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The influences of pulse overlap on cut quality during fiber laser cutting of electrodes for Lithium-ion batteries

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Abstract

Concerning e-mobility and the research of highly developed battery technologies within the automotive sector the quality improvement and cost reduction of Lithium-ion batteries is an important challenge. Therefore the Battery LabFactory Braunschweig (BLB) examines the entire production chain with the objective of improving the energy density, quality and reliability of these traction batteries.
Within this development programme the cutting of the electrodes represents a significant challenge for the production of Lithium-ion batteries. Compared to die cutting the approach of contactless laser cutting offers a higher flexibility and reduced tool costs. Furthermore the decreased edge quality due to the tool wear can be prevented by using laser cutting.
Referring to laser cutting of thin metal and composite sheets by using a fiber laser a particular challenge is the improvement of the cut quality as well as the reduction of the heat affected zone leading to a degradation of properties. This comparative study investigates different process parameters such as pulse frequency or cutting speed and focuses on the influence of pulse overlap or respectively yielded energy to minimize the heat affected zone and thus improve the quality of the cut. The influences of the pulse overlap on the delamination width which is defined as the delamination of the coated layer of the metal substrate at the laser cut kerf are examined.

Keywords: Laser cutting; Lithium-ion battery; Fiber laser; Pulse overlap

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1. Motivation / State of the Art

With focus to the increasing market of electronic vehicles within the automotive sector a major challenge consists in the mass production of the Lithium-ion batteries. Due to the high requirements in product quality and cost efficiency a sophisticated production chain has to be developed.

Therefore the Battery LabFactory Braunschweig (BLB) investigates the entire production chain from the manufacturing of the electrodes to the cell, module until the system integration with the objective of improving the energy density, quality and reliability of these traction batteries. The production chain is shown in Figure 1.

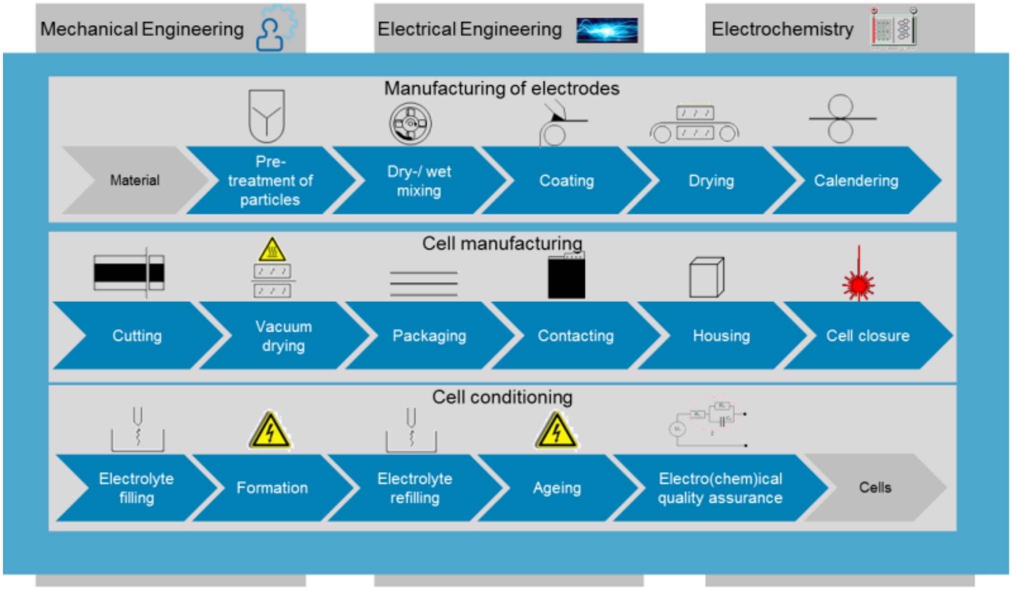

Fig. 1. Overview production chain Battery LabFactory Braunschweig

Within this production chain the interaction of the areas of mechanical engineering, electrical engineering and electrochemistry is required. The process is divided into the manufacturing of the electrodes, the cell manufacturing and the cell conditioning. Referring to the cell manufacturing the cutting of the electrodes forms a significant part and is addressed in this paper.

To achieve the defined goals of the Battery LabFactory Braunschweig the cutting of the electrodes is an important challenge concerning the processing speed, the reproducibility as well as the reliability. Furthermore, the technical requirements as conductivity and resistivity relating to cut quality have to be studied. The entire cutting process should be fully automated. The calendered electrodes are located on a unwind unit and were automatically positioned under the laser cutting system by using vacuum. After cutting the electrodes are taken by a gripper and dropped. The rest of the material is rolled up and can be recycled.

Due to the uncomplicated process and the short cycle times die cutting of electrodes is already state of the art [1]. Regarding the challenging requirements of the mobility sector the reliable and reproducible cut quality, especially a burr and delamination free cutting edge, of the die cut electrodes cannot be ensured. The reason for the deteriorating cut quality results in the direct contact of the tool and the electrodes in the production process and the wear of the die cutting tool. With regard to high production cycles the die cutting tool has to be changed often which results in higher production costs and setup-times. The lower cut quality leads to a reduced life time of the cells as well as a higher resistivity and a diminished conductivity. In addition, a delamination at the cutting edge can cause a short circuit in the cell [2, 3, 4].

The advantage of laser cutting compared with die cutting consists in the contactless cutting process. The setup-times because of wear of the tool can be prevented. Furthermore, different geometries of electrodes can be cut without manufacturing new tools which offers higher flexibility in the production process. The electrodes comprise areas of purely metal for the handling and contacting of the stack as well as coated areas. Regarding the cut quality the laser cutting enables different cutting parameters for the metal and the coated areas [1]. Due to the contactless and reproducible process higher conductivity and lower resistivity can be achieved by using laser cutting. Laser cutting generates a high energy input into the electrodes which leads to a heat affected zone influencing the electrical performance of the electrodes. In addition, the energy input can cause a delamination of the coated electrode [3, 5].

This paper examines various process parameters (i.e. cutting speed, pulse repetition frequency, line energy, pulse overlap) to minimize the heat affected zone (HAZ) as well as delamination at the cutting edge. Due to the different reflection and absorption of the uncoated metal substrates and the coated electrodes the cutting process is depending on the material. Therefore the examinations are divided into two parts. At first the uncoated metal substrates are examined. After that the coated electrodes are studied.

2. Experiments

2.1. Experimental setup

Concerning the potential of integration into an automated production chain of the Battery LabFactory Braunschweig a laser remote cutting process by using a SPI G4 pulsed fiber laser was selected. Furthermore, pulsed fiber lasers offer a cutting process with a low thermal damage due to the reduced energy input [6]. The fiber laser applied here emits radiation with a wavelength of 1062 nm, has an average output power up to 71 W for pulse repetition rates from 70 kHz to 500 kHz and maximum pulse energy up to 1 mJ. The pulse width is in the range of some ten nanoseconds and the spot diameter approximately 90 µm. All trials were carried out in pulse mode. The scanner is defined as a Raylase Axialcan-30-Y with a working distance of 455 mm.

With the focus on reproducibility the electrodes were hold by vacuum in a defined position. The experimental setup is shown in Figure 2.

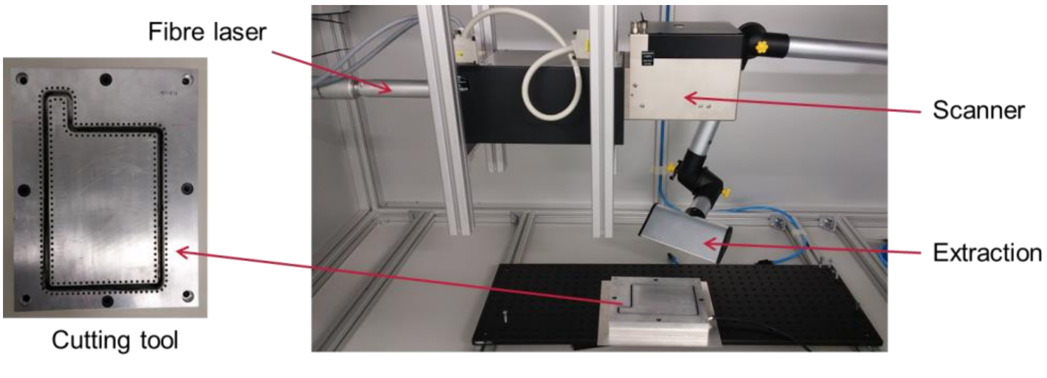

Fig. 2. Experimental setup and cutting tool

The examinations consider not only the coated electrodes but also the uncoated metal substrates which are necessary for the handling and the electrical contacting. Both areas are shown exemplary for the anode in Figure 3.

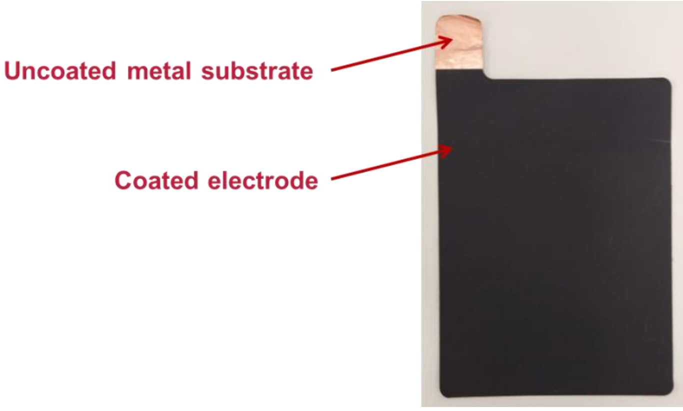

Fig. 3. Experimental setup and cutting tool

2.2. Laser parameter

This paper focuses on the influence of the pulse overlap respectively the yielded energy. The pulse overlap is defined as [7]:

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

The pulse overlap is depending on the cutting speed v_c, the pulse repetition frequency f_{pulse} and the spot diameter d_{spot}. At constant spot diameter the pulse overlap can be varied by altering the pulse repetition frequency and the cutting speed.

Instead of varying the average power the influence of the yielded energy is a promising approach. Therefore the line energy which refers the pulse peak power to an area element with the width of a spot diameter is selected [7].

$$PD_{Line} = \frac{P_{avg}}{f_{pulse} \cdot v_c \cdot d_{spot} \cdot \tau} \tag{2}$$

Calculating the PD_{line} the average power is divided by the product of cutting speed v_c, pulse repetition frequency f_{pulse}, pulse length τ and spot diameter d_{spot}. The average power divided by the cutting speed and the spot diameter considers the pulse peak power.

2.3. Materials and assessment criteria

This paper investigates the anode based on copper substrate coated on both sides with MCMB (Meso Carbon Micro Beads) and additives. The substrate has a thickness of 10 µm whereas each coating has a thickness of 43 µm. The cathode is based on an aluminium substrate coated on both sides with Lithium-NMC (Nickel-Mangan-Cobald) and some additives. The thickness of the aluminium substrate is in a range of 20 µm whereas the coating on each side has a thickness of 42 µm.

The assessment criteria for the cut quality are the heat affected zone as well as the delamination width occurring while cutting electrodes quality and are shown in Figure 4 [2, 3].

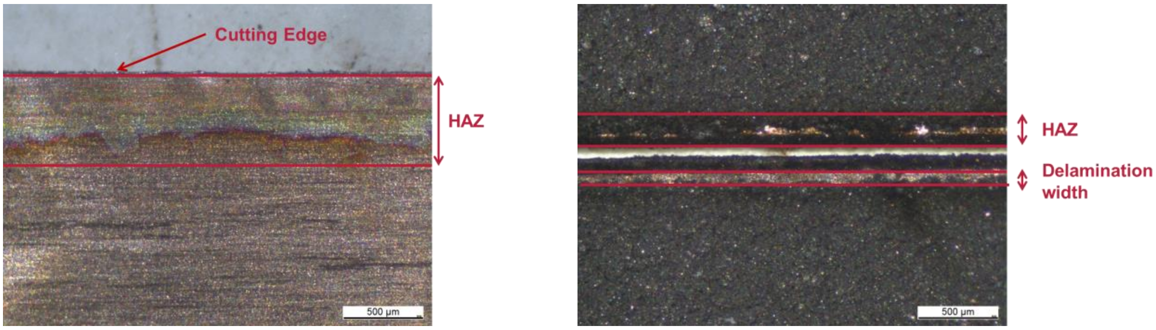

Fig. 4. Assessment criteria cut quality

The heat affected zone is shown for the copper as example for the uncoated metal substrates of the electrodes. The delamination width which is the second important criteria is measured in Figure 4 after cutting the anode. The area of exposed copper is hereby clearly visible.

3. Results and discussion

3.1. Influence of the manufacturing process on cut quality

This chapter focuses on the cutting of the uncoated metal substrates. Regarding the cutting process the uncoated metal layers of the electrodes show a dependency of the direction due to the manufacturing process. Especially the rolling of the metal substrates which is necessary for achieving a defined thickness is responsible for this dependency. The following examinations distinguish between the substrate in longitudinal which means in rolling direction and the transversal direction. Copper which is used as substrate for the anode as well as aluminium for the cathode are considered. The maximum cutting speed depending on the pulse repetition frequency and the pulse energy is shown in Figure 5. The maximum cutting speed is defined as the cutting speed which is the highest cutting speed enabling a complete cut of the metal substrates. The average power is about 71 W, pulse length and spot diameter are constant at the values given in the diagrams.

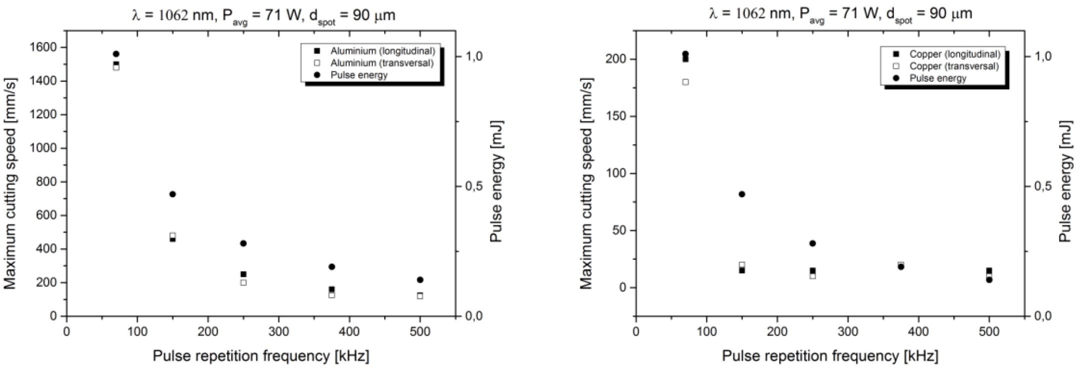

Fig. 5. Maximum cutting speeds metal substrates in dependence of pulse repetition frequency for uncoated metal substrates

Both substrates show a correlation of the maximum cutting speed and the pulse repetition frequency respectively the pulse energy. Lower pulse repetition frequencies enable higher maximum cutting speeds due to higher pulse energies. The maximum cutting speed for the aluminium substrates is a range between 1500 mm/s at a pulse repetition frequency of 70 kHz and 125 mm/s at 500 kHz whereas the copper substrate varies between 200 mm/s at 70 kHz and 15 mm/s at 500 kHz. The copper substrates have a lower maximum cutting speed compared to the aluminium substrates because of the lower absorption of copper [6]. In addition, no dependency of the rolling direction on the maximum cutting speed is identifiable.

To examine the influence on the heat affected zone the maximum cutting speed for the longitudinal as well as the transversal direction depending on the pulse repetition frequency respectively the pulse energy are investigated. All trails are carried out by an average power of 71 W. With the goal of demonstrating the general influence Figure 6 illustrates the results for a pulse repetition frequency of 70 kHz.

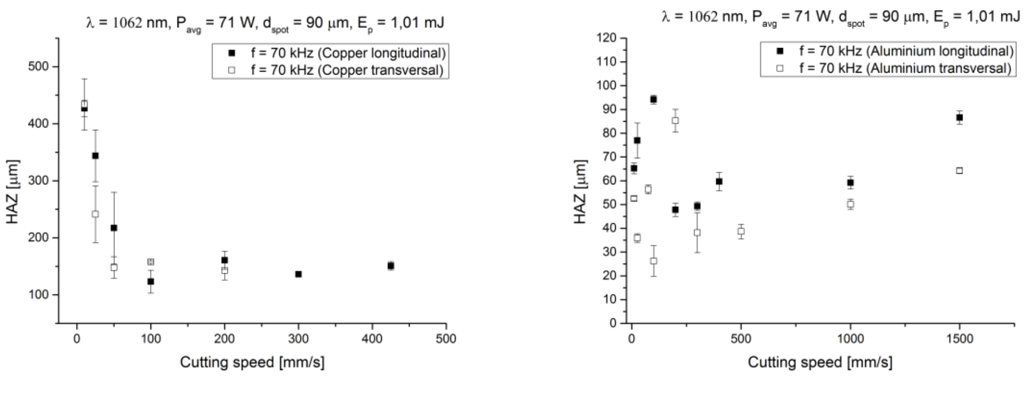

Fig. 6. Heat affected zone metal substrates copper

The HAZ of the copper substrates is in a range between 135 µm and 425 µm depending on the cutting speed. In addition, a high standard deviation at the lower cutting speeds can be observed. During the cutting process a discoloration respectively annealing colors of the copper substrates occur. Due to the reduced absorption of pure copper an oxide formation owing to energy input is necessary for the cutting process. To create these oxide formations the lower energy input is sufficient. Low cutting speeds produce a higher energy input than necessary to create the oxide formation so that the additional energy input produces a higher HAZ compared to higher cutting speeds. Higher cutting speeds with lower energy input are sufficient to produce the oxide formation and in combination a lower HAZ. Furthermore, a difference between the longitudinal and transversal copper can be observed. A possible explanation is the anisotropic thermal conductivity due to the rolling process in the manufacturing of the electrodes.

The HAZ of the aluminium substrates is in the range up to 100 µm. Furthermore, the HAZ does not depend on the cutting speed and the duration of the energy input. Compared to copper the absorption of aluminium at the wavelength of 1062 nm is significantly higher so that no oxide formations enabling cutting are necessary. In contrast to the maximum cutting speeds in Figure 5 a dependency of the rolling direction is identifiable which can be again explained due to anisotropy of the thermal conductivity caused by the rolling process. In comparison with copper the HAZ of the aluminium substrate is significantly lower because of the reduced thermal conductivity.

3.2. Cutting of electrodes

Relating to low production times the maximum cutting speeds for the electrodes, meaning coated aluminium and copper are examined in this chapter. The anode is based on a copper substrate coated with MCMB, the cathode on aluminium substrate coated with NMC. The maximum cutting speed depending on the pulse repetition frequency and the pulse energy is shown in Figure 7. The maximum cutting speed is defined as the highest cutting speed enabling a complete cut of the metal substrates. The average power is 71 W, the pulse length about 46 ns and the spot diameter amounts approximately 90 µm.

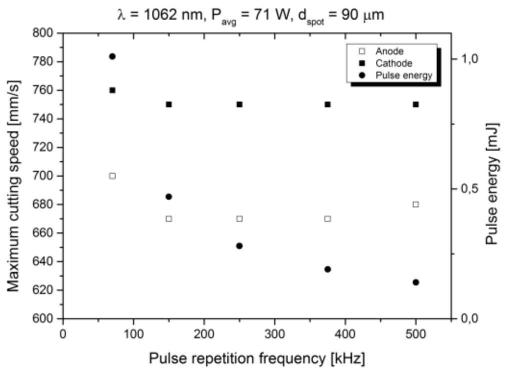

Fig. 7. Maximum cutting speeds electrodes depending on the pulse repetition frequency

The maximum cutting speed for the cathode is in a range of 750 mm/s whereas the maximum cutting speed for the anode is about 680 mm/s. The difference between both electrodes can be explained due to the various thermal conductivities of the substrates. In comparison with the pure uncoated substrates in chapter 3.1 the absolute difference is lower because of the absorption of the coatings. In addition, comparing to the uncoated sheets no dependence of the pulse repetition frequency respectively the pulse energy is identifiable. Referring to this cutting can be enabled by the pulse energy of one pulse due to the absorption of the coating.

The influence of the line energy on the HAZ of the anode as well as cathode is also studied. Two different pulse repetition frequencies are examined. Calculating the line energy at constant pulse repetition frequency is done by variation of the cutting speed. Pulse length, average power and spot diameter are kept constant. Figure 8 demonstrates the influence of the yielded energy on the HAZ of the electrodes.

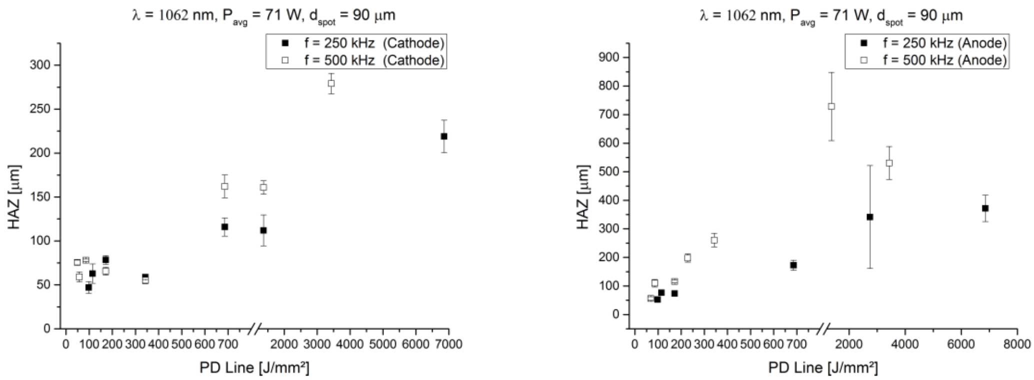

Fig. 8. Influence of the yielded energy on the HAZ

With regard to the cathode as well as anode the HAZ increases with growing PD Line due to the higher energy input whereas the HAZ is higher with growing pulse repetition frequencies. The minimum of the HAZ of the cathode is in a range of 50 µm which is comparable to the examinations of copper. Furthermore, increasing PD Line produces higher standard deviations. Due to the higher absorption of the coatings lower pulse repetition frequencies with higher pulse energies cut the electrodes with one pulse whereas higher pulse repetition require more hits per line increment to cut the materials which implicates a larger HAZ.

In addition, the influence of the line energy on the delamination width of the anode as well as cathode is examined. Three different pulse repetition energies are studied. The line energy at constant pulse repetition frequencies is calculated by variation of the cutting speed. Average power, spot diameter and pulse length are constant. Figure 9 shows the influence of the yielded energy on the delamination width.

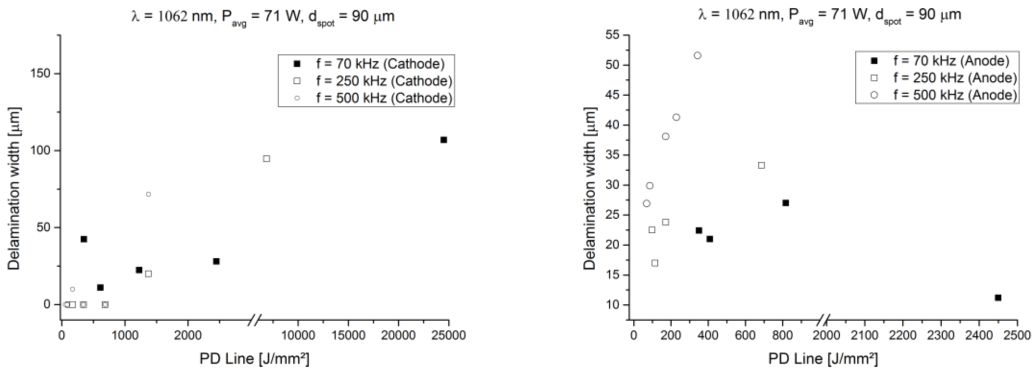

Fig. 9. Influence of the yielded energy on the delamination width

The delamination width of the anode is in a range up to 52 µm whereas the highest values can be observed for the pulse repetition frequency of 70 kHz. The delamination cannot be avoided referring to the examined pulse repetition frequencies. With increasing line energy the delamination width also grows due to the higher energy input. A possible explanation of the influence of the pulse repetition frequencies is that at lower pulse repetition energies in connection with the high absorption of the coating and the thermal conductivity of copper one pulse with increased pulse energy is enough for cutting.

Considering the cathode the delamination width also reduces with increasing line energy due to the lower energy input. In comparison with copper the delamination can be totally avoided at high pulse repetition frequencies and low line energy. The coating of the cathode and the lower thermal conductivity of aluminium comparing to copper prevents a negative influence of higher pulse repetition frequencies on the delamination width. Lower pulse repetition frequencies produce higher delamination width because of higher pulse energies.

The pulse overlap is depending on the spot diameter, the pulse repetition frequency as well as cutting speed. With regard to the previous studies minimum pulse overlap respectively minimum line energy depending on the pulse repetition frequency is necessary for cutting the electrodes. The minimum pulse overlap for cutting the anode at a pulse repetition frequency of 70 kHz is about 88.89 % which signifies minimum line energy of 349.99 J/mm². Cutting the anode at a pulse repetition frequency of 70 kHz requires a minimum pulse overlap of 87.94 % respectively minimum line energy of 326.66 J/mm². To examine the influence of an increasing pulse overlap on the HAZ as well as the delamination width at a constant line energy the pulse overlap is increased in Figure 10 by non-varying line energy. Therefore by increasing pulse overlap the pulse repetition frequency is adjusted with the goal of a constant yielded energy. The cutting speed also changes due to the variation of the pulse overlap. The average power and the spot diameter are still non-varying.

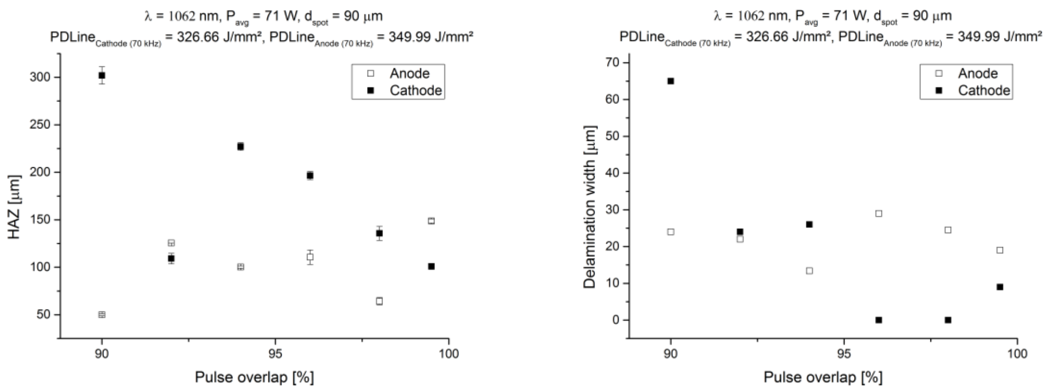

Fig. 10. Influence of the pulse overlap at constant line energy

The HAZ of the cathode is in a range between 300 µm at a pulse overlap at 90.0 % and 100 µm at a pulse overlap at 99.0 %. In addition, the HAZ decreases with increasing pulse overlap due to the higher pulse repetition frequencies respectively lower pulse energies. Referring to the anode no tendency is identifiable whereas the values of the HAZ are lower compared to the cathode. This difference can be explained with the higher thermal conductivity of copper.

Regarding to the delamination width of the cathode an increase of the pulse overlap causes a decrease in the delamination width. By using higher pulse overlap a complete avoiding of a delamination is possible.

Higher pulse overlaps significates a higher pulse repetition frequency and lower pulse energies. This effect could be also observed in Figure 9 by regarding the influence of the yielded energy. Considering the anode no influence of the pulse overlap on the delamination width is visible. This fact is explainable by regarding the higher thermal conductivity of the copper substrate. Comparing to the cathode the delamination width cannot be avoided totally.

4. Conclusion

The paper focuses on the influence of different laser parameter on the heat affected zone as well as the delamination width to evaluate the cut quality. Regarding the metal substrates a dependency of the direction on the heat affected zone due to the manufacturing process was shown. The copper substrate of the anode is much more critical because of the lower absorption. Increasing pulse energies which depend on the pulse repetition frequency allow lower production times for the cutting process.

Relating to the electrodes the maximum cutting speed is independent from the pulse repetition frequency respectively the pulse energy due to the higher absorption of the coating. The heat affected zone can be decreased by using lower pulse repetition frequencies. The increase of the line energy causes a higher heat affected zone as well as delamination width. With regard to the cathode a complete avoiding of the delamination could be achieved by applying low line energies and high pulse repetition frequencies. The influence of the pulse energy on the heat affected zone as well as the delamination width is thus contrary. The variation of the pulse overlap at constant line energy showed the potential of improving the cut quality, especially the heat affected zone, of the cathode.

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