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Research Article

WELDABILITY AND THICKNESS STUDY OF ELECTROLESS NICKEL COATING ON ALUMINIUM CONDUCTOR FOR LI-ION BATTERY PACK

N. Chumni[1]
C. Charoenphonphanich[1]
D. Tanprayoon[2]
T. Yenwichai[3]
M. Masomtob[3,*]
[1] *School of Engineering, King Mongkut's Institute of Technology Ladkrabang, Chalongkrung Road, Ladkrabang, Bangkok, 10520, Thailand*
[2] *National Metal and Materials Technology Centre (MTEC), National Science and Technology Development Agency (NSTDA), Pathum Thani, 12120, Thailand*
[3] *National Energy Technology Center (ENTEC), National Science and Technology Development Agency (NSTDA), Pathumthani, 12120, Thailand*

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ABSTRACT:
Aluminium (Al) is used as an electrical conductor for battery modules to reduce the cost of battery modules but still provides high performance. An electroless nickel (EN) coating is applied to the surface of the Al conductors to meet the mentioned requirements, as it is well known in the automotive industry for its hardness and wear resistance. This paper presents a novel study on the influences of EN thickness on the weldability between the EN coated Al conductors and the tin coated copper wires using resistance spot welding (RSW). The two main parameters of this study are nickel (Ni) thickness and Al thickness. A total of twelve thickness conditions of the material are used. It consists of three differences in the thickness of Al; 2, 3 and 4 mm, that their surfaces are coated by four different thicknesses of Ni; uncoated, 10 µm, 20 µm and 30 µm. The electrical conductivity, the pull force and the peel force are measured after the specimens are welded with the tin coated copper wires. Poor and good weldabilities are studied to discover the cause of the behaviours. This study assists the primary purpose of using Al as the electrical conductor for battery modules, reducing the cost of battery modules but still offering high performance.

Keywords: *Weldability, Electroless nickel coating, Aluminium conductor*

1. INTRODUCTION

As the world focuses on cutting down CO_2 emission and using fossil energy, the latest trend of vehicle type is an electric vehicle (EV) which involves main power from the battery. Li-ion battery is a common choice for EV battery. An equal quality but a lower price is sought after by the consumers, suggesting that the EV companies are continually searching to enhance efficiency and reduce cost to minimize the market price of their vehicles [1].

The connection between individual cells is a crucial for battery pack to ensure the highest capacity, amperage requirement, or enhance the supplied power. The battery cells can be connected in parallel, series, or mixes types by wire, strip, or other materials, depending on the design [2]. Figure 1 illustrates the sample drawing of battery module. The cylindrical cells are connected in parallel. The wires are jointed with cells and busbars (electrical conductors).

There are a variety of joining techniques used to connected individual battery cells. The common techniques are ultrasonic welding, wire bonding, force fitting, soldering, laser beam welding, and resistance welding [2].

* Corresponding author: M. Masomtob
E-mail address: manop.mas@entec.or.th

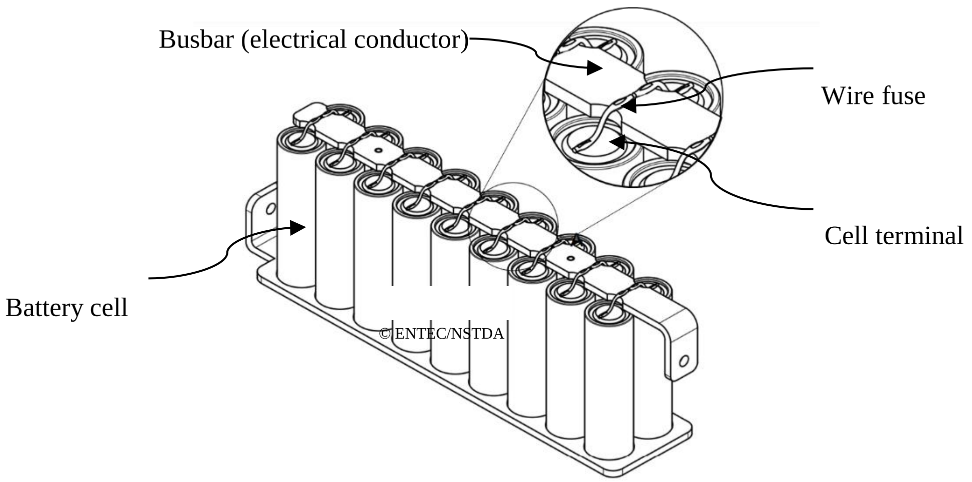


Fig. 1. The sample drawing of battery module.

Some leading EV companies such as Tesla, BMW, and Nissan prefer laser welding, wire bonding, and ultrasonic welding for their high efficiency [3, 4]. Nevertheless, there is another technique, resistance spot welding (RSW), which has advantage over other techniques due to low infrastructure costs [5]. The difficulty of RSW is its inferior quality as the high thermal and electrical conductivity of materials and can be affected by many factors [6, 7]. However, proper factors can be applied to improve welding quality. Therefore, the conductor material is studied in this work as material selection is one of the key factors which allows for better quality and low cost advantages of RSW [8].

An electrical conductor is a device of a battery pack for local high current power distribution, usually a metal strip or bar. Copper (Cu) and aluminium (Al) and are two main materials which are used as the electrical conductors. Cu is the most widespread since it holds a high conductivity, while Al is also customarily used because of its cost and weight. The conductivity of the Cu is 100% IACS (The International Annealed Copper Standard), and Al has the conductivity of 57.00 - 61.80 % IACS. Although Al has only 61% conductivity of Cu, it shows about 30% higher conductivity by weight, which assists in reaching economic demand. According to Kirkpatrick [9], the electrical conductivity, cost, and weight are not only three properties that deliver Al to be considered as a more fabulous conductor than Cu but also strength, workability, corrosion resistance, creep, compatibility with insulation. All previously mentioned properties are especially suitable for automotive components, and there is a rise in Al-usage as the electrical conductor in EV batteries nowadays [8-13]. Consequently, Al is chosen as conductor material in this work.

The use of fuse wires in Li-on battery packs has been studied. McKeown claims that [14], there are several ways to connect cylindrical Li-ion cells, such as welding, manual attachment and soldering, but using a wire is a securer method because wire itself can be applied as a fuse. The wires are welded from the cylindrical cell to the busbar as depicted in Fig. 1. According to Landgraf et al [15], the small wires are also designed to use as fuses in Li-ion battery pack. The small wires also act as fuses in Tesla Li-ion battery pack. These wires are used to interconnect between the individual cells by bonding from the plates to the centre of the cell terminals. This design can assist in the situation of the short failure of any individual battery cell [16].

The Al conductor is used to join with the wire fuse by RSW in this study. The wire fuse is Cu coated with tin, despite that, the weldability of Al and Cu wire fuse, which are dissimilar material is not acceptable because the bond is too weak. Therefore, finding method to enhance the joint strength becomes challenge. Improving stability can be achieved by the coating of Al by different metals such as tin (Sn), cadmium (Cd) and nickel (Ni). The electroless nickel (EN) coating is selected because Ni coating is the best functional coating in terms of economy, metallurgical and contact properties [17]. As stated by Parkinson [13], The EN coating has been worldly accepted for its outstanding uniformity. In the case of the intricate design, the EN coating can provide a remarkable feature of the deposit uniformity which is considered as an advantage over the selection of the electrolytic coating.

The EN coating is a chemical process for the deposition of Ni-alloy from solution onto the surface without the use of electricity. The most common reducing agent is sodium hypophosphite [6]. It is used in many manufacturing applications, such as high-precision components, the recovery of complex parts of over-machined or overlapping parts, large vessels used in the chemical industry and vehicle tanks, including small aluminum parts used in the aerospace industry [18].

As stated earlier, the conductor material is studied due to material selection is a key factor in improving RSW efficiency and saving cost. It is critical to study the behaviours between EN coating thickness toward Al conductor to select the proper thickness, due to the excessive Al and EN thicknesses can result in unnecessary costs. The thickness of the Al plate, which acts as a conductor, differs to determine the effect on weldability when coated with Ni of the same thickness. It is designed with a thickness of 2, 3 and 4 mm. These numbers are chosen to reduce errors during the specimen preparation and provide a practical number. The thickness of the Ni surface is designed to be uncoated, 10, 20 and, 30 μm. The thickness starting from the uncoated can make a difference in behavior between with and without Ni can be observe. By consulting the EN coating manufacturer, the thickness difference of 10 μm is a proper thickness that can differ in behavior with a limited cost. Al plates are welded with the wire fuses by RSW at 36 N electrode force. After RSW, the weld joints are measured for electrical resistance. The wire fuses are distinguished the intensity level of the bond by the mechanical tests which are the pull test and the peel test. The weldability is presented in terms of the electrical conductivity, the pull force, and the peel force.

2. METHODOLOGY

The objective of this work is to study the relationship between the Al plate thickness and the effect of the Ni coating thickness on the wire using RSW. The weldability in this paper is determined using the electrical conductivity and the joint strength. According to Brand et al.[6], the electrical resistance and pulling the specimens apart can be used to evaluate the welding quality. The electrical resistance is used to judge the electrical conductivity of the specimens, where fewer numbers indicate better electrical conductivity [6]. The lap shear test is generally performed to evaluate the joint strength for welding techniques; however, the wire fuses are used instead of thin plates in this paper; hence, the pull test and the peel test are mechanical tests that are applied to determine the joint strength, expressed in Newtons. The larger force numbers indicate better strength [6, 19, 20].

2.1 Experimental materials and machines

Grade 1100 Al alloy with the thickness of 2, 3 and 4 mm is cut to 10 mm × 50 mm. The Al plate conditions are listed in Table 1. The wire is cut to a length of 90 mm, and its properties are presented in Table 2. The spot-welding machine is Mingda MD-500. The Al plates acting as the electrical conductors are welded by RSW with the tin coated copper wires which act as the fuse as illustrated in Fig. 2. After that, the electrical conductivity is obtained with all the specimens by measuring the electrical resistance (Ω) using HIOKI BT3554 battery tester which is a resistance meter with measurement accuracy ±0.8%. The measurement is taken place by measuring at the end of the wire on the non-spot-welding side with the 2-mm-Al plate coated with 20-μm-Ni, and another measuring point is next to the welding area. The resistance measurement method of the welded point is demonstrated in Fig. 3.

After that, the mechanical tests are performed by Sundoo force gauge SH series to obtain the intensity level of the bond by separating into two cases; the pull test where the specimens are pulled apart in a longitudinal direction, and the peel test where the specimens are pulled apart in 180° direction. The specimens of the pull test are represented in Fig. 4a and the specimens for the peel test are represented in Fig. 4b. Then, the specimens are evaluated for the weldability using the result from previous tests. After the electrical and mechanical tests are performed for purpose of evaluating the weldability, the cause of the behaviour is identified using cross-sectioning. The welded specimens are analysed using optical microscopy (OM) to study the behaviour of the material at the joint area.

Table 1: The conditions of aluminium plates.

Aluminium thickness (mm)	Electroless nickel thickness (μm)
2	0, 10, 20 and 30
3	0, 10, 20 and 30
4	0, 10, 20 and 30

Table 2: The properties of the wire.

Length (mm)	Diameter (mm)	Resistance (Ohms/km)
90	0.295	0.878

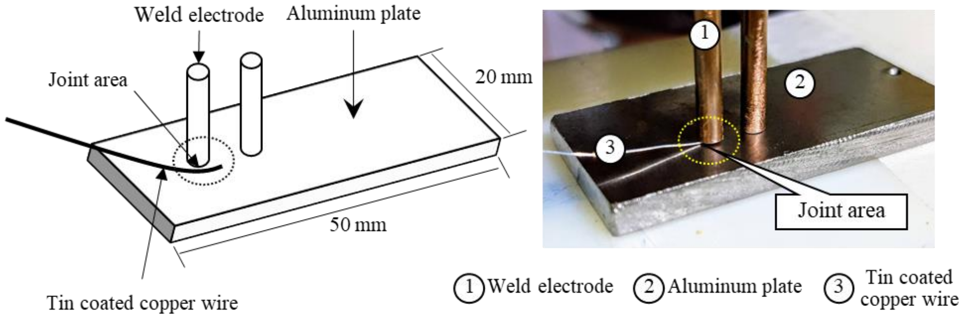


Fig. 2. The weld specimens.

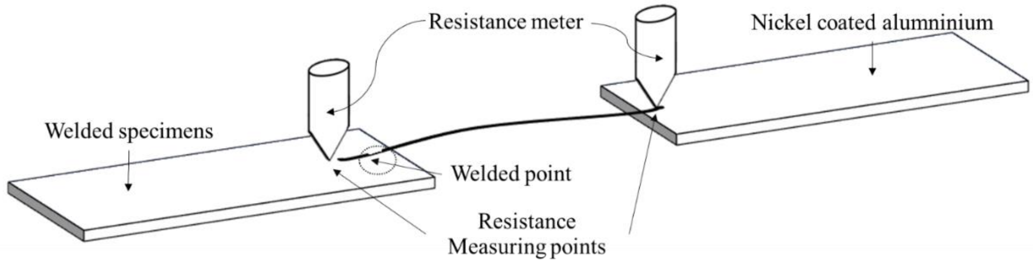


Fig. 3. The resistance measurement method of the welded point.

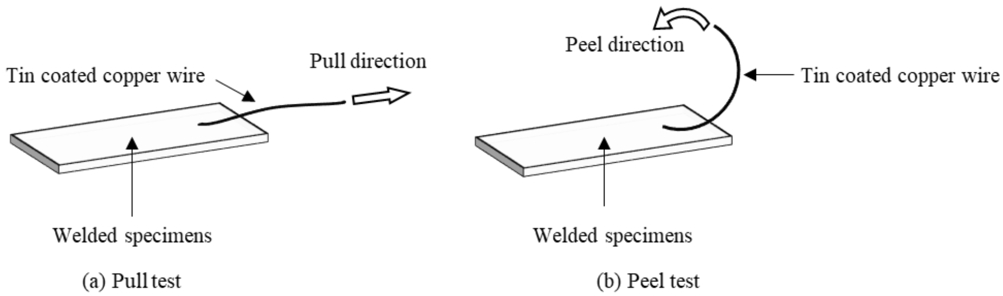


Fig. 4. The specimens for mechanical tests.

Table 3: Process parameter of RSW.

Voltage (V)	Peak current (A)	Electrode force (N)	Pulse type	Welding time (ms)	2nd pulse time (ms)	Squeeze time (ms)	Hold time (ms)	Off-time (ms)
1.2	2200	36	Double	0.99	9.9	99	99	99

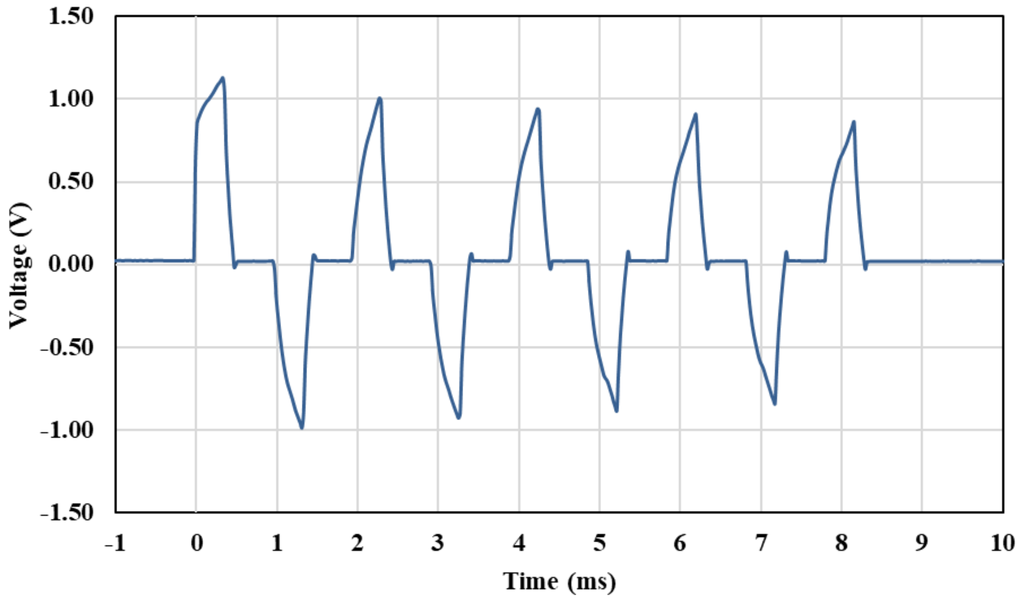


Fig. 5. Sample of the voltage profile from the experiment measured by oscillator.

2.2 RSW parameter selection

RSW is a sensitive welding method as it can be affected by many factors. The welding current is the most critical parameter as it has a direct effect on the strength. If it is too high, the insufficient strength can appear, and it means that the wires fuse may have blown during the spot event. In contrast, when the current is too low, the welding strength can be limited [21]. The double pluses are preferred since it is more suitable for the different materials bonding process [18, 21]. The peak weld current of this work is limited to be 2200 A, with an adjustment to the voltage of 1.2 V. A Hioki Clamp on Meter AC / DC HiTester 3285 with basic accuracy ±1.5% is used to measure current and voltage during welding by connected to an oscilloscope (ROHDE&SCHWARZ HMO1202 with DC gain accuracy all ranges 3% of full scale.) Voltage is measured by directly connecting the oscilloscope to the electrode. Figure 5 shows an example of measurement from the experiment.

The second parameter is the electrode force, which is the force that the electrode presses on the specimens. It has a significant effect on both electrical conductivity and strength. Too low electrode force causes a high contact resistance. On the other hand, too high electrode force results in low strength and unnecessary wear on the electrode. Moreover, the suitable material of electrode for RSW of Al should provide high electrical conductivity as well as high thermal conductivity. Therefore, Cu possessing the conductivity of 100% IACS can be the best electrode material [18, 21]. The electrode material of this study is Cu with a diameter of 3 mm and a constant force of 36 N.

The third parameter is the welding time. It is the time for an electric current to pass through the specimens. Increased welding time can result in improved tensile shear loads; however, the welding time that is too long can affect the hardness and decrease the welding strength. Table 3 represents the welding time and other RSW process parameters of the experiment. In this study, the first pulse is set at 0.99 ms and the second pulse is set at 9.9 ms; however, the actual welding time may be inconsistent due to a machine inaccuracy. Therefore, an oscillator is used to observe and control the welding time, for example, Figure 5 demonstrates the example of the measurement that the welding process ends in about 8.4 ms.

3. Result and Discussion

3.1 Weldability by the electrical resistance measurement

The measurement of the electrical resistance is taken place. The average value of the electrical resistance of each condition is shown in Fig. 6. The results indicate that the numbers of the electrical resistance are not significantly different because the measuring point is next to the end of the wire, which provides only the electrical resistance of the welded point. Thus, the thickness of Al has a small effect on this measurement. This method is used for studying the exact electrical resistance of welding bonds. It can be obtained that the highest electrical resistance is 31.68 mΩ and the lowest number is 30.62 mΩ, the difference is 1.06 mΩ. A significant trend cannot be observed. Hence, the weldability cannot be assessed only by measuring electrical resistance.

3.2 The strength by the pull test and the peel test

After the electrical resistance measurement is completed, all the specimens are evaluated the strength using the pull test. The thickness of all Ni-coated-Al plates has significant results because the wires are torn apart before they are pulled out from the welded points. The average pull force of wires is approximately 11.8 N. In contrast, the strength of uncoated-Al plate is failed. For all uncoated-nickel-Al plates, the wires are quickly pulled from the welded points, and the pull force is too small to measure. This result relates to Habashi's work [22], Ni is a metal that provides superior strength. In industrial terms, if the battery module is designed to be fixed, then it is not necessary to have a Ni coating of more than 10 µm thick as the electrical resistance does not decrease with the thickness of the thicker Ni coating. However, the effects of Ni thicknesses on its behaviours are required to study. Therefore, additional studies are conducted.

The peel test is performed to obtain the welding strength of each condition. It is good to be noted that there is a large gap of the peel force between the 10-µm-Ni and 20-µm-Ni coating thicknesses. According to Fig. 7, for the 2-mm-Al, the uncoated-Ni plates have too small average peel force to measure, and these values are demonstrated as 0 N. The 10-µm-Ni plates have 0.30 N. The 20-µm-Ni and 30-µm-Ni plates have 2.06 N and 2.00 N, respectively. The thickness of the 3-mm-Al tends to be similar.

Moreover, the 20-µm-Ni and 30-µm-Ni coating thicknesses also show approximate numbers. These numbers indicate that the 20-µm-Ni coating thickness is sufficient in terms of strength. This work aims to study behaviour. Therefore, further studies on optimization can be investigated.

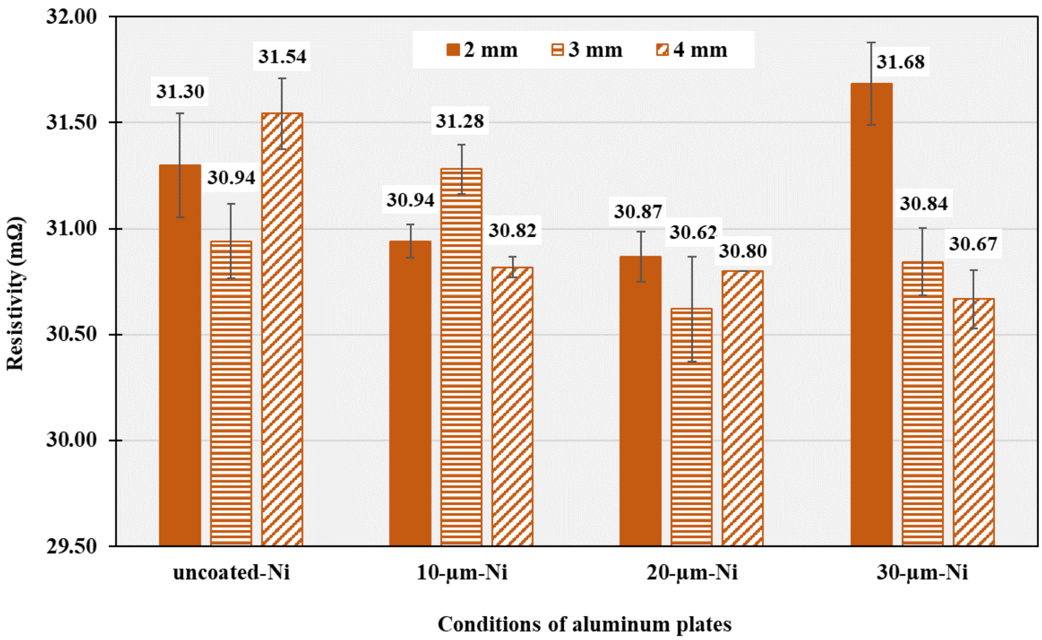


Fig. 6. The resistivity of each condition of aluminium specimens.

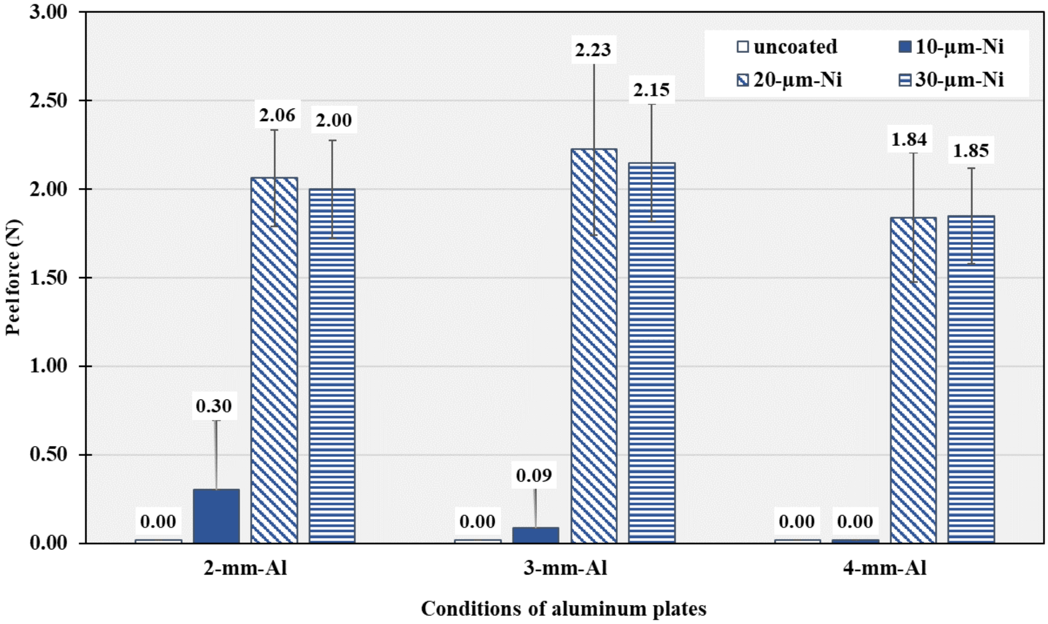
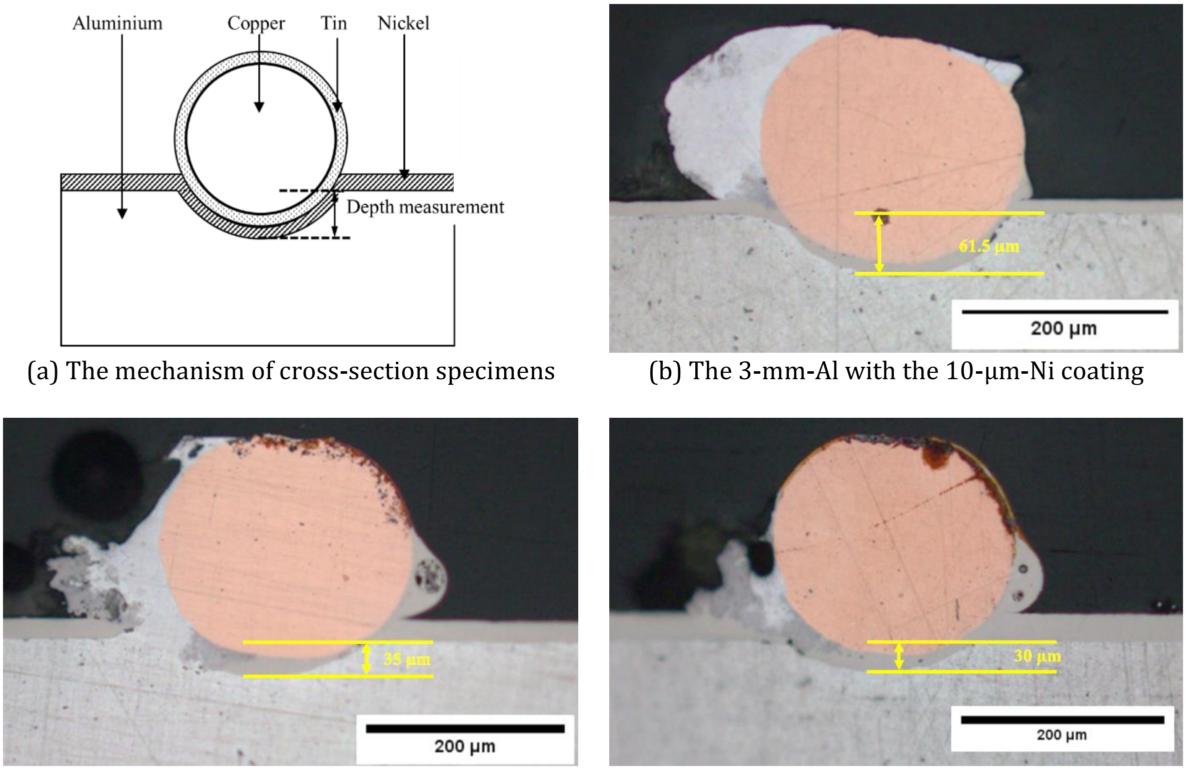


Fig. 7. Average peel force of aluminium plate at each condition.



(a) The mechanism of cross-section specimens (b) The 3-mm-Al with the 10-µm-Ni coating

(c) The 3-mm-Al with the 20-µm-Ni coating (d) The 3-mm-Al with the 30-µm-Ni coating

Fig. 8. Cross-section at welded point of the 3-mm-Al plate.

3.3 The study of behaviour by a cross-sectioning

After the cross-sectioning of 3-mm-Al plates is performed, the dents occurring due to RSW appear on the Al surface. The shape of the Cu slightly altered but remained round while the shape of tin changed. Ni at the weld point had a semi-circular dent following the Cu trace. The depth measurement is performed using ImageJ, showing that the 10-µm-Ni coating has an immense depth of 61.5 µm. While the 20-µm-Ni coating and the 30-µm-Ni coating have a depth of 35 µm and 30 µm, respectively. The thicker the Ni is, the smaller the dent depth, and this result is consistent with the primary purpose of EN coating in the coatings industry, which is to increase the surface hardness of the material [23]. However, the depth of the dent does not parallel to the welding strength because the peel test of the 10-µm-Ni coating is too small. As illustrated in Fig. 8, the Ni surface of both 20-µm and 30-µm Ni coating surfaces crack, which leads to the merging of metals, causing the bonds are strong.

On the other hand, the 10-µm-Ni surface does not fracture, and the metal merging area is smaller compared to the other two conditions. Hence, the merging of metals has a significant effect on the welding strength. The 10-µm-Ni coating does not have a large boundary of the merging to enable the bond to become as strong as those of 20-µm and 30-µm Ni coating.

4. CONCLUSION

The three thicknesses of Al plates; 2, 3 and 4 mm which act as conductors are coated by four thicknesses of EN coating; uncoated, 10, 20 and 30 µm to study its effects on the weldability, which defined by the electrical conductivity and the joint strength. The specimens are welded with tin coated Cu wires which act as fuses using RSW. After that, the electrical resistance measurement, the pull test, and the peel test are performed. The experiment shows that the EN coating has a significant effect on the welding strength. In a longitudinal direction, the wires are torn apart before the wires at the welding point are broken with all the Ni-coated-Al plates, while the wires are easily torn with the uncoated-Al plates. The 20-µm-Ni and 30-µm-Ni coatings produce more than twice the peeling strength in comparison to uncoated and 10-µm-Ni coatings. The 20-µm-Ni coating is sufficient for all Al plate thicknesses.

The merging of metals at the welding point directly affects joint strength. Ni-coating affects the depth of tin coated Cu wire at the welding point; however, the depth of Cu wire has no significant effect on the joint strength.

Although the EN coating increases material costs, when consider about replacing the conductor by copper or using other welding techniques such as laser or ultrasonic welding, it becomes one of the best selections to enhance the weldability between Al conductor and the tin coated Cu wire by RSW, especially in terms of strength which requires the lower infrastructure costs than other methods. The 10-µm-Ni coating provides sufficient weldability for all Al conductor thicknesses. However, the 20-µm-Ni coating is recommended for greater joint strength.

This work is intended to study behaviour; hence, further study to optimization the best EN coating thickness may be required. To clearly understand the phase at the joint point, further study is needed to identify the exact phase.

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