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Research Article

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The effect of using the metal tube on laser welding of the battery case and the tab for lithium-ion battery

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Abstract: Given the drawbacks of the conventional welding methods in joining the battery case and tab in the lithium-ion battery, the laser welding technique using the metal tube has been introduced for the weld. The metal tube is supposed to contribute a positive effect on protecting the outside structure by blocking the injection of the spatters. However, the use of the metal tube is believed to affect the intensity as well as the power distribution of the laser gaussian beam. Through the observation and analysis in this study, both advantages and disadvantages of the application of the metal tube on the weld have been clarified. The use of the metal tube prevents the ejection of the spatter to the outside of the welding zone, the gap between the battery case and tab in the weld is also minimized. Besides, the limitation of the intensity and the power energy distribution of the laser Gaussian beam has caused significant changes in the morphology, mechanical, and electrical properties of the weld.

Keywords: Gaussian Beam; Metal Tube; Surface Appearance, IMCs, Tensile Strength, Electrical Resistance.

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1. Introduction

In recent life, the use of lithium-ion battery is increasing rapidly due to its multiple advantageous features. Long lifespan, environmental friendliness, and low-cost are practical requirements for the energy storage system in our modern industry. Having met these requirements, the rechargeable lithium-ion battery has been employed as the power supply or energy storage system in various industries, especially in automotive applications [1]–[3]. The lithium-ion battery has outstanding characterizations such as high energy intensity, high power density, low self-discharge rate, and wide temperature range of operation in comparison with conventional batteries [4]. The design of a lithium-ion battery cell is based on its applications. The typical battery cell designs include button cell, prismatic cell, cylindrical cell, and pouch cell. Among the different cell designs, the cylindrical cell is produced with the lowest manufacturing cost. Additionally, the given cell design attributes with high specific energy, good mechanical stability, and long cycle life. As a result, the cylindrical cell is the most common cell design used for primary and secondary batteries. The major physical components of a cylindrical cell battery are jellyroll, current collectors, and safety devices as shown in *Figure 1*. A jellyroll consists of a positive electrode, a negative electrode, and separators, which are prepared in sheets. The jellyroll is fabricated in a sandwich structure, the separator is placed between the positive and negative electrode sheets. In the cylindrical cell, the current collectors imply the positive and negative terminals, these are conductive material used for electron transmission. The safety devices includes battery case, insulation plates, exhaust gas hole, anti-explosive valve which assist and protect the energetic materials and electrolyte inside the battery cell.

Figure 1. Cross section of a lithium-ion battery cylindrical cell.¹

During the battery manufacturing process, there are some joints must be welded. Above all, the joint between battery case and tab is considered as the most challenging for the manufacturers due to the dissimilar involved materials, their thicknesses, and low electrical resistance requirement. The tab is usually made of copper or aluminum due to its high electrical conductivity as well as weight per unit volume ratio. Meanwhile, the battery case is required to have high strength as well as high corrosion resistance so that it can prevent the central part of the battery from the deformation caused by an external force. Steel is one of the most suitable materials which can meet the requirements. Moreover, the battery case is commonly manufactured with a nickel plating layer on the surface to improve the joint and increase the electrical conductivity of the joint [5]. In joining the battery case and tab, the typical challenge is the difference in chemical and physical properties of the material of the battery case and the tab. Steel has a melting temperature of around 1425-1540°C, while the melting point of aluminum is 660°C. This makes it difficult to weld these materials using conventional fusion welding methods. Moreover, the low solubility of the dissimilar materials causes the formation of intermetallic compounds (IMCs) which negatively affects the mechanical properties of the joint. The IMCs are believed to cause the formation of several weld defects such as pores and cracks which causes the low strength of the weld [6]–[10]. Recently, many manufacturers have used the resistance spot welding method to weld the tab and battery case during battery manufacturing. However, a practical issue has been detected during the welding process. The high temperature generated during welding and the pressure from the top part make the electrode be bent as shown in **Figure 2**, this results in the non-uniform weld. Therefore, the need of improving the welding method or finding a substitute welding technique is essential. Previously, several studies have investigated the joint of these dissimilar materials using different methods. A solid-state welding method was first thought to have the potential for joining the dissimilar materials. Taban et al. [11] have attempted to weld the dissimilar metals of 6061-T6 aluminum and AISI 1018 steel using friction welding technique. The result showed that the strength of the weld was in the interval of 170-250 MPa. Besides, the thickness of the intermetallic compounds layer at the interface of the joint was measured at about 350 nm. Its composition was suggested including FeAl (Fe-rich) and Fe₂Al₅ (Al-rich). However, one of the drawbacks of this welding technique was the relatively long welding cycle (time). Another solid-state welding technique, ultrasonic welding, has been attempted to weld these dissimilar metals. Patel et al. [12] have

¹ https://batteryuniversity.com/learn/article/types_of_battery_cells

Figure 2. a) Resistance spot welding, b) Electrode bending due to high temperature.

investigated the microstructural change and the mechanical performance of the dissimilar metal joint between aluminum alloy Al5754-O and the galvanized high-strength low-alloy (HSLA) steel welded by the ultrasonic spot-welding process. The analysis result reported that the intermetallic compounds found at the interface were FeAl_3 and Fe_2Al_5 , the eutectic Al-Zn film was also found in the region. The lap shear tensile load of the joint reached a maximum of 3.7 kN. It was also reported that the failure during the tensile shear test could firstly take place between the eutectic Al-Zn film and the IMCs. When the load force increased, the joint was completely detached in the Al-containing region. However, this welding technique is only can be used on the designed joint (lap joint) as well as the technique requires custom tooling for every new project. Recently, an advanced technology, laser processing, has been developing and applying in diverse industries, especially in lithium-ion battery manufacturing [13]–[19]. Moreover, the laser welding is well known for the non-contact process which provides various benefits for the weld such as low heat input, small heat-affected zone, fast processing, and low thermal deformation. Based on the analysis of the welding techniques for the dissimilar of aluminum and steel as well as the problem during the welding of tab and battery case using the conventional methods, the laser technology is introduced to improve the weld. In the present experiment, the laser welding technique is used to weld the battery case and tab in the lithium-ion battery. What is more, a metal tube is utilized with the purpose of minimizing the spread of the spatters. Moreover, as the metal tube is placed over the tab and the battery case, the gap between them should be minimized. However, the metal tube might affect the laser beam transmission, therefore, the investigation of using the metal tube in the process is needed. In other words, this experiment aims to investigate the effect of using a metal tube in laser welding of the battery case and tab in different laser powers.

2. Materials and Methods

2.1 Materials

Due to the high electrical conductivity and lightweight characteristics, aluminum and copper have been used in many applications, especially in the electrical field. In lithium-ion batteries, the tab is usually made of copper and

Figure 3. Experimental setup.

aluminum. Meanwhile, in the present experiment, the tab which is made of pure aluminum is employed for the weld. The dimension of the tab is given as $40 \text{ mm} \times 7 \text{ mm} \times 0.087 \text{ mm}$ corresponding to length $\times$ width $\times$ thickness. In the cylindrical cell, the battery is manufactured to protect as well as prevent the central part of the battery from the external damages, therefore, the material for the battery case must have the sufficient strength and low temperature deformation. Steel is considered as the most suitable material for the battery case as it is a well-known material for high strength as well as low thermal expansion coefficient. In this experiment, the battery case made of steel (chemical composition of 0.03% C, 0.003% Si, 0.23% Mn, 0.011% P, 0.008% S) with a nickel-plated layer on the surface. the battery case is a commercial design with the thickness of 0.4 mm, and 73.5 mm in height. Moreover, a metal tube which the laser beam transfer through is also used, the inner diameter of the tube is 4.5 mm. The metal tube is made of aluminum and the length of the tube is 80 mm.

2.2 Experiment procedure.

The experimental schematic for the weld of the battery case and the tab is shown in **Figure 3**. The laser source employed for the experiment is Ytterbium pulsed fiber laser (IPG-YLPM, IPG photonics, Southbridge, USA). The feature of the laser source includes the maximum laser power of 20 W, the wavelength of 1064 nm, and the spot size of 30 μm . In the current experiment, the laser power in the interval of 10-20 W is chosen to perform the weld. The additional laser parameters include pulse duration and

Figure 4. a) Specimen setup, b) Welding path.

repetition rate are set at 200 ns and 20 kHz, respectively.

The setup of the weld configurations, as well as dimensions for the specimens, are shown in **Figure 4** a). The experiment is conducted without the metal tube to compare with the experiment using the metal tube. In both cases, the tab is placed over the battery case and the weld is conducted in overlap organization. In the weld with the metal tube, the tube is placed over the overlap configuration, and the laser beam irradiates through the tube. An appropriate welding path is designed to be suitable for the movement of the laser irradiation inside the tube, which is exhibited in **Figure 4** b). The welding path consists of two parts: 1) circular line and 2) zigzag hatching lines. The advantages of this designed welding path are an increase in the contact area between the welded specimens as well as multiple options for the cross-section observation. Consequently, the entire welding process lasts for 30 seconds.

3. Results and discussion

3.1. Gaussian beam distribution.

It is interesting to note that the laser beam in the present experiment characterizes the Gaussian beam

distribution. The intensity of the Gaussian beam is shown in equation (1):

$$I(r) = \frac{2P_0}{\pi W_R^2} \cdot e^{\frac{-2r^2}{W_R^2}} \quad (1)$$

Where P_0 is the given laser power, r is the distance from the center of the beam, W_R can be calculated as below:

$$W_R = W_0 \sqrt{1 + \left(\frac{z}{Z_R}\right)^2} \quad (2)$$

Where the Z_R is the Rayleigh range which is determined as below:

$$Z_R = \frac{\pi \cdot W_0^2}{\lambda} \quad (\lambda \text{ is the wavelength of the laser beam})$$

And w_0 is the radius at which the amplitude is $1/e$ of its value on the axis (see below).

Figure 5. a) Gaussian beam profile; b) Intensity distribution.

The intensity distribution of the gaussian beam is given in **Figure 5 b)**. Now, The power distribution of this gaussian beam can be determined as the integral of $I(r)$ which is shown in (1).

$$\int_0^{2\pi} \int_0^{\infty} \frac{2P_0}{\pi W_R^2} \cdot e^{\frac{-2r^2}{W_R^2}} r dr d\theta \quad (3)$$

In the present experiment, the use of the metal tube has affected the distribution of the laser beam

(Gaussian beam) on the material. As mentioned above, the inner diameter of the metal tube is 4.5 mm, which means the intensity and power distribution of the laser beam (Gaussian beam) are limited by the area of the metal tube's entrance. As a result, the power distribution of the laser beam transmitting into the metal tube should be integrated with respect to r in the limit from 0 to the radius of the metal tube (2.25 mm) as below:

$$\int_0^{2\pi} \int_0^{2.25} \frac{2P_0}{\pi W_R^2} \cdot e^{\frac{-2r^2}{W_R^2}} r dr d\theta \quad (4)$$

The result of the equation (4) is:

$$P_0 \left(1 - e^{\frac{-2.22,5^2}{W_R^2}} \right)$$

The W_R is determined as in equation (2) where z equals the length of the metal tube (800 mm). Consequently, the final result of the equation (4) will be 0,95 P_0 . This means there is only 95% P_0 transmitting the metal tube. In other words, the use of the metal tube has affected the power distribution which the material will absorb in the weld. Therefore, the analysis of the loss of the power distribution on the weld is performed in the following sections.

3.2. Macrostructure.

The morphology of the weld is firstly analyzed with the observation on the top surface of the weld. **Figure 6** shows the comparison of the top surface in the weld with and without the metal tube in different laser powers. This observation is taken at the center of the welding zone. The surface appearance reveals a significant amount of the weld metal as well as several weld defects such as blowholes and spatters. The formation of the blowholes is directly caused by the evaporation of the thin plated nickel of the surface of the battery case. The thin plated nickel is heated while the laser beam is melting the upper material (aluminum). Together with the low evaporation temperature, the plated nickel is easy to evaporate while the upper material (aluminum) is still in the liquid state. The nickel evaporation produces a high pressure which is so-called recoil pressure. This pressure subjects to the melt of the upper material and creates the hole entrance. Consequently, the blowholes are formed after the cooling process. In the present experiment, at the laser power of 10 W, the surface of the weld without the metal tube exhibits the formation of both blowholes and spatters, as shown in **Figure 6 a)**. Moreover, the weld metal is detected to formed in overlap

configuration, this contributes to the formation of the weld bead with the width of 64.29 μm . In contrast, the surface of the weld using the metal tube shows a significant difference. In this weld, more blowholes are produced in the region. Sometimes, these blowholes link together and generate a linear trench. It is noteworthy that spatters are founded progressively when the metal tube is applied. The measurement of the width of the weld bead with the use of the metal tube reports a width of 60.71 μm , which is slightly narrower than that in the previous weld. Together with the increment of the laser power, the spatters formation and the weld metal also grow. The observation of the surface of weld with and without the metal tube at the laser power of 15 W is shown in **Figure 6** b) and e), respectively. Meanwhile, an increase of the weld metal in the weld without the metal tube is clearly observed. It is also interesting to note that, a reduction of the formation of the blowholes on both surfaces is obtained as the higher laser power is used. As the laser power of 20 W is used, both welds produce the messy surfaces caused by the growth of the weld metal as well as the generation of the spatter. A clear comparison of the spatter distribution on the surface between two welding configurations is shown in **Figure 7**. The spatter distributing on the surface of the weld with the metal tube is more than that in the weld without the metal tube. In addition, one can be obtained from the observation is the formation of the explosive holes at the intersection of the hatching path and perpendicular path. The explosive hole is believed to be formed after the generation of the blowholes. As the blowholes are created during the circular path welding, massive power energy will be absorbed inside the blowholes at which the hatching welding is the circular welding intersect. This results in greater metal evaporation as well as the recoil pressure. Since a large amount of the melt evaporates quickly, the blowholes largely expand to become the explosive holes. The difference in the size of the explosive holes between two welding configurations is also recognized.

Figure 6. SEM images at the center of the welding zone on the top surface. a, b, c: Welding without the metal tube; d, e, f: Welding with the metal tube.

From the above result, it is clear that the use of the metal tube has both negative and positive contributions on the weld surface appearance. It is important to highlight the fact that, the influence of the metal tube on the power distribution is assumed to have a significant effect on the weld morphology. In particular, a large number of blowholes is formed on the surface when the metal tube is used, while a few blowholes are found in the weld without the metal tube at the laser power of 10 W. In comparison with the welding using the metal tube, higher power energy is absorbed in the weld without the metal tube, this seems to reduce the formation of the blowholes on the surface. The reduction of the blowholes also happens when the laser power increases. This implies that the higher power energy, the higher recoil pressure is produced by the Ni evaporation. This allows the nickel evaporation to completely blows out. One additional explanation for the disappearance of the blowholes on the surface is that the increase of the power energy absorption also results in more material (upper material) melted. Therefore, the melt is sufficient to fill the blowholes. As can be seen in **Figure 6**, the width of the weld bead in the weld without the metal tube is slightly wider than that in the weld using the metal tube. As we can see, the weld bead mainly comprises of weld metal. Then one can be concluded that the expansion of the weld bead is caused by the growth of the

Figure 7. SEM images at the boundary of the welding zone on the top surface. a, b, c: Welding without the metal tube; d, e, f: Welding with the metal tube.

weld metal. Another finding on the surface is the spatter distribution on the surface. From the result of the observation, the difference of the amount of the spatters around the welding zone on the surface weld is due to the fact that the metal tube has prevented the ejection of the spatter. In the weld without the metal tube, spatter freely ejects to space, while in the weld using the metal tube, the spatter ejection is blocked by the metal tube wall. As a result, the spatters would drop back on the surface. The increase of the spatter distribution around the welding zone is considered as a drawback of using the metal tube. As discovered on the surface appearance, the explosive holes are formed along the boundary of the welding zone. In the comparison of the size of the explosive between two welding configurations, it implies that the lower power energy absorption at the weld using the metal tube results in the smaller entrance of the explosive holes.

The cross-section of the weld is obtained by cutting perpendicularly with the welding path at the center of the welding zone. The cross-section is etched with the 4% Nital solution (4ml ethanol C_2H_5OH + 100ml nitric acid HNO_3). A comparison of the observation of the cross-section in the weld with and without the metal tube is shown in **Figure 8**. A novel finding is that the lower material is withdrawn to the upper material. The phenomenon is suspected to be accelerated by the recoil pressure, as well as the characteristics of the

nanosecond pulsed fiber laser. It should be noted that the recoil pressure is produced by metal evaporation, this pressure tends to flow the remaining melt in the keyhole away. Meanwhile, a high aspect-ratio weld is created by the nanosecond pulsed fiber laser. Therefore, the combination of the recoil pressure and the thin weld produced in the experiment force the melt of the lower material flow upwards.

The comparison of the cross-section between two welding configurations presents the difference in the amount of the lower material pushed upwards. It can be seen that the weld without the metal tube has a slightly higher amount of the upward flow of the lower materials in comparison with the other. Moreover, the height of the upward flow is also relatively reduced when the metal tube is employed. A further novel finding is that there is a gap between the upper and lower material in the weld without the metal tube, while the gap is minimized when the metal tube is used. Moreover, the cross-section observation reveals the formation of pores and opening cracks within the weld. The pores are mostly found at the low laser power such as 10 W, while several opening cracks are formed at the laser power of 20 W at both welding configurations. The marked points in the Fusion Zone (FZ) indicate the supposed intermetallic compounds (IMCs) area as those either reveal a unique structure or locate at the interface between diffused materials. The Al and Fe composition of the marked points as well as the possible phases which are determined according to the Fe-Al phase diagram are shown in **Table 1**. The result shows that FeAl intermetallic is found at the interface of the diffused upper material and the diffused lower material at the laser power of 10 W in both welding configurations. However, the Al-rich IMCs including FeAl₂ and Fe₂Al₅ are obtained when both joints are welded with the laser power of 15 W. The intermetallic of Fe₂Al₅ is likely found at the upper part of the FZ as indicated at marked point 3 and 5. Interestingly, the weld without the metal tube produces α -Fe (ferrite) at the top part of the FZ at the laser power of 20 W, while Fe₂Al₅ is still produced in the same region in the

Figure 8. SEM images of the cross-section observation. a), c), e): Weld using the metal tube; b), d), f): Weld without the metal tube.

Point	Al (at. %)	Fe (at. %)	Ni (at. %)	Possible phase
1	51.02	11.45	13.17	FeAl
2	54.38	17.45	5.49	FeAl
3	74.63	9.63	0.43	FeAl ₃
4	66.17	9.11	2.71	FeAl ₂
5	49.03	16.95	0.48	FeAl
6	59.27	10.78	0.95	Fe ₂ Al ₅
7	57.83	15.72	2.65	Fe ₂ Al ₅
8	56.20	16.04	1.95	Fe ₂ Al ₅
9	17.8	47.55	0	α -Fe

Table 1. EDS result of the marked points in the Fusion Zone (FZ) in the weld.

weld using the metal tube. Moreover, the finding of the IMCs explains the formation of voids as well as opening cracks since these IMCs are relatively brittle. The IMCs are formed due to the low solubility of the substrate materials (Al and Fe). Besides, the existence of the Ni at the interface of the diffused upper material and diffused lower material is evident for the formation of the blowholes, which is caused by the Ni evaporation. The observation at the laser power of 20 W exhibits the significant difference in the FZ between two welds. When the metal tube is used, the FZ is observed with the solidified lower material surrounded by a thick IMCs layer. Meanwhile, the weld without the metal tube shows a relative thinner straight flow of the lower material which is supposedly due to high power energy absorption. Without the use of the metal tube, the upward flow of the lower material partially inserts to the gap between the upper and lower material. Moreover, the use of the metal tube causes the heat accumulation inside it, this accelerates the diffusion of the upper material, and the lower material pushed upwards. As a result, a thick IMCs layer is created in the interface of the diffused steel and the diffused aluminum, especially at the laser power of 20 W.

3.3. Hardness test

In order to analyze the effect of the IMCs on the hardness distribution on the fusion zone, the hardness measurement is conducted in both horizontal and vertical directions. *Figure 9* exhibits the schematics of the hardness measurement of the welds in both horizontal and vertical directions at the laser power of 10 W, 15 W, and 20 W. In the horizontal direction, the center of the fusion zone is set as the origin of the distance, the total number of the measured points is 9 points. However, in the vertical direction, the measurement is performed along the fusion zone from the upper material (UM) to the lower material (LM). There is a total of 12 measured points, as shown in *Figure 9 b*).

Figure 9. Schematics of the hardness measurement: a) Horizontal direction, b) Vertical direction.

The hardness distribution in the horizontal direction of the weld in both configurations is shown in *Figure 10*. The hardness profile in both welds has the same trend, an increase of the hardness is recognized as the distance is close to the fusion zone. In both welding configurations, the maximum hardness is obtained at the center of the fusion zone. At the laser power of 10 W and 15 W, the hardness remains under 60 HV, while the weld without the metal tube reveals higher hardness distribution than the weld using the metal tube. A significant difference between two welding configurations is observed at the distance of 20 μm on both sides from the center of the fusion zone. In particular, at the laser power of 10 W, the hardness at the distance of 20 μm from the center of the fusion zone is 178.6 HV and 184.3 HV on the left and right, respectively. In comparison, the hardness distribution at the region in the weld using the metal tube remains at 44.3 HV on the left and 44 HV on the right. However, at the laser power of 15 W, the hardness at the

distance of 20 μm from the center of the fusion zone in the weld using the metal tube increases significantly. At the laser power of 20 W, the hardness distribution at the distance of 20 μm from the center of the FZ in both welds are mostly equal as shown in *Figure 10 c*).

The difference of the hardness profile of the weld with and without the metal tube is explainable with the amount of the upward flow of the lower material as well as the IMCs. The relative higher upward flow of the lower material in the weld without the metal tube corresponds to a higher amount of the lower material solidified in the region. It should be noted that the lower material (steel) has high hardness. Besides, the hardness significantly increases when the metal is melted and solidified. As a result, the high hardness is obtained at the center of the FZ and the hardness distribution in the weld without the metal tube is generally higher than the other. In other words, the use of the metal tube produces the weld with the lower hardness distribution cross the FZ. However, the hardness distribution in both weld configurations reveals a promising finding of the effect of the plated Ni. The typical hardness value of Fe-Al IMCs are as follows: Fe_2Al_5 -1013 HV, FeAl-470 HV, FeAl_2 -1060 HV [20], while the maximum hardness obtained in this measurement is 327.6 HV. It is evident that the current reported hardness is lower than the typical hardness value of the IMCs. Moreover, the Ni is also found in the region of the IMCs. Therefore, it can be assumed that the Ni joining in the Fe-Al IMCs helps to slightly reduce the hardness of the IMCs. The comparison of the hardness between two welding configurations at the laser power of 20 W reports an unfamiliar result. When the metal tube is used, the hardness at the distance of 20 μm from the center of the FZ is relatively higher than the weld without the metal tube. The most reliable explanation for this comparison is the wide formation of IMCs layer around the lower material which penetrates the upper material as shown in *Figure 8 e*). In contrast, the IMCs are less found in the same region in the weld without the metal tube.

Figure 10. Hardness following the horizontal direction. a) 10 W, b) 15 W, c) 20W.

Figure 11. Hardness following the vertical direction. a) 10 W, b) 15 W, c) 20W.

II. As shown in the graphs, the weld using the metal tube tends to produce an average lower hardness profile than the weld without the metal tube. As all the measured points are in the order from the upper material (UM) to lower material (LM), the hardness distribution firstly increases when the distance is close to the interface of the upper and lower material. Within the lower material, the hardness continuously rises to reach a peak at the distance of 100 μm from the interface of upper and lower material, and then the hardness decreases gradually. However, in each laser power, there is a remarkable difference in hardness distribution between two weld configurations. At the laser power of 10 W, the maximum hardness of the weld without the metal tube at this laser power is 320.1 HV, while the maximum hardness of 285.2 HV is obtained at the given laser power when the metal tube is applied. At the laser power of 15 W, the hardness distribution of the weld without the metal tube remains consistently higher than that in the weld using the metal tube. At the distance of 100 μm from the interface of the upper and lower material, both the maximum hardness of the weld with and without the metal tube are obtained, which are 314.1 HV and 331.2 HV, respectively. When the joint is welded with the laser power of 20 W, the similar hardness distribution along the direction can be obtained. The hardness increases sharply when the distance is close to the interface, the peak hardness in both weld configurations is observed at the distance of 60 μm from the interface in the lower material as shown in *Figure 11 c*). The lower hardness distribution of the weld using the metal tube is indirectly caused by the lower absorbed power energy. The lower power energy absorption correlates to the lower penetration of the laser beam into the lower material in the weld using the metal tube in comparison to the weld without the metal tube. This leads to less material melted. Meanwhile, higher absorbed energy in the weld without the metal tube causes more material melted and solidified. As a result, the hardness distribution is slightly higher without the use of the metal tube.

3.4. Tensile strength test

Figure 12. Tensile strength between the weld with and without the metal tube.

The tensile strength profile in both welding configuration is shown in **Figure 12**. The tensile test is performed with the speed of 1mm/s. As shown in the graph, the tendency of increasing tensile strength at the higher laser power is obtained at both welds with and without the metal tube. Nevertheless, there is a considerable difference in the tensile strength between the two welding configurations. Overall, the lowest tensile strength is obtained at the laser power of 10 W in both welds. In particular, the tensile strength at the laser power of 10 W in the weld without the metal tube is 0.47 MPa, the average tensile strength of 0.41 MPa is obtained at a laser power of 10 W in the weld using the metal tube. However, the use of the metal tube results in the higher tensile strength at the laser power within the laser power range of 11-19 W in comparison with the other weld. There is a significant difference in the average tensile strengths at the laser power of 20 W in the weld with and without the metal tube, which are 0.82 MPa and 1.02 MPa, respectively. Moreover, one should be noticed that the failure during the tensile test occurs at the boundary of the welding zone.

It can be seen that the tensile strength of the weld is affected by the use of the metal tube. The average lower tensile strength of the weld without the metal tube is due to the gap between the upper and lower material in the weld. This gap makes the tab and the battery case easy to be detached. Nevertheless, the

opposite result is obtained at the laser power of 10 W and 20 W. As discussed, the low strength of the weld using the metal tube at the laser power of 10 W is due to the increase of the formation of the blowholes on the weld surface and pores in the weld seam. On the other hand, the formation of the IMCs layer mentioned above is suspected of degrading the tensile strength of the weld at the laser power of 20 W. In summary, the use of the metal tube generally strengthens the weld by reducing the gap between the battery case and the tab, while the exception is caused by the weld defects and the IMCs.

3.5. Electrical resistance

Figure 13. The electrical resistance of the weld with and without the metal tube.

The electrical resistance of the weld is measured with the four-wire method, the result is shown in **Figure 13**. Overall, the weld using the metal tube produces lower electrical resistance in comparison with the weld without the metal tube. As shown in the graph, the weld without the metal tube produces the electrical resistance in the interval of 0.31 mΩ to 0.46 mΩ, while the weld using the metal tube reports the resistance in a range of 0.174 mΩ to 0.375 mΩ. Without the metal tube, the electrical resistance tends to decrease when the higher laser is used. In contrast, A reduction of the electrical resistance of the weld using the metal tube is obtained when laser powers of 10 W, 11 W, and 12W are used, but the electrical resistance varies in the interval of 0.174 mΩ-0.258 mΩ as the laser power is in the range of 13 W-20 W.

It should be noted that minimizing the gap between the upper and lower material significantly increases the electrical conductivity between them. As shown above, the use of the metal tube results in the average lower electrical resistance in comparison with the weld without the metal tube. Therefore, the result is explained due to the minimized gap between the upper and lower material when the metal tube is applied. Moreover, an interesting finding is the relationship between the tensile strength of the weld and the electrical resistance. As the higher tensile strength in the welding configuration with the metal tube corresponds to the lower electrical resistance. The increment of the electrical resistance at the laser power of 10 W and 20 W correlates with the degrading of the tensile strength of the weld. As analyzed, the result is induced by the formation of the voids and the effect of IMCs. Those are the factors rising the electrical resistance of the weld.

4. Conclusions

In the present experiment, the application of the metal tube assisting laser welding of the battery case and the tab is investigated. A comparison of the weld with and without the metal tube is analyzed in morphology, mechanical, and electrical properties. The use of the metal tube reports significant improvement to the weld, but several negative effects are discovered. According to the analysis, several considerations are withdrawn as follows:

- When the metal tube is used, the weld surface exhibited with more spatter distribution around the welding zone. At the low laser power (10W), the weld surface using the metal tube reveals more blowholes, while the size of the explosive holes is smaller in comparison with the weld without the metal tube.
- Heat accumulation inside the metal tube accelerates the diffusion of the materials which results in more IMCs at the laser power of 20 W.
- The hardness distribution as well as the tensile strength of the weld is improved by the use of the metal tube, while the exception is suspected by the heat accumulation inside the metal tube at the laser power of 20 W.

- The application of the metal tube reduces the gap between the battery case and the tab, this significantly increases the electrical conductivity of the weld.

Though such positive effects have been recognized with the application of the metal tube, it is important to designate the optimum laser parameters which provide the greatest weld in combination with the use of the metal tube. Moreover, the influence of different dimensions of the metal tube should be further investigated.

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Figures

Figure 1

Cross section of a lithium-ion battery cylindrical cell.

Figure 1

Cross section of a lithium-ion battery cylindrical cell.

Figure 2

a) Resistance spot welding, b) Electrode bending due to high temperature.

Figure 2

a) Resistance spot welding, b) Electrode bending due to high temperature.

Figure 3

Experimental setup.

Figure 3

Experimental setup.

Figure 4

a) Specimen setup, b) Welding path.

Figure 4

a) Specimen setup, b) Welding path.

Figure 5

a) Gaussian beam profile; b) Intensity distribution.

Figure 5

a) Gaussian beam profile; b) Intensity distribution.

Figure 6

SEM images at the center of the welding zone on the top surface. a, b, c: Welding without the metal tube; d, e, f: Welding with the metal tube.

Figure 6

SEM images at the center of the welding zone on the top surface. a, b, c: Welding without the metal tube; d, e, f: Welding with the metal tube.

Figure 7

SEM images at the boundary of the welding zone on the top surface. a, b, c: Welding without the metal tube; d, e, f: Welding with the metal tube.

Figure 7

SEM images at the boundary of the welding zone on the top surface. a, b, c: Welding without the metal tube; d, e, f: Welding with the metal tube.

Figure 8

SEM images of the cross-section observation. a), c), e): Weld using the metal tube; b), d), f): Weld without the metal tube.

Figure 8

SEM images of the cross-section observation. a), c), e): Weld using the metal tube; b), d), f): Weld without the metal tube.

Figure 9

Schematics of the hardness measurement: a) Horizontal direction, b) Vertical direction.

Figure 9

Schematics of the hardness measurement: a) Horizontal direction, b) Vertical direction.

Figure 10

Hardness following the horizontal direction. a) 10 W, b) 15 W, c) 20W.

Figure 10

Hardness following the horizontal direction. a) 10 W, b) 15 W, c) 20W.

Figure 11

Hardness following the vertical direction. a) 10 W, b) 15 W, c) 20W

Figure 11

Hardness following the vertical direction. a) 10 W, b) 15 W, c) 20W

Figure 12

Tensile strength between the weld with and without the metal tube.

Figure 12

Tensile strength between the weld with and without the metal tube.

Figure 13

The electrical resistance of the weld with and without the metal tube.

Figure 13

The electrical resistance of the weld with and without the metal tube.