Parametric Effects of Resistance Spot Welding between Li-ion Cylindrical Battery Cell and Nickel Conductor Strip

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Abstract. The resistance spot welding method is commonly used in the cylindrical battery packing because of production costs. However, its quality is lower than other welding methods. To improve the quality, three parameters which are slot geometries of nickel conductor strip, welding position and welding position sequence are studied in this paper using both simulations and experimental methods. According to different slot geometries, if the slot length is longer than the positive battery terminal diameter, the high welding current flows through the welding point. To weld different positions, it results in structural deformation of the positive battery terminal which directly affects the contact pressure. As different welding position sequences for three welding spots on the positive battery terminal, it is found that the sequence starting at the middle is better than which from the sides. In conclusion, these parameters can be used to improve the welding quality; nevertheless, there are still other parameters which will be studied in the future.

1. Introduction
Welding is commonly used in the battery packing industry for battery connection, especially resistance spot welding because of low production cost. However, the quality of resistance spot welding in battery packing is lower than that of other methods due to the high thermal and electrical conductivity properties of materials [1]. This causes low mechanical strength and high electrical contact resistance at the welded battery connection, which has significant impact on battery pack quality [2-3]. Nevertheless, proper welding parameters can be used to improve the welding quality.

Since cylindrical battery cells are widely used, this research focuses on parametric study of resistance spot welding between cylindrical cell and nickel conductor strip for welding quality improvement. There are three studied parameters being studied; the slot geometries of nickel conductor strip, welding positions and welding position sequence. Finally, best parameters setting is evaluated and presented.

2. Effects of resistance spot welding parameters on heat generation
Heat from electric current flow though connecting point is used to melt materials and form solid joint [4] as shown in Figure 1. The heat occurs in welding process based on Joule’s raw [5] as Eq. (1) which requires proper parameters setting to obtain decent heat generation for good quality joint [3].
Where $Q$ is heat input in generation (J), $I$ is electric current in amperes (A), $R$ is resistance in ohms ($\Omega$) and $t$ is time in seconds (s).

The parametric effect on heat generation can be separated to two categories; direct and indirect effect.

- Direct parametric effect; involving with heat generation directly though Joule effect which basically parameters are welding current and welding time.
- Indirect parametric effect; involving with heat generation though current flow concentration which relate to deformation and contact pressure in specific area.

![Diagram](image1)

**Figure 1.** Schematic of resistance spot welding in cylindrical battery pack

3. Methods of parameters study

In this research, an experimental is conducted to define the effects of welding parameters on welded connection quality which are electrical contact resistance and ultimate shear force. Meanwhile, the simulation is used to observe deformation, temperature and current distribution during welding process that are difficult to observe with the experimental. The ratio between flow through and inflow workpiece current in simulation will be used to define the effects of parameters on welding performance.

3.1. Experimental setup

AP5KB AC spot welding machine is used for welding between 0.15 mm of slotted Nickel 200 strip and 0.3 mm of Nickel 200 strip with 1.5 mm of contact diameter electrodes to estimate results before conducting actual welding on real battery cells. The parameters setting on the spot welding machine are 2250 A of maximum welding current, two cycle welding time and 35 N of each electrodes pressing force. A current clamp meter and an oscilloscope are connected to electrode in order to measure current and see the voltage profile, which will be further used by the simulation to observe other behaviours during the welding process.
To determine the contact resistance without taking into account the intrinsic resistance of the specimen materials, the measurement setup as depicted in Figure 2 is conducted with HIOKI BT3554 battery tester. The contact resistance can be calculated using Eq. (2).

\[ R_{\text{contact}} = R_{\text{measured}} - R_{\text{ideal}} \]

where \( R_{\text{ideal}} = \sum_{n=1}^{N} \left( \frac{R_{\text{0.15 mm @ contact}}}{\rho_{\text{0.15 mm nickel}}} \right)^n \left( \frac{R_{\text{0.3 mm @ contact}}}{\rho_{\text{0.3 mm nickel}}} \right)^{N-n} \)

\( R_{\text{contact}} \) is electric contact resistance while \( R_{\text{measured}} \) is measured resistance from HIOKI BT3554 battery tester and \( R_{\text{ideal}} \) is materials resistance from calculation where \( \rho \) is material resistivity, \( A \) is conductor cross section and \( l \) is conductor length.

3.2. Simulation setup

To simulate the actual welding process, the corresponding CAD models are imported together with the properties of the materials into the simulation with the following welding process analysis modules, namely Solid Mechanic Module, Electric Current Module, and Heat Transfer Module. The simulation process is divided into two steps in order to reduce computational time [3] as shown in Figure 2. The number of meshes in the given models is increased until the result of simulation converges.

![Figure 2. Schematic view and resistance diagram of welded specimen](image)

![Figure 3. Coupling of resistance spot welding model in simulations](image)
The contact conditions, which are surface roughness, contact pressure, Young’s modulus and Poisson’s ratio, are required by the electric current and the heat transfer module to calculate contact conductivity. Hence, the solid mechanic module in step#1 is used to obtain the contact condition between the materials and the deformation of the workpiece as a result of the electrode force. After that, the electric current module in step#2 will use the data from step#1 and the voltage profile from the experiment to calculate current distribution, which will be further used by the heat transfer module to calculate heat generation. However, surface roughness cannot be obtained from the solid mechanic module since it is a function of time spent by the actual welding process. Therefore, surface roughness needs to be adjusted until the current profile from the simulation converges to the actual welding process as shown by the example in Figure 4.

![Surface roughness and current profile during welding in simulation](image)

**Figure 4.** Relation between surface roughness and current profile during welding in simulation

The contact conditions, which are surface roughness, contact pressure, Young’s modulus and Poisson’s ratio, are required by Electric Current Module and Heat Transfer Module to calculate electrical and thermal conductivity at the contact, respectively. Hence, Solid Mechanic Module in Step#1 is used to obtain the contact condition between the materials and the deformation of the workpiece as a result of the electrode force. After that, electric current module in Step#2 will use the data from Step#1 and the voltage profile obtained from the experiment to calculate current...
distribution, which will be further used by Heat Transfer Module to calculate heat generation. However, surface roughness cannot be obtained from Solid Mechanic Module since it is a function of time spend by the actual welding process. Therefore, surface roughness needs to be adjusted until the current profile of the simulation is similar to the actual welding process as shown by the example in Figure 4.

4. Results and discussion

4.1. Effect of slot geometries in nickel conductor strip

The slot in a conductor strip can improve welding by restricting the current flow in such a way that it only flows along the path through the connecting strip and the battery terminal [3]. Figure 5 shows that increasing both length and width of the slot can increase current ratio, which means that better heat generation can be achieved, thereby yielding better welding performance and quality. However, the same dimension length of a slot on the current flow between the conductor strip and the battery terminal than the width of the slot. With increasing of slot geometries, the electrical conductivity is reduced because of less conductor strip area.

Because multiple spot welding is required for better connection, the length of slot geometry should be increased for multiple spots on terminal. In Figure 6 shows the amount of current flow is increased by length of slot especially when length of slot is longer the diameter of positive terminal area which is 9.7 mm in this case.

Normally, current flows along the path of least resistance. When the length of the slot in the conductor is greater than that of the battery terminal, most current is forced to flow along the path between the conductor strip and the battery terminal in the inner area, which has less resistance than the outer area. This results in larger current concentration in the welding area. Therefore, the length of the slot should be longer than the diameter of the terminal area to obtain best welding performance with minimum effect on the operation current.

![Figure 5. Slot geometric varying and comparing](image-url)
4.2. Effect of welding position on battery terminal

The positive terminal experiences less deformation than the negative terminal when subject to an equal electrode compressive force thanks to its supporting columns [3]. However, the number of columns on the positive terminal depends on the design choice. Generally, there are two design choices, namely a design with an even number and one with an odd number of supporting columns. In this research, three supporting columns are used as an odd number of supporting columns, whereas four supporting columns are used as an even number of supporting columns. Figure 7 shows various deformation behaviours for different welding positions with different positive terminal designs where the distance between the two electrodes remains the same.

Figure 6. Effect of slot length on positive terminal welding performance

(a) Deformation of positive terminal with even number of support columns
Figure 7. Deformation in metres from different electrode position on positive terminal

- In Figure 7 (a), shows the electrode welding position on the terminal with an even number of supporting columns. This design provides symmetric support and hence leads to uniform deformation by the electrode force. However, welding in the area near the supporting columns (yellow dots) results in more deformation than that in the area on the supporting columns (red dots).

- In Figure 7 (b), shows the electrode welding position on the terminal with an odd number of supporting columns. With this geometric design, it is possible to cause non-uniform deformation from the electrode force exerted by each electrode since the column provides asymmetrical support between the positions of the electrodes (yellow dots). Though, there is a position that provides symmetrical support located at the border of the supporting columns (red dots).

This means welding on terminal with an even number of supporting columns is easier than welding on terminal with the odd number of supporting columns thanks to better heat generation, which yields less deformation. Meanwhile, symmetric deformation on a terminal with an even number of supporting columns also provides symmetrical wear on the electrode from its symmetrical heat generation.

Moreover, welding on the positive terminal requires more attention than the negative terminal since it is possible to melt insulating ring that separates the positive and the negative side when welding at the edge of the terminal as shown in Figure 8. Therefore, welding at the caution positions can potentially cause an electrical short circuit and hence an explosion.
4.3. Effect of welding sequence on battery terminal

Based on the relation between the number of weld spots on a battery terminal and the electrical contact resistance, the design with four welding spots is a suitable choice [2]. However, only three welding spots can be performed on the positive terminal due to the limited positive terminal area. With this number of weld spots, there are three possible welding sequences as shown in Figure 9.

The multiple spots on the battery terminal create a strong connection between the conductor strip and the battery terminal. During mechanical stress testing, the conductor strip itself is more likely to fail under mechanical stress before the weld joint. Therefore, electrical contact resistance is primarily considered in this case. Figure 10 (a) shows the results of (1) the middle-before-side sequence, which yields lowest electrical contact resistance, followed by (2) the side-before-middle sequence and (3) the side-to-side sequence sequences. The middle before side sequence can deliver the lower resistance from the first weld step; however, the electrical contact resistance reduction from further step is lesser than other sequences.

When looking at the current ratio from the simulation in Figure 10 (b), it shows the previous welding step compromises the welding current and the heat generation of the further step which corresponds to welding quality results in Figure 10 (a). The middle position is the most important position in any welding sequence. It can be compromised from both side weld joints if it is the last welded spot. Meanwhile, it can also compromise the weld current of the other positions if it is the first
welded spot. The slot in the conductor also has an impact on this result since it affects the current flow concentration, especially in the middle of the slot area.

![Electrical contact resistance](attachment:image)

(a) Welding sequence effect on electrical contact resistance in each step from experiment

![Flow throughput/final current ratio](attachment:image)

(b) Welding sequence step current ratio comparing from simulation

**Figure 10.** Effect of welding sequences on contact quality

5. Conclusion

In this research, simulation and experiments are conducted to investigate the effects of certain resistance spot welding parameters, namely welding position, welding position sequence, and geometry of the slot in a nickel conductor strip to improve battery pack quality. The results are compared to define the effects of these parameters. Furthermore, best parameters setting is evaluated and presented below.

- **Effects of slot geometries in a nickel conductor strip**
Increasing both width and length of the slot can improve welding performance. However, it also minimizes battery pack performance due to its smaller conductor area. Thus, the length of the slot should be longer than the diameter of the terminal area for the positive terminal welding while having enough width so that the slot can be visible, to yield optimal welding performance and allow for an easy welding operation with minimum negative effect. As for the slot in the negative terminal conductor, it should be located at the edge since it is the optimal welding position for the negative terminal.

- **Effects of welding position on a battery terminal**
  The welding on the positive the terminal with an even number of supporting columns results in uniform and less deformation than welding on the terminal with an odd number of supporting columns from its symmetric support. This behaviour results in good heat generation, which makes it convenient to weld on the terminal with an even number of supporting columns. Moreover, welding on the supporting columns results in less deformation because of its better support and welding at the edge of the positive terminal can cause an electrical short circuit and even a battery explosion.

- **Effects of welding sequence on a battery terminal**
  In multiple spot welding, the previous welding step compromises the welding current and the heat generation of the further step. To obtain optimal welding quality, the middle position, which is the worst compromised position, must be welded before the other positions to minimize such a compromise. Thus, the middle-before-side sequence should be performed on a battery terminal. The result may be different if the conductor strip contains no slot. Even though the obtained data can be used to improve the welding quality of resistance spot welding, there are still other parameters that can be studied for further research in future.

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**Acknowledgement**
This research is a part of researches supported by Thailand automotive institute (TAI) which the authors would like to gratitude including National Science and Technology Development Agency (NSTDA) for providing the necessary facilities. Both researcher and professor from National Metal and Materials Technology Centre (MTEC) and King Mongkut's University of Technology Thonburi (KMUTT) counsel useful knowledge in this work. Lastly, the author admiringly acknowledges for personal financial support from Thailand Graduate Institute of Science and Technology Scholarship (TAIST).

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