis scanner with 80 mm F-theta lens was used to achieve diffraction limited small spot of 11 μm at focus position. Electrode was kept stationery during cutting and only the laser beam was moved in 2-axis.

Very high speeds of up to 300 m/min could be achieved for both electrode and tab cutting The cutting speeds are at least 500% higher than any other investigated cutting processes. The cut edge quality is slightly lower than that from pulsed cutting but the quality is consistent along the entire cut contour. Most of the debris associated with process is ejected to the top side of the cutting kerf requiring an efficient debris collection system.

Due to the unique dynamics of remote cutting process, it performs better at very high speeds. This parameter combination leads to high SMR at average PPI of about 0.50 GW/cm2.

Multiple pass remote cutting was also investigated for thicker electrodes where cutting is either not feasible in single pass due to limited power or cut quality was very poor. Using this approach, thick electrodes were cut at reasonable cut quality. It was found that total line energy required for multiple pass cutting remains constant although laser power and number of cutting passes were changed.

Remote cutting is a relatively new cutting process and provides an alternative approach for cutting thin electrodes especially when highest productivity is required, albeit limited by the electrode size.

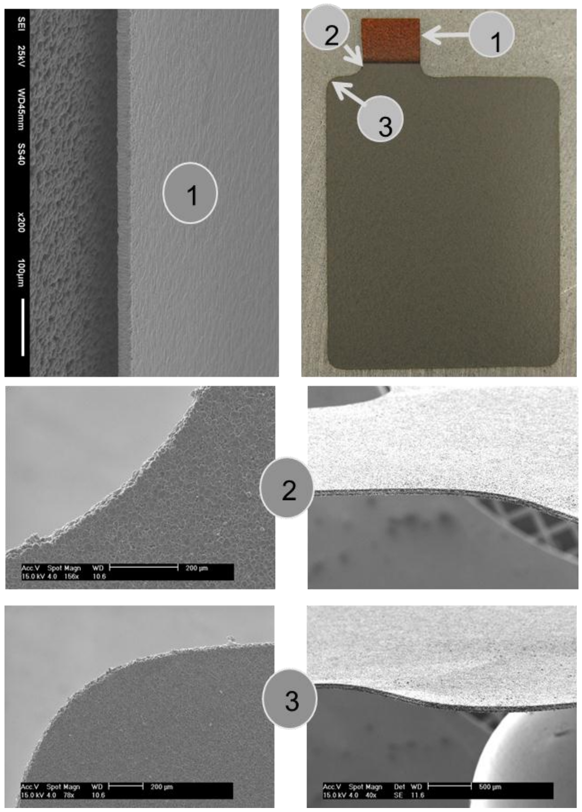


Figure 6 Remote cut prismatic cell electrode

## Conventional Cutting

A stationary cutting head fitted with a single mode fiber laser was used for conventional cutting for both cylindrical and prismatic cell electrodes.

For cutting of electrode strips used in cylindrical cells, a prototype web handling system was used to move the electrode foil continuously underneath the stationary cutting head. The cut was performed in uncoated sections of the coated web. A special roller assembly was used to guide and support the web at the point of cutting. The web tension was adjusted by an adjustable electronic brake on the decoiler. Since this process is in line with other electrode fabrication processes such as coating, drying etc. the speed requirement is based on the line speed. Cutting speeds of 25 m/min were achieved that exceeded the line speed of other operations. The cut quality is lower compared to pulsed cutting processes mainly due to dross attachments at the cut edge.

To cut electrodes for prismatic cells, the coated foil was moved horizontally in 2-orthogonal axes using high speed linear drive motion system under a stationary cutting head. This system configuration does not put any constraints to the size of the electrode. Process variables such as nozzle size, nozzle standoff, cutting gas pressure, gas type besides common laser parameters of power, speed and focal position were optimized to achieve best possible cutting quality. Despite this effort, the achieved cut quality was much lower than that achieved with pulsed and remote cutting processes.

In contrast to scanning systems, a conventional laser cutting machine requires significant capital investment for fast moving linear axes systems since stringent accuracy and repeatability requirements must be met at high cutting speeds. Moreover, system dynamics might constrain the maximum possible speed and acceleration. Nevertheless, conventional cutting systems are widely used in production for sheet cutting and have been successfully proven over long time.

High cutting speed and low-medium cut quality can be achieved using the conventional fusion cutting approach, however optimization of a large number of process variables is required that affect the cutting quality.

## Summary and Conclusions

In summary, four different cutting strategies have been investigated for sizing of electrodes for Li-ion batteries. They are pulsed cutting with IR laser, pulsed cutting with UV laser, remote cutting and conventional cutting. Investigation of these cutting processes showed that laser cutting process can produce excellent cut quality and achieve high cutting speeds by optimizing a number of processing parameters including peak power intensity, specific material removed and pulse energy. A thorough comparison was conducted between these processes and it was concluded that the process selection should depend on a number of factors including quality requirement, productivity goals, and electrode shape and size. Since there is not one single process that can fulfil all these requirements, a careful case analysis must be performed to determine suitable cutting process based on these factors.

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## Meet the Author


Rahul Patwa is an engineer at Fraunhofer USA, Center for Laser Technology in Plymouth, MI. He holds master's degree in Mechanical Engineering from the Purdue University in West Lafayette. He specializes in laser micromachining and laser processing for manufacturing of advanced batteries and solar cells.