Experimental Study of Electrode Structuring using Nanosecond Laser for Enhanced Battery Performance

리튬이온 배터리 성능 향상을 위한 나노초 레이저를 이용한 전극의 구조화 실험적 연구

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Abstract

Currently, alternative energy sources are attracting attention owing to environmental pollution and the depletion of fossil fuels. Lithium-ion batteries have a light weight, high energy density, high power density, and long cycle life, making them attractive alternative energy sources. Numerous studies have been conducted on high-performance batteries. However, most studies have focused on improving active material characteristics. Thus, there is a lack of research on battery performance enhancement through the improvement of the battery manufacturing process. In this study, we performed electrode structuring using a nanosecond laser in the power range of 1 W to 19 W (2 W intervals). The geometric changes after laser structuring were observed using a scanning electron microscope, and the electrode geometries were classified and measured in terms of ablation width and depth. The aspect ratio, removal amount, and removal rate of the active material were analyzed after laser structuring. A maximum aspect ratio of 0.77 was achieved. Additionally, the removal amount and removal rate of the active material increased with the increase in laser power. Therefore, we concluded that electrode geometry can be controlled using a nanosecond laser.

Key Words : Lithium-ion battery; Laser structuring; Nanosecond laser; Aspect ratio

1. Introduction

Lithium-ion batteries have attracted attention as a solution for environmental pollution and fossil fuel depletion due to their benefits of light weight, high energy density, high power density, and long cycle life. A lithium-ion battery consists of a cathode, an anode, an electrolyte, and a separator. In particular, the cathode and anode are important elements that determine the energy and power densities of the battery¹⁻²⁾. Therefore, many studies have been conducted to improve battery performance in the electrode manufacturing process and to address the existing problems with the battery processing process. As for studies related to battery performance improvement, Li et al.³⁾ improved the power density by forming the coating layer of carbon

and GdPO₄ on LiFePO₄ and thereby increasing the ion diffusion rate. Lee et al.⁴⁾ cut electrodes using a laser to complement the shortcomings of the existing electrode cutting process. They compared cutting characteristics between compressed and uncompressed electrodes, and reported that compressed electrodes are more favorable for obtaining a uniform cutting width when electrodes are cut using a laser.

In recent years, many processes, such as cutting, welding, heat treatment, and surface processing, have been successfully replaced with laser⁵⁻⁹⁾. Laser is used for non-contact processing. They require low maintenance cost and can reduce the contamination of workpieces. They also enable micro-scale processing and can easily process complex geometry. Moreover, laser can process sensitive materials, such as plastics, glass, and thin films, with minimal deformation^{10,13)}.

In this study, electrode structuring was performed using a laser to improve the power density of the lithium-ion battery. A problem with the existing electrode structure is that applying a thick coat of an active material to increase the energy density decreases the power density and, conversely, applying a thin coat of the active material to increase the power density decreases the energy density and accelerates the discharge of the battery. To overcome these limitations of the electrode structure, three-dimensional electrodes have been proposed. In a previous study, laser structuring was performed using femtosecond-laser, picosecond-laser, and nanosecond-laser pulses on LiFePO_4 electrodes, and the formed grooves and battery performances were compared¹⁴⁾. As the pulse duration was shorter, the aspect ratio of the structured electrode increased. As the aspect ratio increased, an increase in power density was reported in the battery performance test. In a previous study, however, only the influence of the pulse duration was observed and information on changes according to the laser power was not provided. In addition, the femtosecond laser, which has a small thermal effect and is favorable for selectively removing materials, is still an expensive device¹⁰⁾. Therefore, this study was conducted as a basic study to fabricate a high-power battery by forming geometric shapes on the electrode surface using the nanosecond laser, which requires lower investment cost than the femtosecond laser. Using nanosecond laser, the influence of the laser power was observed through the ablation width, ablation depth, and aspect ratio. In addition, the removal amount and the removal rate of active material were analyzed.

2. Experimental Materials and Methods

2.1 Material

Fig. 1 shows the photograph of the electrode used in the experiment and the schematic of its cut surface. The electrode was fabricated in a dry room where the room

Fig. 1 Image of electrode used for the experiments

Table 1 Information of electrode used for the experiments

Classification	Information
Structure	One-side sandwich
Active material	LiFePO_4 (8)
Binder	Polyvinylidene fluoride (1)
Conducting agent	Super P (1)
Active electrode thickness	$90 \mu\text{m} \rightarrow 74 \mu\text{m}$
Current collector	Aluminum Foil
Current collector thickness	$20 \mu\text{m}$

temperature was 20°C and the dew point was maintained at -40°C or less. Table 1 shows detailed information on the electrode. The slurry used for the electrode was prepared by mixing LiFePO_4 (active material), polyvinylidene fluoride (binder), and Super P (conducting agent) at a mass fraction ratio of 8:1:1. The prepared slurry with a thickness of $90 \mu\text{m}$ was coated only on one side on $20 \mu\text{m}$ aluminum foil to make an electrode with the one-side sandwich structure. It was subjected to primary drying in an oven at 120°C for two hours and the electrode was compressed by performing calendaring to create an electrode with a total thickness of $94 \mu\text{m}$. Finally, secondary drying was performed at 120°C for 24 hours.

Fig. 2 Schematic of the nanosecond laser for laser structuring of electrode

Table 2 Laser parameters used for the experiments

Parameters	Specifications
Average power	1~19 W
Mode	Pulsed laser
Wavelength	1064 nm
Pulse duration	4 ns
Pulse repetition rate	500 kHz
Scanning speed	500 mm/s
Focal length	189 mm
Spot size	Approx. 30 μm
Beam quality (M2)	1.5

2.2 Laser processing

The ytterbium pulsed fiber laser (YLPM-1-4x200-20-20, IPG) used for electrode structuring had a maximum average power of 20 W and a wavelength of 1,064 nm. It could also change the pulse duration from 4 to 200 ns. Its M^2 value was 1.5. The experiment was simplified by only changing the average power among various laser processing parameters. The average power was increased by 2 W from 1 to 19 W.

2.3 Analysis method

Fig. 3 shows a scanning electron microscope (SEM) image captured after laser irradiation on the electrode. The ablation top width (W_{top}), ablation bottom width (W_{bot}), and ablation depth (D) were defined to analyze the geometric change of the electrode. The ablation top width is the top width of the groove formed when the active material was removed by laser processing on the electrode. The ablation bottom width is the bottom width of the groove formed when the active material was removed by laser processing on the electrode, and the ablation depth is the depth of the groove formed when the active material was removed by laser process-

Fig. 3 Measurement method of the ablation top width, ablation bottom width, ablation depth

ing on the electrode. The aspect ratio was calculated using the measured ablation top width and ablation depth.

3. Experiment Results and Discussion

3.1 Ablation width and Ablation depth

Fig. 4 shows the SEM images of the electrode after laser processing. As can be seen from the figure, as the laser power increased, both the ablation width and ablation depth increased. The top view (Fig. 4(a)) shows that the depth of the groove generated in the active material layer increased and reached the surface of the current collector as the laser power increased, but the Al foil with the active material completely removed was not observed. Fig. 5 shows the ablation width and ablation depth measurements according to the laser power. Fig. 5(a) shows that the ablation top width linearly increased as the laser power increased. The largest width of approximately 102 μm was observed when the power was 19 W. The ablation bottom width, on the other hand, was not formed until 13 W, and it was formed from 15 W as most of the active material was removed. Fig. 5(b) shows that the ablation depth linearly increased as the laser power increased. It increased more rapidly compared to the ablation width, but it no longer increased after the coated active material was removed to the surface of the current collector. For a more accurate comparison, the trend lines and correlation coefficients (γ) of the ablation width and ablation depth were calculated through regression analysis. As the ablation depth no longer increased due to the complete removal of the active material from 13 W of the laser power, only the data before the complete removal of the active material were used for the regression analysis. As shown in Fig. 5, the trend line slope of the ablation width was 5.1643 and that of the ablation depth was 5.9063, indicating that the slope of the ablation depth increased more rapidly.

3.2 Aspect ratio

Fig. 6(a) shows the aspect ratio results according to the laser power calculated using the above ablation top width and ablation depth measurements. For structured electrodes, the aspect ratio of the formed groove is important because the electrode with a relatively higher aspect ratio has an increased surface area that can react electrochemically when grooves with the same width are formed. Consequently, an increase in the diffusion path of L^+ is favorable for the high-speed charging and discharging of the battery (Fig. 6(b))¹⁴⁾. After laser irra-

(a) Top view

(b) Cross section view

Fig. 4 SEM image of the electrode after laser structuring in 1pass (a) Top view (b) Cross section view **Fig. 5** (a) Ablation width and (b) ablation depth depending on power at 1pass

diation, the aspect ratio of the groove formed in the electrode sharply increased as the power increased from 1 to 11 W, and it gradually decreased from 13 W. This is because the ablation top width increased with almost the same slope as the power increased from 1 to 19 W, but the ablation depth no longer increased after 13 W despite its relatively rapid increase when the power increased from 1 to 13 W. In addition, the aspect ratio was highest (approximately 0.77) when the power was 11 W.

3.3 Removal amount and Removal rate of active material

Fig. 7 shows the removal amount of active material and the active material removal rate after the laser structuring process of the electrode. The amount of the active material of the electrode is closely related to the energy density of the battery. This is because the energy density of the battery increases as the amount of the active material increases. Laser structuring of the

Fig. 6 (a) Aspect ratio of structured-electrodes depending on laser power and (b) comparison of Li⁺ diffusion path in high and low aspect ratio groove in structured-electrodes

Fig. 7 (a) Removal amount and (b) removal rate of active material depending on power

electrode, however, is a method for increasing the power density by partially removing the active material and thereby causing electrochemical reaction on a larger surface. Therefore, the removal amount of active material needs to be analyzed, and further optimization is required. In addition, it is necessary to analyze the active material removal rate to determine the efficiency of the processing process. The removal amount of active material per unit volume and the removal rate per minute were calculated using equations (1) and (2).

$$\text{Removal amount of active material (mm}^3\text{)} = \frac{1}{2}(W_{top} + W_{bot}) \times D \times 1\text{mm} \quad (1)$$

$$\text{Active material removal rate (}\frac{\text{mm}^3}{\text{min}}\text{)} = \frac{1}{2}[(W_{top} + W_{bot}) \times D] \times \nu \quad (2)$$

The removal amount of active material per unit length (1 mm) was calculated using the measured ablation top width (W_{top}), ablation bottom width (W_{bot}), and ablation depth (D) as shown in equation (1). The active material removal rate was calculated using the ablation top width (W_{top}), ablation bottom width (W_{bot}), ablation

depth (D), and scanning speed (ν) as shown in equation (2). Fig. 7(a) shows that the removal amount of active material increased as the laser power increased. It slowly increased as the power increased from 1 to 13 W, and then relatively sharply increased after 15 W. This appears to be because multiple reflections actively occurred from 15 W as most of the active material was removed and the laser beam reflected from the Al foil increased. Fig. 7(b) shows the active material removal rate per minute. The active material removal rate per minute increased as the laser power increased. Therefore, the efficiency of the laser structuring process increased as the laser power increased.

4. Conclusion

This study is a basic study on the electrode laser structuring process for high-power batteries. The electrode used in the experiment used LiFePO₄ as an active material, and the possibility of the laser structuring process that uses the nanosecond laser was discussed.

1) As the laser power increased, the ablation top width and ablation bottom width increased. Under the experimental conditions, the maximum ablation top width and ablation bottom width were measured to be approx-

imately 102 and 53 μm , respectively.

2) The ablation depth increased as the laser power increased, but it no longer increased after 74 μm at which most of the active material was removed. In addition, the depth of the groove formed by laser processing reached the surface of the current collector, but the Al foil with the active material completely removed was not observed.

3) The removal amount of active material and the active material removal rate showed a tendency to increase as the laser power increased. The increase in laser power exhibited high efficiency in terms of process, but decreased the energy density of the battery by increasing the removal amount of active material in terms of battery performance.

4) The electrode laser structuring process overcomes the existing limitations of the electrode structure and improves the power density of the battery, but decreases the energy density due to the removal of the active material during the process. Therefore, appropriate laser processing parameters are required to maximize the effect of the electrode structuring process.

To verify the validity of this study, a rate capability test will be conducted by fabricating a coin cell. In addition, various processing parameters, such as the laser power, scanning speed, repetition rate, pulse duration, and number of passes, will be analyzed for the optimization of the electrode laser structuring process.

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리튬이온 배터리 성능 향상을 위한 나노초 레이저를 이용한 전극의 구조화 실험적 연구

Experimental Study of Electrode Structuring using Nanosecond Laser for Enhanced Battery Performance

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1. 서 론

현재 리튬이온 배터리는(Lithium-ion battery)는 가벼운 중량, 높은 에너지밀도, 높은 출력밀도, 긴 사이클 수명의 장점이 있어, 환경오염 및 화석연료의 고갈 문제의 해결책으로 관심이 높아지고 있다. 리튬이온 배터리는 cathode, anode, electrolyte, separator로 구성되어 있다. 특히, cathode와 anode는 배터리의 에너지 밀도 및 출력 밀도를 결정하는 중요한 요소이다^{1,2)}. 따라서, 전극제조공정에서 배터리 성능 향상 및 기존의 배터리 가공공정의 문제점을 개선하기 위하여 많은 연구가 진행되고 있다. 배터리 성능 향상 관련 연구에서 Li 등³⁾은 LiFePO₄에 Carbon과 GdPO₄의 코팅층을 형성하여 이온 확산 속도를 증가시켜 출력밀도를 높였다. 한편, 기존의 전극 절단 공정의 단점을 보완하기 위하여 Lee 등⁴⁾은 레이저를 사용하여 전극을 절단하였으며, 압축전극과 비압축전극의 절단특성을 비교하였고 레이저를 이용하여 전극을 절단할 때 압축된 전극이 균일한 절단폭을 얻기 유리하다는 것을 제시하였다.

최근 절단, 용접, 열처리, 표면가공 등 많은 공정들이 레이저로 성공적으로 대체되고 있다^{5,9)}. 레이저는 비접촉식 가공으로 유지보수비용이 적으며, 가공물의 오염을 줄일 수 있다. 그리고 micro-scale의 가공이 가능하며, 복잡한 형상의 가공도 쉽게 할 수 있다. 게다가 플라스틱, 유리 및 박막 등 민감한 재료도 변형을 최소화하여 가공할 수 있다^{10,13)}.

본 연구에서 배터리의 출력밀도를 향상시키기 위하여 레이저를 이용한 전극구조화를 진행하였다. 기존의 전극 구조의 문제점은 에너지밀도를 증가시키기 위해 활물질을 두껍게 코팅하면 출력밀도가 감소하며, 반대로 출력밀도를 높이기 위해 활물질을 얇게 코팅하면 에너지밀도가 낮아 배터리가 빠르게 방전된다. 이러한 전극

구조의 한계를 극복하기 위하여 3차원 형태의 전극이 제시되고 있다. 선행된 연구에서 LiFePO₄ 전극에 femtosecond-laser, picosecond-laser, nanosecond-laser를 각각 사용하여 레이저 구조화(laser structuring)을 진행하여 형성된 groove 및 배터리 성능을 비교하였다¹⁴⁾. Pulse duration이 짧을수록 구조화된 전극의 홈(groove)의 aspect ratio가 증가하였다. 또한 aspect ratio가 증가할수록 배터리 성능테스트에서 출력밀도가 증가하는 것을 보고하였다. 하지만, 선행된 연구에선 pulse duration에 대한 영향만 관찰하였으며, 레이저 출력에 따른 변화에 대한 정보는 부족하다. 그리고, 열영향이 적으며, 선택적으로 재료를 제거하기 유리한 femtosecond-laser는 여전히 고가의 장비이다¹⁰⁾. 따라서, 본 연구는 femtosecond-laser 보다 투자비용이 적은 nanosecond-laser를 이용하여 전극표면에 기하학적 형상을 가공하여 고출력 배터리를 제작하기 위한 기초연구이다. Nano-second-laser를 이용하여 레이저 출력에 따른 영향을 ablation width, ablation depth, aspect ratio를 통해 관찰하였다. 또한, 활물질(active material)의 제거량과 활물질의 제거율을 분석하였다.

2. 실험재료 및 실험방법

2.1 전극제작

Fig. 1는 실험에 사용된 전극의 사진과 절단면을 모식도로 표현하였다. 실험에 사용된 전극은 실내 온도 20 ℃ 와 이슬점(Dew Point) -40 ℃ 이하로 유지되는 dry room 안에서 제작됐다. Table 1은 실험에 사용된 전극의 자세한 정보를 나타냈다. 전극에 사용된 slurry는 LiFePO₄(active material)와 Polyvinylidene Fluoride (Binder)과 Super P (Conducting agent)를 질량분율 8 : 1 : 1로 섞어 제작되었다. 제

Fig. 1 Image of electrode used for the experiments

Table 1 Information of electrode used for the experiments

Classification	Information
Structure	One-side sandwich
Active material	LiFePO ₄ (8)
Binder	Polyvinylidene fluoride (1)
Conducting agent	Super P (1)
Active electrode thickness	90 μm → 74 μm
Current collector	Aluminum Foil
Current collector thickness	20 μm

작된 slurry는 20 μm aluminum foil에 90 μm의 두께로 한쪽 면만 코팅되어 One-side sandwich 구조의 전극을 만들었다. 그리고 오븐에서 120 °C에서 2시간 동안 1차 건조를 한 뒤, Calendaring을 진행하여 전극을 압축하여 총 94 μm두께의 전극을 제작하였다. 마지막으로 120 °C에서 24시간동안 2차 건조를 했다.

2.2 레이저 가공

전극을 구조화하기 위하여 사용된 Ytterbium Pulsed Fiber Laser (YLPM-1-4×200-20-20, IPG)의 max average power는 20W이며 1064 nm의 파장을 갖고 있다. 또한 4 ns~200 ns까지 pulse duration을 가

Table 2 Laser parameters used for the experiments

Parameters	Specifications
Average power	1~19 W
Mode	Pulsed laser
Wavelength	1064 nm
Pulse duration	4 ns
Pulse repetition rate	500 kHz
Scanning speed	500 mm/s
Focal length	189 mm
Spot size	Approx. 30 μm
Beam quality (M2)	1.5

변 할 수 있는 장점이 있다. 그리고 1.5의 M²값을 갖고 있다. 본 실험은 다양한 레이저 가공변수 중 오직 average power만 변경하여 실험을 단순화하여 진행하였다. Average power는 1 W~19 W까지 2 W 간격으로 조사하였다.

2.3 분석 방법

Fig. 3는 전극에 레이저 조사 후 주사주사현미경 (SEM)으로 촬영한 사진이며, 전극의 기하학적 변화를

Fig. 3 Measurement method of the ablation top width, ablation bottom width, ablation depth

Fig. 2 Schematic of the nanosecond laser for laser structuring of electrode

분석하기 위하여 ablation top width(W_{top}), ablation bottom width(W_{bot}), ablation depth(D)를 정의하였다. Ablation top width는 전극의 레이저 가공 후에 활물질이 제거되어 형성된 상단 폭(width)이다. Ablation bottom width는 전극의 laser 가공 후 활물질이 제거되어 형성된 하단 폭이며, ablation depth는 레이저 가공 후 활물질이 제거되어 형성된 홈의 깊이(depth)를 측정하였다. Aspect ratio는 측정된 ablation top width(W_{top})와 ablation depth(D)를 이용하여 계산되었다.

3. 실험결과 및 고찰

3.1 Ablation width and Ablation depth

Fig. 4는 레이저 구조화 가공 후 전극을 전자주사현미경(SEM)을 통해 관찰한 사진이다. Fig. 4를 보면, 레이저 출력이 증가할수록 ablation width와 ablation depth(D) 모두 증가한 것을 관찰할 수 있다. Top view (Fig. 4(a))에서 출력이 증가함에 따라 활물질층에 생긴 홈의 깊이가 증가하여 집전장치(current collector)의 표면까지 형성되었지만, 활물질이 완전히 제거된

aluminum foil은 관찰되지 않았다. Fig. 5는 레이저 파워에 따른 ablation width와 ablation depth의 측정값이다. Fig. 5(a)를 보면, ablation top width는 레이저 출력이 증가함에 따라 선형적으로 증가하였다. 그리고 19 W에서 약 102 μm 로 가장 넓게 형성되었다. 반면, ablation bottom width는 13 W까지 형성되지 않았으며, 15 W부터 활물질이 대부분 제거되면서 ablation bottom width가 형성되었다. Fig. 5(b)에서 ablation depth는 레이저 출력이 증가함에 따라 선형적으로 증가하였다. 또한, ablation top width와 비교하여 가파르게 증가하였으며, 코팅된 활물질이 집전장치의 표면까지 제거된 이후에 더 이상 증가하지 않았다. 더 정확한 비교를 위하여 회귀분석을 통하여 ablation top width와 ablation depth의 추세선과 상관계수(r)를 계산하였다. 레이저 출력 13 W이후부터 활물질이 완전히 제거되어 더 이상 증가하지 않아 회귀분석은 활물질이 완전히 제거되기 전까지 데이터만 사용하였다. Fig. 5를 보면, ablation top width의 추세선의 기울기는 5.1643이고, ablation depth의 추세선의 기울기는 5.9063으로 ablation depth의 기울기가 상대적으로 가파르게 증가하였다.

Fig. 4 SEM image of the electrode after laser structuring in 1 pass (a) Top view (b) Cross section view

Fig. 5 (a) Ablation width and (b) ablation depth depending on power at 1pass

3.2 Aspect ratio

Fig. 6(a) 앞서 측정된 ablation top width와 ablation depth를 통해 계산된 aspect ratio를 레이저 출력에 따라 나타냈다. 구조화된 전극에서 형성된 홈의 aspect ratio가 중요한 이유는 동일한 폭의 groove가 형성되었을 때, 상대적으로 높은 aspect ratio가 형성된 전극은 전기화학적으로 반응할 수 있는 표면적이 증가된다. 결과적으로 L^+ 의 확산경로 증가는 배터리의 고속 충·방전에 유리하기 때문이다(Fig. 6(b))¹⁴⁾. 레이저 조사 후 전극에 형성된 홈의 aspect ratio는 1 W~11 W까지 급격하게 증가하였고 13 W부터 완만하게 감소하였다. 이러한 이유는 ablation top width는 1 W~19 W까지 거의 동일한 기울기로 증가하는 반면 ablation depth는 1 W~13 W까지 상대적으로 급격하게 증가되지만 13W 이후 더 이상 증가되지 않았기 때문이다. 또한, aspect ratio는 11 W에서 약 0.77로 가장 높았다.

3.3 활물질의 제거량과 제거율

Fig. 7는 전극의 레이저 구조화 공정 후에 활물질 제거량(removal amount of active material)과 활물

질 제거율(active material removal rate)이다. 전극의 활물질의 양은 배터리의 에너지밀도와 밀접한 관계가 있다. 예를 들어, 활물질의 양이 증가할수록 배터리의 에너지밀도가 증가하기 때문이다. 그러나, 전극의 레이저 구조화는 활물질을 부분적으로 제거하여 전기화학적 반응을 보다 넓은 표면에서 발생시켜 출력밀도를 높이는 방법이다. 따라서 활물질 제거량에 대한 분석이 필요하며, 더 나아가 최적화가 필요하다. 또한, 활물질 제거율은 가공공정의 효율성을 판단하기 위해 분석이 필요하다. 단위 부피 당 활물질 제거량과 분당 제거율은 각각 eq. (1) 과 eq.(2)을 통해 계산하였다.

$$\text{Removal amount of active material (mm}^3\text{)} = \frac{1}{2} (W_{top} + W_{bot}) \times D \times 1\text{mm} \quad (1)$$

$$\text{Active material removal rate (}\frac{\text{mm}^3}{\text{min}}\text{)} = \frac{1}{2} [(W_{top} + W_{bot}) \times D] \times \nu \quad (2)$$

활물질 제거량은 Eq.(1)과 같이 측정된 ablation top width(W_{top}), ablation bottom width(W_{bot})와 ablation depth(D)를 이용하여 계산하였으며, 단위길이(1mm)

Fig. 6 (a) Aspect ratio of structured-electrodes depending on laser power and (b) comparison of Li^+ diffusion path in high and low aspect ratio groove in structured-electrodes

Fig. 7 (a) Removal amount and (b) removal rate of active material depending on power

당 제거량으로 나타났다. 활물질 제거율은 Eq. (2)를 통해 계산되었으며, ablation top width(W_{top}), ablation bottom width(W_{bot}), ablation depth(D), 그리고 조사속도(ν)를 사용하였다. Fig. 7 (a)를 보면 활물질 제거량은 레이저 출력이 증가할수록 증가하였다. 1 W~13 W까지 완만하게 증가하며 15 W 이후 비교적 급격히 증가하였다. 이러한 현상은 15 W부터 활물질이 대부분 제거되어 aluminum foil에 반사된 레이저 빔이 증가하여 다중반사가 활발히 일어나 ablation width가 증가한 것으로 추측된다. Fig. 7 (b)는 분당 재료가 제거된 재료 제거율을 보여주며, 레이저 출력이 증가할수록 활물질 분당 재료 제거율은 증가한다. 따라서, 레이저 출력이 증가할수록 레이저 구조화 가공 효율이 증가된다.

4. 결 론

본 연구는 고출력 배터리를 위한 전극 laser structuring 가공의 기초 연구이다. 실험에 사용된 전극은 LiFePO₄를 활물질로 사용했으며, 나노초 레이저를 이용한 레이저 구조화 공정의 가능성에 대해 논의하였다.

1) 레이저 출력이 증가함에 따라 ablation top width와 ablation bottom width는 증가하였으며, 실험 조건 내에서 ablation top width와 ablation bottom width는 각각 최대 약 102 μ m, 약 53 μ m으로 측정되었다.

2) Ablation depth는 레이저 출력이 증가할수록 증가하였으며, 활물질이 대부분 제거된 74 μ m 이후 증가되지 않았다. 또한, 레이저 가공 후 형성된 홈이 집전장치 표면까지 형성되었지만, 활물질이 완전히 제거된 aluminum foil은 관찰되지 않았다.

3) 활물질 제거량과 활물질 제거율은 레이저 출력이 증가함에 따라 증가하는 경향이 있다. 레이저 출력의 증

가는 공정측면에서 좋은 효율을 보여주지만 배터리 성능측면에서 활물질 제거량이 증가하여 배터리의 에너지 밀도를 감소시킨다.

4) 전극의 레이저 구조화 공정은 기존의 전극 구조의 한계를 극복하여 배터리의 출력밀도를 향상시키지만 공정 중 제거되는 활물질로 인하여 에너지 밀도를 감소시키므로 전극구조화 공정의 효과를 극대화하기 위해 적절한 레이저 가공변수가 필요하다.

본 연구의 유효성을 검증하기 위해 코인 셀을 제작하여 rate capability test가 진행될 계획이며, 전극의 레이저구조화 공정의 최적화를 달성하기 위하여 레이저 출력뿐만 아니라 조사속도(scanning speed), 반복률(repetition rate), 펄스 폭(pulse duration), 조사 횟수(the number of pass) 등 다양한 가공변수에 대한 분석을 진행할 계획이다.

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