Ultrafast laser micro-machining of electrode materials for lithium-ion battery

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Abstract. Electrode materials with composite structures are one of important components in the lithium-ion battery. Currently, mechanical methods such as punching and die cutting have been applied in cutting these cathode and anode materials. However, these conventional methods have such disadvantages as tool wear, low flexibility and process instability. Laser cutting can overcomes these drawbacks because of its characteristics such as contact free process, ease of automation and high energy concentration. At the same time, localized heating would occur during laser process, causing temperature rise near the irradiated region leading to the heat affected zone. Ultrafast pulse laser could effective reduce heat affected zone due to its capacity of focusing laser energy onto sample surface in picosecond or femtosecond time scale. In this paper, cutting of graphite coated copper anodes is presented. Dependence of incision depth and heat affected zone on laser power, scanning speed, marking times and pulse width are investigated. Burr and cross-section quality are analyzed. Results show that kerf with heat affected zone less than 42µm and no burrs are obtained when ultrafast laser cutting anode materials. The present study provides a high quality cutting method for electrode anode materials of lithium ion battery.

1. Introduction

Hybrid-electric vehicles, electric vehicles, cellular phones and other mobile equipment require battery electrical energy with increasing demand in recent years[1]. Batteries with high energy density and specific energy, low cost and long service-life are crucial components for these devices. The lithium ion battery represents one of the most promising technologies for the abovementioned vehicles[2], become battery choice of portable electric devices[3].The crucial components of lithium ion battery consist of electrode materials, which are graphite coated copper anodes and lithium metal oxide coated aluminum cathodes[4]. They are processed into different shapes for various applications. In production, electrode films are cut to size and rolled or stacked consecutively, separated by a porous film that permits the passage of electrolyte. These materials are currently cut by punching and die cutting technologies. The utilization of mechanical cutting devices during fabrication leads to low flexibility with cut geometry being fixed for any particular die arrangement and high repair and replacement costs due to the use of expensive tooling. Cutting quality degrades with the tool wears out. The abovementioned problems can be solved by laser cutting due to the contact-free nature and ease of automation, which is proved and widely utilized in industry[5].

Laser cutting of lithium ion battery electrodes has seen relatively limited research. Kronthaler[6]...
et al. utilized a 30nspulsed 1070nm laser with a maximum average beam power of 100W to cut lithium ion battery cathodes and anodes, evaluating cut quality on the basis of cut edge roughness, delamination width and burr height for specific cases, in which the effects of beam average power and focal position offset were investigated. Luetke[7] et al. presented cuts on lithium ion electrode materials with a 5kW continuous-wave 1070nm laser, obtaining clearance and frazzling widths (ablation width of upper coating layer and protrusion of lower layer, respectively) of less than 35mm. They also performed cuts on electrode sheets with 100ns pulsed 1070nm laser with a maximum average power of 42.5W to compare with the former. Lee[8] et al. presented theoretical models for laser cutting of multi-layer electrode materials, studied the remote cutting of electrodes thin films by means of simulation and experimental investigations. They concluded that the remote laser cutting of copper is a laser intensity and interaction time-dependent process. They also proposed a material mechanism based on sublimation for graphite coating and fusion for copper, suggested that the molten copper expels towards the graphite layer and the uneven molten copper pool reflects the laser beam over the graphite layer[9]. The obtained clearance was around 29µm. Schmieder[10] et al. studied the ablation threshold and heat-affected zone characteristics of remote cut anodes as a function of pulse duration.

While the dependence of cutting quality on specific laser parameters has been presented, however, there remains scope for further investigation of laser cutting lithium ion electrode materials. Heat affected zone (HAZ) and burrs would exist on the electrode films with laser cutting, degrading the service life of the battery. Ultrafast laser cutting of lithium ion electrode materials has not been fully investigated. Ultrafast laser (pulse width less than 10ps) processing with the characteristics of obvious threshold effect[11] and minimal heat affected zone[12], has attracted much attention in the field of fine machining in recent years[13]. It could effective reduce heat affected zone due to its capacity of focusing laser energy onto sample surface in picosecond or femtosecond time scale. In this paper, cutting of graphite coated copper anodes is presented. Dependence of cutting depth and heat affected zone on laser power, scanning speed, scanning times and pulse width are investigated experimentally, which can offer references to ultrafast laser cutting for lithium ion electrode materials.

2. Experimental methods and setup

Commercial lithium ion battery anode films were utilized for the experiments, which were based on thin metallic sheets sandwiched between coating layers. The anode material consisted of 10µm thick copper coated with 60µm graphite on each side, as shown in Fig. 1.

![Fig. 1. Schematic cross-section of anode film](image)
controlled by the gavla-scanner. Fig. 2 shows the schematic of the ultrafast laser cutting system. The laser system was an ultrafast fiber laser in 1030nm wavelength with 250fs~10ps pulse duration and 175KHz~2000KHz (TANGERINE HP2 35W from Amplitude Systems, France). Its maximum average power is 35 W. The spot has a Gaussian energy distribution. A 2D galva-scanner (Scanlab, scanning galvanometer system, Intelliscan III 14 1064nm SL2-100) is used for higher scanning speed and different cutting shapes. The laser beam is focused to a spot diameter of 30µm on the surface of the work piece. Electrode materials are cut to a rectangle of dimensions 5×10mm. Each incision depth and HAZ was analyzed at 3 different points with a 3D microscope system with super depth of field.

Fig. 2. Schematic of the ultrafast laser cutting system

Dependence of cutting depth and heat affected zone on laser power, scanning speed, scanning times and pulse width are investigated experimentally in this paper. The experiments were performed at the laser power 10.7W, 14.6W, 20W, 24.2W, 28.8W and 34.2W and pulse width 250fs, 1ps and 10ps , respectively, with a repetition rate of 175KHz. Cutting speeds applied are 100mm/s and 20mm/s, including \( V \) for the single scan cutting speed and \( V_{\text{avg}} \) for the average cutting speed. \( V_{\text{avg}} \) is obtained as follows:

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V_{\text{avg}} = \frac{V}{N}
\]

where \( V \) is the scanning speed of the gavla-scanner, \( N \) is the scanning times. Thus, study on the influence of scanning times on cutting quality is expressed by that of the cutting speed.

3. Results and discussion

3.1. Incision depth

The incision depth of the anode subject to all laser test groups is presented in Fig. 3(a) for \( V_{\text{avg}}=100\text{mm/s} \) and Fig. 3(b) for \( V_{\text{avg}}=20\text{mm/s} \). An increase in incision depth with average laser power may be observed. At \( V_{\text{avg}}=100\text{mm/s} \), partial removal of the upper graphite coating layers of anodes takes place at the low and moderate tested laser power for all test groups, while complete removal of the graphite layers and partial removal of the metallic layers at high power. Little increase and lower growth rate are observed with the rise of power. A maximum ablation depth of 65µm is obtained with the maximum tested laser power of 34.2W. At \( V_{\text{avg}}=20\text{mm/s} \), it is evident that the incision depth is a piecewise function of the average laser power for anode, as shown in Fig. 3(b).
Initially, incision depth increases with power before complete removal of the coating layer takes place. After this stage, incision depth increases more slowly as the metallic layer is removed. Once penetration of the metallic layer takes place, a minor promotion in laser power is required to achieve a complete cut. A sharp rise in ablation depth is observed in Fig. 3(b). The incision depth is defined as the total anode thickness while a complete penetration takes place. This indicates that the metallic layer is of huge influence on the process despite their relatively low thickness, which is the critical factor in anode cutting. This is due to the great differences in physical properties between the metallic layer and the graphite. Better thermal conductivity and poor optical absorptance of the copper leading to higher ablation thresholds and lower material removal rates in these layers, appearing as higher resistance to the incident laser beam than the coating graphite\(^{14}\). It can be also observed that a gradual increase in incision depth with laser pulse width over the range 250fs~10ps at constant laser power. However, pulse width exerts lower influence on ablation depth than power. In addition, incision depth improves as average cutting speed decrease. As mentioned above, there exists great difference in physical properties between the graphite and the metallic layer while the latter is the key factor during anode cutting. Thus a composed form of process parameters may be applied to the anode cutting for better process capacity.

3.2. Heat affected zone

HAZ can be found on the films during the electrode cutting process and ultrafast pulse laser could effective reduce HAZ. In this paper, a superficial HAZ comprising the clearance width and black regions, while the former is the width of the uncoated metallic layer and the latter is a visible color-changed region after laser ablation.

The kerf of the anode at 28.8W with 10ps pulse width is presented in Fig. 4(a) for \(V_{avg}=100\text{mm/s}\), and Fig. 4(b) for \(V_{avg}=20\text{mm/s}\). Complete removal of the graphite layers and partial removal of the metallic layers may be observed in Fig. 4(a), and a 45\(\mu\)m wide HAZ including a 15\(\mu\)m wide clearance width and a 30\(\mu\)m wide black region is obtained. It can be observed that the inhomogeneity presented in the metallic layer is better than the coating layer in Fig. 4(a), which is attributed to the granular nature of the graphite. Noting that little materials were removed in the black region of the graphite, the observed color changes may therefore be the result of binder
degradation or redeposition of ablated materials from agaseous phase. At $V_{avg}=100\text{mm/s}$, HAZ with an inconspicuous clearance width is presented in Fig. 4(b). This due to part of the metal and graphite were melted and then mixed near the cutting edge so that the clearance width is not obvious at lower average cutting speed. A 66µm wide HAZ is obtained on each side of the kerf, lager than the velocity of 100mm/s. Noting the focused laser spot diameter of the incident laser beam, 30µm, and the narrow incision achieved in the copper layer. Progressive heating and lateral heat transfer in the copper conductive layer leads to removal of the graphite layer via combustion well outside the area directly exposed to the laser beam and expansion of the color changed region$^{[15]}$.  

The HAZ size of anode may be observed in Fig. 5(a) for $V_{avg}=100\text{mm/s}$ and Fig. 5(b) for $V_{avg}=20\text{mm/s}$. An increase in HAZ size with average laser power is presented. More heat is absorbed and transferred by the anode material leading to expansion of HAZ size and color changed
region with laser power increasing. It could also be observed in Fig. 5 that the HAZ size grows with laser pulse width over the range 250fs~10ps at constant laser power, which may be interpreted as an increasing interaction time between single pulse and materials contributing to heat transfer. A maximum HAZ size of 48µm and 72µm for $V_{\text{avg}}=100\text{mm/s}$ and $V_{\text{avg}}=20\text{mm/s}$ is obtained at the highest tested laser power of 34.2W, respectively. Lower average cutting speed brought itself with larger HAZ size may be obtained by comparing Fig. 5(a) with Fig. 5(b), this is due to an increasing interaction time between laser beam and the anode which is contributed to heat accumulation and transfer. Therefore, a suitable power, a smaller pulse width and a higher cutting speed could be applied to ultrafast laser cutting of anode materials when it comes to less HAZ size.

### 3.3. Burrs and cross-section quality

Burrs and the quality of kerf cross-section are also important aspects of the cutting quality. There are two cutting speed in this paper, including $V$ for single scan cutting speed and $V_{\text{avg}}$ for average cutting speed, as mentioned above. Effects of the two cutting speed on burrs and quality of the kerf cross-section had been analyzed in this section. Results show that they have similar processing capacity with a maximum complete cutting speed of 40mm/s. However, differences can be found in cutting quality. On one hand, burr size is dissimilar under the two cutting speed. There exists two kinds of burrs on anode materials, including burrs in XY plane and Z direction, while the XY plane is vertical to the laser beam and Z direction is parallel to it. And burr in Z direction is of great concern to cutting quality. At $V_{\text{avg}}=20\text{mm/s}$ and $V=20\text{mm/s}$, burrs in XY plane with a size of several microns and 13µm are presented, respectively. This is due to the irregular burrs are removed by subsequently scanning process under an average cutting speed condition, which improves the edge homogeneity. But burrs in Z direction are both eliminated with the two cutting speed, as shown in Fig 6. On the other hand, quality of the kerf cross-section with the single scan cutting speed is better.
than average cutting speed. A large amount of widely distributed molten metallic layer could be observed on the cross-section with an average cutting speed, which does not exist under the single scan cutting speed. This may contributed to fusion, flow and spatter of the metal during the cutting with an average speed, which is a process of multiple scanning. The cross-section of anode is presented in Fig 6. In addition, HAZ size less than 42µm is presented at V=20mm/s.

Minimal burr sizes in Z direction and better quality of the cross-section are presented with a single scan cutting speed, and burr size in XY plane is also acceptable because it exerts smaller influence on cutting quality than in Z direction. Therefore, the single scan cutting speed is more applicable to cut anode materials taking burr size and cross-section quality into consideration.

4. Conclusions

Dependence of incision depth and heat affected zone on laser power, scanning speed, marking times and pulse width are investigated. Burrs and cross-section quality are analyzed. Results show that kerf with heat affected zone less than 42µm and no burrs are obtained with ultrafast laser cutting of anode materials. The analysis has led to the following findings:

(1) Incision depth is a piecewise function of the average laser power for anode. The metallic layer is of huge influence on the process despite their relatively low thickness. A gradual increase in incision depth with laser pulse width over the range 250fs~10ps at constant laser power could also be observed. However, pulse width has a lower influence on ablation depth than power. Thus a composed form of process parameters could be applied to the anode cutting for better process capacity due to the great difference in physical properties between the graphite and the metallic layer while the latter is the critical factor during anode cutting.

(2) The size of the HAZ is significantly related to laser average power, pulsed width and cutting speed. On one hand, an increase in HAZ size with average laser power may be observed. On the other hand, the HAZ size grows with laser pulse width over the range 250fs~10ps at constant laser power. In addition, lower average cutting speed brought itself with lager HAZ size. Suitable power, minor pulse width and higher cutting speed could be applied to ultrafast laser cutting of anode materials when it comes to less HAZ size.

(3) Effects of the two cutting speed on burrs and kerf cross-section quality had been analyzed. Results show that they have similar processing capacity, but differences in burr size and quality of cross-section could be found at a single scan cutting speed and average cutting speed both of 20mm/s. Acceptable burr size, better cross-section quality and smaller HAZ size were obtained with a single scan cutting speed, which is more applicable to ultrafast laser cutting of anode materials.

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References


