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บทความวิจัย

Study of Strength and Corrosion Behavior on Aluminum A1050 and Copper C1100 Joints by Mechanical Steel Bolt, Blind Steel Rivet, and Resistance Spot Weld

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Abstract: A1050 and C1100 are normally used as terminal tabs, they are connected either by mechanical joining, e.g. mechanical bolt, or rivet, or by welding, e.g. resistance spot welding. This study aimed to compare the mechanical bolt, blind rivet, and resistance spot welding methods by measuring important joining properties to support the process selection for joining terminal tabs in pouch cell batteries. T-peel-shaped were created and immersed in a 3.5 wt% NaCl electrolyte solution over different durations. Tensile tests were conducted to ascertain the maximum load-bearing capacity of the various joints. Furthermore, the electrical resistivities of the joints were measured using the 4-point probe technique. The corrosion rates of various joints were calculated from the corrosion current density (I_{corr}) measured from the Tafel polarization technique. ANOVA and Tukey's test were used for analyst data comparison of the three joining techniques. Based on the mechanical properties, the mechanical joints by either steel bolt or steel rivet exhibited higher shear peeling strength than the resistance spot welding. The mechanical joining processes were simple with ease of maintenance, however, the use of steel components correlated with heightened corrosion rates and higher resistivity. Spot welding joints tended to produce low joining strength due to the brittleness of the welding spot. Nonetheless, the spot weld joints demonstrated minimal changes in resistivity following corrosion exposure as opposed to the mechanical joining counterparts.

Keywords: Corrosion; Resistivity; Aluminum; Copper; Mechanical joining; Resistance spot weld; ANOVA

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1. Introduction

The electrical vehicle fields (EVs) are speedily growing according to the environmental issues because EVs can contribute to the reduction of global warming by producing zero pollutant emissions. Terminal tabs of pouch cell batteries, which are one of the core components of EVs, are of interest in this work. Al and Cu are commonly used as terminal tabs due to their great mechanical and electrical properties. An Al tab is used as a positive electrode and Cu is a negative one. Due to their different electrochemical potentials, galvanic corrosion may occur due to the connection of Al and Cu tabs for battery cells connected in series. The corrosion issue could affect the performance of a battery and raise safety concerns. In terms of corrosive environment, the surface has more rust or white flake which are signs of corrosion behavior [1].

In recent years, several joining techniques of terminal tabs have been used, including mechanical bolt joints, resistance spot welding, ultrasonic welding, and laser welding. Welding techniques provide direct contact between the two tabs without extra joining components, enabling good electrical contact and compact joining. However, the welding processes normally require high-budget equipment and good welding practice. A mechanical bolt joining is simple, low-cost, does not require high technical skill, and can be easily removed. Therefore, it is a popular joining technique among small-business and hobbyist communities of battery module packaging. However, the electrical contact, galvanic corrosion of the steel bolt, and long-term bolt tightening of the mechanical bolt joint are of concern. Rivet joining method, commonly used in the aviation industry, is another good alternative mechanical joining technique, which offers a fast and simple joining process [2]. Solid riveting is used widely for metal joining process. For the riveting process, holes are made through sheets and a rivet is used to join the sheets through the holes. The aviation industries commonly use a riveted lap joint to make a strong joint in fuselage of aircraft [3]. A blind rivet was used to join Al and Cu sheet for comparison with Cu-Cu and Al-Al sheets; the results were shown that the strength of Al-Al and Cu-Cu were lower than strength of Al-Cu combination, which was tested by the tensile testing [4]. The mechanical and electrical properties have been tested in many techniques to ensure safety and performance, then the selection of terminal-tab joining techniques must consider the joining strength, corrosion behavior, and electrical contact quality. However, to date, there is no report on the comparison of the terminal tab joining performance among resistance spot welding, mechanical bolt joining, and rivet joining. Terminal tabs experience a harsh environment, including fatigue damage and chemical reactions.

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Resistance spot welding (RSW) is a popular welding method for joining metal sheets in industries like automotive and aerospace. It involves applying pressure and passing an electric current through the sheets, creating heat that melts the metal at the joint. When pressure is maintained, the molten metal solidifies, forming a strong bond known as a weld nugget. RSW is favored for its high production rates, quality welds, and suitability for automation, but it requires precise control of welding parameters for consistent and reliable results, including current level, electrode force, and welding time [5]. Yang et al. [6] studied the behavior of corrosion of spot weld zone on dissimilar metals (Al and Al-Li) by immersion and electrochemical tests. The polarization curve ensured the increase of immersed time in electrolyte, the corrosion was spread widely on the surface of metals.

In this study, we investigated the joining of Aluminum A1050 and Copper C1100 plates, comparing the resistance spot welding, mechanical bolt, and rivet joining methods. Both A1050 and C1100 are common alloy grades used as terminal tabs in pouch-cell battery manufacturing. Additionally, Aluminum 1050 is known for its high purity, good corrosion resistance, and high electrical conductivity. It's suitable for general applications where these properties are sufficient, while Copper1100 is also an excellent choice when high electrical conductivity, good thermal conductivity, and corrosion resistance are crucial [7]. The mechanical joining, corrosion behaviors and electrical contact conductivity of the three joining techniques were studied and compared to provide useful information for a proper selection of the terminal tab joining techniques.

2. Experimental procedure

According to JIS Z 3136-1978 standard (ASTM International, 2000), the 30 mm width, 100 mm length, and 0.3 mm thickness of Al A1050 and Cu C1100 plates were prepared and connected to form a T-peel shape as shown in Fig. 1, which is similar to a joining configuration of the pouch cell battery terminal tabs. Chemical compositions of both metals are shown in Table 1. Moreover, Fig. 2 shows a diagram of the experimental process. Before the joining processes, the surfaces of the workpieces were cleaned with a solvent cleaner. For the mechanical bolt joining, a mechanical steel bolt (low head socket cap screw M4, 4-mm diameter) was applied with a tightening force of 2.5 N.m. (DIN 7984 standard). For the rivet joining,

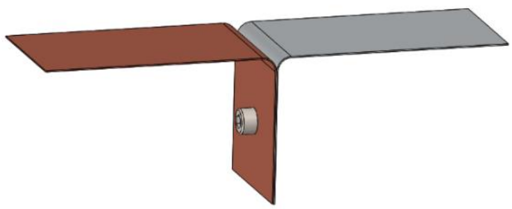

Fig. 1 Geometrical illustration of T-peel shape workpiece

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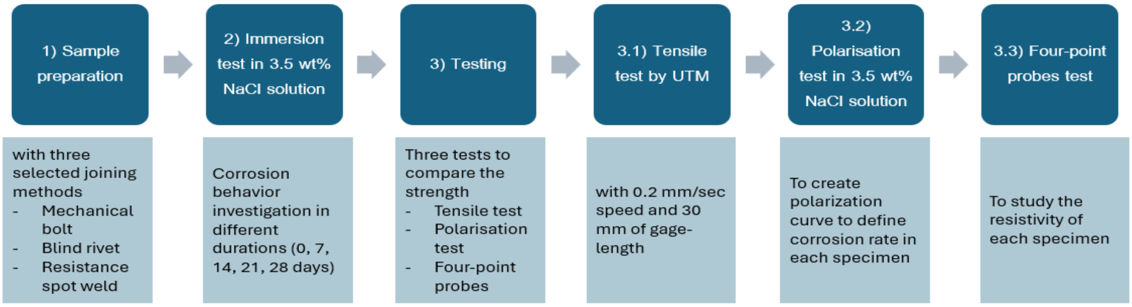

Fig. 2 The diagram of the experimental process

a 4 mm-diameter blind steel rivet was clamped by a rivet gun with the clamping force. For the resistance spot welding, we used the optimal spot weld conditions of the laboratory spot welding equipment reported by Saowapa et al. [8]. During the spot weld process, heat and pressure were applied on the terminal tabs joining by the pressing spot electrodes. The spot weld electrodes of the spot weld equipment are a 5-mm Copper Chrome alloy (type E Truncated).

To prevent the overheating damage of the Al and Cu plates, two C1100 plates of 0.7-mm thickness were added both Al and Cu plates, as busbars. The three key parameters of the laboratory resistance spot welding equipment were set as following: (i) electrode pressure is 1.5-2 MPa, (ii) welding frequency is 35 cycles/sec, and (iii) weld current is 8500 A or 85% of max current [8]. It should be noted that we have controlled the joining areas for all three joining techniques to be as close as possible using available components in the market, including 4-mm diameters for both mechanical and blind rivet joining and 5-mm spot-welding electrodes.

Table 1 Chemical composition of C1100 and A1050, according to JIS, Japanese Industrial Standard (Japanese Standard Association, 1978)

C1100	**Percentage, wt%**
Copper (Cu)	≥99.9
(Pb, S, Fe, Ni, Zn, Cu)	≤0.01

A1050	**Percentage, wt%**
Aluminum (Al)	≥99.9
Titanium (Ti)	≤0.40
Silicon (Si)	≤0.25
Iron (Fe)	≤0.05
Copper (Cu)	≤0.05
Magnesium (Mg)	≤0.05
Manganese (Mn)	≤0.025

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2.1 Joining strength and immersion tests

The specimen from three different joining methods, including (i) mechanical steel bolt, and (ii) blind steel rivet, (iii) resistance spot welding, were prepared for mechanical, corrosion, and electrical characterizations. Three replications of the workpieces were characterized for all testing to mean calculation. The workpiece was immersed in 3.5 wt% NaCl solution for different durations (0 to 4 weeks) for corrosion behavior investigation and mechanical tensile test. Additionally, 3.5 wt% sodium chloride solution was referred to ASTM G44-21 for a corrosion investigation. The mechanical tensile test is conducted according to ASTM E8 [9], with the purpose of achieve stress-strain behavior as referring to Fig. 3. The T-peel shape specimens (as illustrated in Fig. 1) were prepared for the mechanical tensile test with 30 mm gage length and performed with force-displacement graph record via Universal testing machine (UTM).

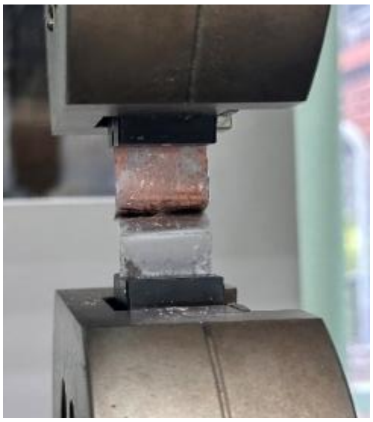

Fig. 3 T-peel shape test in UTM alignment

2.2 Electrochemical test

Electrochemical test was performed using a “PGSTAT302N auto lab” electrochemical workstation for polarization curve to determine the corrosion resistance of the specimens in an electrolyte solution of 3.5 wt% NaCl at room temperature. The polarization test was conducted by initiated electrode potential -1.5 V to 1.5 V at sweep rate of 20 mV/min with the study area was 90 mm^2, this chosen range was sufficient to evaluate corrosion current density measurement, I_{corr} in A/cm^2, by Tafel extrapolation. The three-electrode system was used, including a silver wire coated with silver chloride (Ag/AgCl/saturated KCl) as a reference electrode, a platinum-coated mesh as a counter electrode (CE), and the workpiece as a working electrode (WE). After the electrochemical test, the exposed surface was cleaned and rinsed with acetone and dried in air. For Tafel potentiostatic analysis, the polarization curves of current density-vs.-applied potential (vs. Ag/AgCl) could reveal the corrosion potential (E_{corr}) and corrosion current (I_{corr}) at the interception of the cathodic and anodic polarization curves. I_{corr} value represents the flow of electrons from the working metal to the electrolyte environment during the corrosion process. Therefore, the corrosion rate could then be calculated from I_{corr} using Faraday’s Law. The corrosion rate measures the rate at which the metal surface corroded under the concentrated NaCl environment.

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2.3 Resistivity measurement

The four-point probe method was used for measuring the resistivity of the joints. The four-point probe technique used an alignment of four conductive probes in series with equal spacing between adjacent probes. A current (I mode) was passed between the two outer probes, so the current flowed through the specimen along the alignment of the four probes. A voltage (V) was then measured across the two inner probes. The Al/Cu joints of the T-peel shape specimens were placed in between the two inner probes. Therefore, a pair of outer and inner probes would be pressed on Al side and another pair would be on Cu side. This was to ensure that the current flowed through the joints and the joint resistivity was measured. The resistance could then be calculated from the slope of a voltage-current linear graph. The resistivity could be calculated from the resistance data and the probe spacing parameters.

2.4 Statistical data analysis

Tukey Honestly Significant Different (HSD) test was used to compare the resultant mechanical, electrical, and corrosion data for Al/Cu specimens with varying joining methods. Tukey analysis was used to assess the significance of effects of different joining methods on the joining properties of interest. For the treatment conditions with non-significant difference in the response values, they are labeled with the same letter. For the treatment groups, which show significant difference, they are labeled with different letters. The letters are conventionally labeled from highest to lowest values in the order of 'a', 'b', 'c' and so on ('a' as the maximum value). A treatment group might be labeled with two letters, which reflect overlapping values with two other treatments or more.

The Tukey's test is used in conjunction with the analysis of variance (ANOVA) via excel. In this analysis, the ANOVA tested the overall hypothesis whether the varying joining methods and the immersion durations had significant effect on the mechanical, electrical and corrosion characteristics of the specimens. For both Tukey's test and ANOVA, the confidence interval or confident level of 95% (α= 0.05) was applied. If ANOVA reports a P-value less than α (= 0.05), the treatment of interest shows significant effect on the measured characterization behavior (rejecting null hypothesis).

3. Results and Discussion

3.1 Joining strength test

Fig .4 presents a bar chart of the average maximum tensile load for different joining methods with Tukey's labeled difference. The average tensile loading of the mechanical bolt joining appeared to be the highest. However, with Tukey's comparison analysis at 95% confidence level (α= 0.05), the difference between the average maximum tensile loadings of the mechanical bolt joining and the blind rivet joining is not statistically significant.

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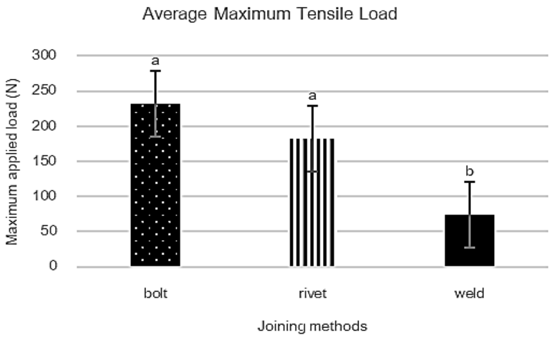

Fig. 4 Bar chart of the maximum tensile loads for the three joining methods with Tukey's HSD letter display

As a result, both joining methods were labeled with 'a'. Meanwhile, the resistance spot weld joining showed the lowest average tensile load.

3.2 Immersion

Fig. 5 shows the bar charts of the maximum tensile load bearing of different joining methods after immersion period from 0 – 4 weeks for (a) mechanical bolt, (b) blind rivet, and (c) spot welding with Tukey's analysis labels. Additionally, the statistical test was a tool to confirm the accuracy of all data in each joining method. One-way ANOVA test showed that the P-value for bolt, rivet, and spot weld was lower than 0.05 (for 95% confidence level), as $2.9x10^{-7}$, $6.7x10^{-7}$, and $3.5x10^{-7}$, respectively. It is clearly seen that an increase of immersion time decreased the joining strength of the specimens. Additionally, it is evident that both before and after exposure to corrosive environment period, the bolt method consistently attains the highest maximum tensile load, thus signifying its robust mechanical integrity and load-bearing capacity under normal conditions. On the other hand, the spot weld process consistently exhibits the lowest maximum tensile load, even at the outset of corrosion period (0^{th} week immersion). This lower load-bearing capacity is indicative of the mechanical characteristics of spot weld method, which tend to be more vulnerable to tensile stresses compared to mechanical assemblies. For the spot-welding method, the maximum load dropped significantly from zero week to first week and then slightly decreased in next three weeks. For the mechanical bolt and blind rivet methods, the maximum loads appeared to drop slightly after the 1^{st} week, then decreased significantly after the 2^{nd} week. The joining strength of the spot weld specimens decreased the most over 4-week immersion period with more than 65% maximum load tensile from Week 0 to Week 4. The rivet method specimen's joining strength decreased around 42% after four weeks, while the joining load of the steel bolt specimen showed the lowest drop of 37% after 4-week immersion.

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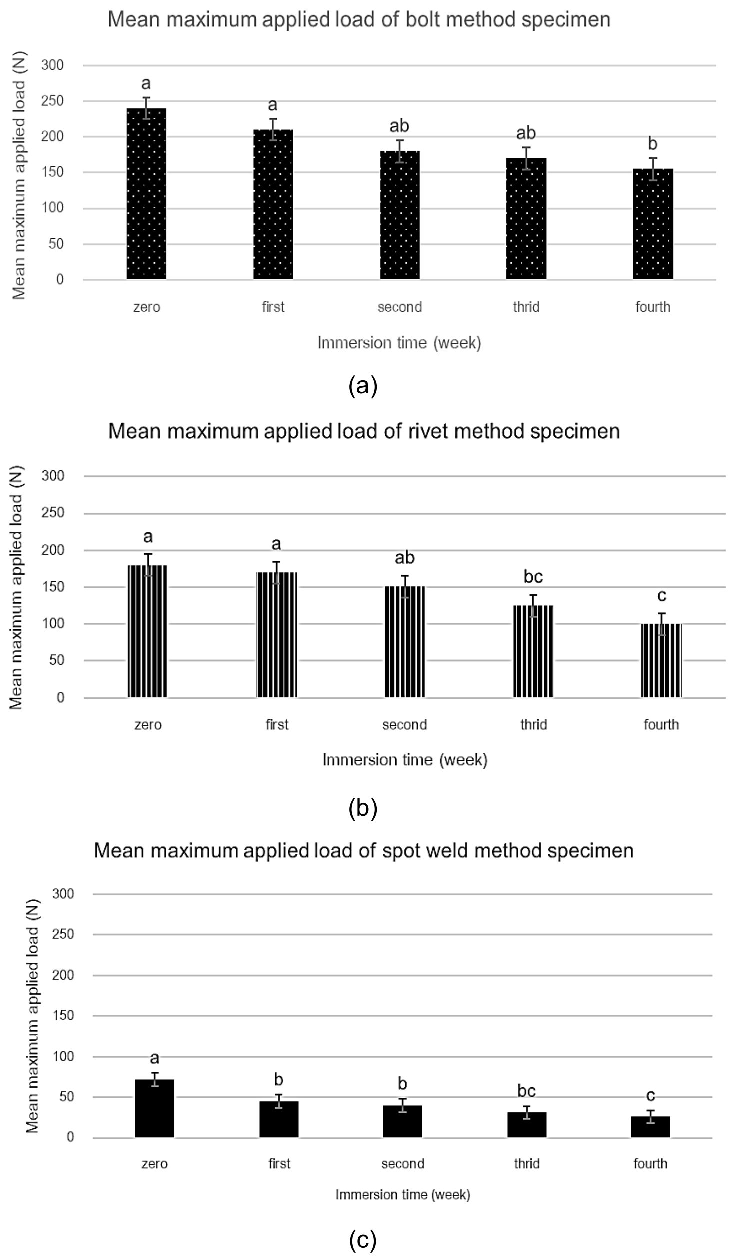

Fig. 5 Bar chart plot of the tensile strength results for over different immersion durations with Tukey's analysis labels for (a) Mechanical steel bolt, (b) Blind steel rivet, and (c) spot welding

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Spot welds exhibit higher susceptibility to corrosion compared to mechanical joining (bolts and blind rivets) due to the lack of protective coatings in their heat-affected zones (HAZ). Therefore, spot welds are more prone to degradation when exposed to corrosive environments such as water or chemicals. These may explain significant drop in the joining strength of the spot welding as compared to the mechanical bolt and blind rivet joining.

3.3 Failure mode

Fig. 6 displays pictures of the failure onsets of the workpieces under tensile loading for all three joining methods. For both mechanical bolt joining and rivet joining (Fig. 6 (a, b)), it is clearly seen that the damage occurred on the Al sides, which ripped along the steel tool length. Under the tensile load, the connector was uniformly loaded at the initial loading phase, then the Al sheet was bent slightly due to its lower strength than either the steel tools or the Cu sheet. As the tensile loading continued, the steel connectors (either bolt or rivet) remained strongly connected to both Al and Cu sheets. As a result, the Al sheets were the weakest links and sheared along the steel connectors. After the tensile test, both heads of steel bolt and blind rivet were struck on the metal sheets with a little bend on the Cu sheets. On the other hand, for the resistance spot welding, the fracture occurred along the weld nugget, as shown in Fig. 6 (c). From the fracture surfaces, it is clearly seen that the welding nugget was the molten Al on the Cu sheet. There were Al pieces throughout the fractured surface on the Cu, while a fractured weld-nugget hole was observed on the Al sheet. Fig. 7 illustrates the cross-sectional microstructure of the Al/Cu spot welding area, taken by Scanning Electron Microscope (SEM). The melting and pressure on dissimilar metals during welding leads to the formation of several phase within the weld nugget upon solidification [10]. Moreover, an intermetallic welding area is evident between the Al and Cu sheets. The intermetallic layer provided the bonding strength however, it was brittle and easily fractured, especially by shearing strength. As a result, the spot-welding provided the weakest joining strength as compared to bolt and rivet methods.

3.4 Corrosion characteristics

Fig. 8 presents the polarisation curves, which provides the corrosion potential (E_{corr}) of materials: steel bolt, steel rivet, Al A1050, Cu C1100. The corrosion potentials of A1050, steel bolt, steel rivet, and C1100 were found to be approximately -1.08, -0.98, -0.96, and -0.90 V vs Ag/AgCl, respectively. These values reflect the materials' inherent tendencies to undergo corrosion within the given experimental conditions (3.5 wt% NaCl solution): the lower potential, the higher corrosion tendency (poorer corrosion resistance). The Al A1050 showed the lowest potential, while the Cu C1100 the highest. Difference in corrosion potentials between

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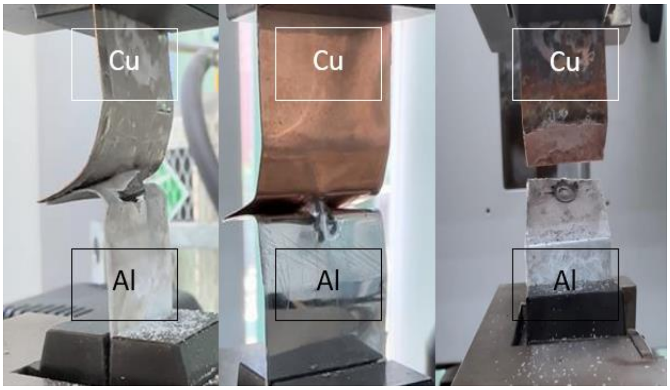

Fig. 6 Failure modes observation of workpieces which connected by (a) bolt, (b) rivet, and (c) weld

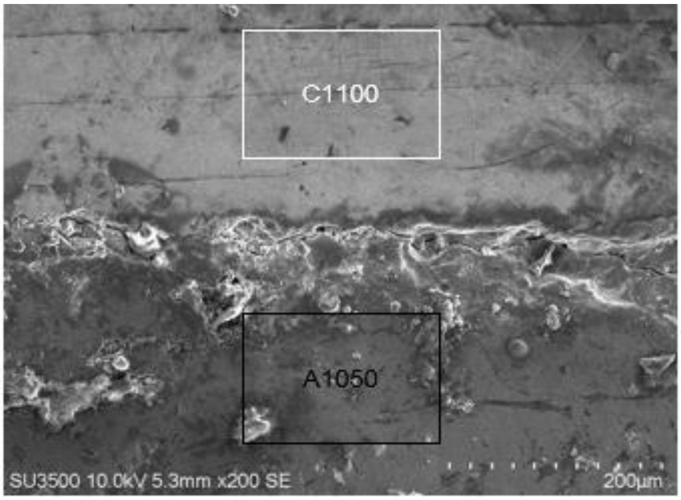

Fig. 7 SEM micrograph of the cross-sectional area of a representative Al and Cu nugget

coupled metals can lead to galvanic corrosion to the lower-potential metal. The current densities (I_{corr}) of A1050, steel bolt, steel rivet, and C1100, are $7.7x10^{-5}$, $4.4x10^{-5}$, $3.4x10^{-5}$, $6.3x10^{-5}$ A/cm^2, respectively. The Cu C1100 showed the lowest corrosion density, while both steel bolt and steel rivet showed the highest corrosion density. Fig. 9 presents polarization curves of Al/Cu specimens with the three joining methods. The corrosion potentials of the Al/Cu specimens joined with steel bolt, steel rivet, spot welding, are -1.05, -1.11, and -1.00 V vs. Ag/AgCl, respectively. The corrosion potentials of the three specimens are comparable with difference by less than 0.1 V. The couple potentials of the joint Al/Cu are in between the potentials of Al and Cu.

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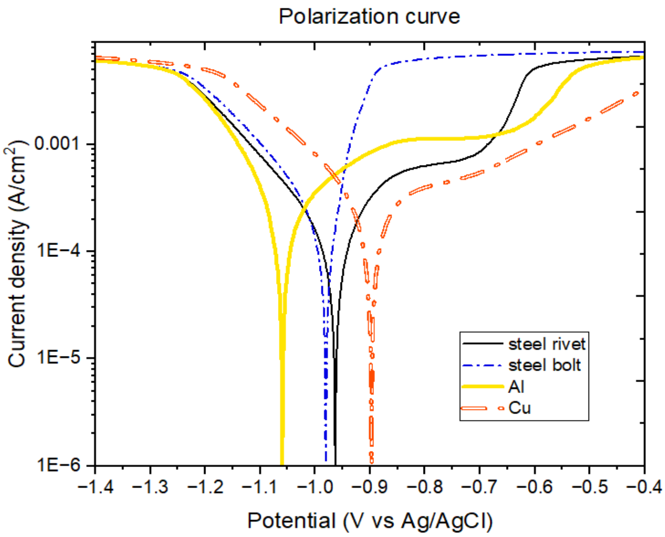

Fig. 8 Polarization curves of Al A1050, Cu C1100, bolt, and steel rivet

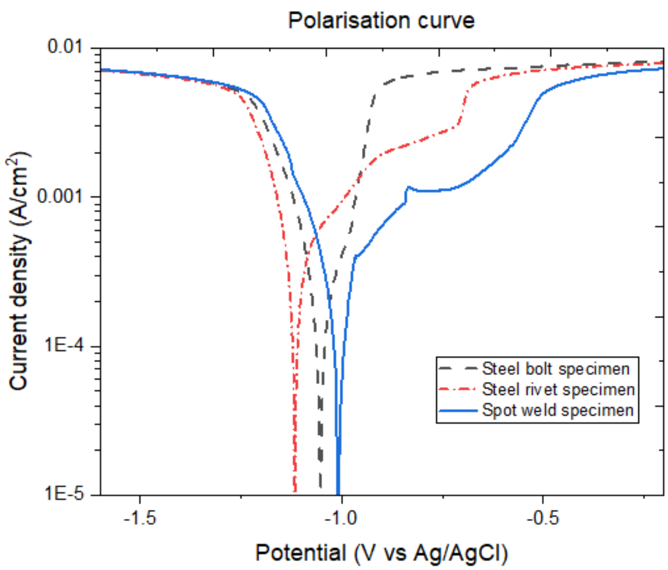

Fig. 9 Polarization curves of the Al/Cu workpieces joined with bolt, rivet, and weld

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Furthermore, the presence of steel tools appears to have shift the potential to more negative (more anodic) than the spot-welding specimen, with the corrosion potential of bolt and rivet specimens being lower than that of the weld specimen. The current density of the Al/Cu specimens joined with steel bolt, steel rivet, spot welding, are 7.9×10^{-5}, 1.7×10^{-4}, and 7.7×10^{-5} A/cm^2, respectively. The corrosion current density data were used to calculate the corrosion rates, which is a measure of how fast a material undergoes corrosion in a controlled environment (expressed in mm/year). This metric provides valuable insights into a material's durability and its susceptibility to chemical degradation. The calculation of corrosion rate from corrosion current is based on Faraday's equation, as shown in corrosion rate Equation (1):

$$corrosion\ rate, r = \frac{0.00327 i_{corr} EW}{d} \quad (1)$$

where i_{corr} is corrosion current density (A/cm^2), EW is an equivalent weight ($\frac{atomic\ weight}{number\ of\ electrons}$), and d is density of material.

Table 2 Corrosion rates from Polarization curves

Joining methods	Corrosion rate (mm/year)
By steel bolt	0.57
By steel rivet	0.76
By resistance spot weld	0.45

Table 2 shows the calculated corrosion rates of all joining specimens. Interestingly, when comparing the corrosion rates between different joining methods, it became evident that the spot weld method exhibited the lowest corrosion rate in contrast to the method involving the addition of steel tools assemblies. Bolt and rivet can create gaps between the fastener and the jointed material, providing a favorable environment for corrosion the steel tools contact with other metal like Al and Cu in a joint, galvanic corrosion can accelerated the corrosion rates of less stable steel and Al components. Furthermore, the concentration of electrolyte of 3.5 wt% NaCl was very high, the concentrated chloride ions could destroy the passive film of Al. Normally, the corrosion rates of A1050 and C1100 in neutral environment are typically less than 0.1 mm/year [11].

Therefore, in this experiment, the high corrosion rates of the three joining specimens are obviously due to the galvanic corrosion under the controlled environment of 3.5 wt% NaCl electrolytes. The concentration of 3.5 wt% NaCl was relatively high and could accelerate the corrosion process, which sodium chloride is a corrosive agent that can be particularly aggressive in promoting corrosion [12,13]. Interestingly, in corrosive environment like NaCl, the surface of metal has a sign of corrosion behavior. Al surface, which Al is known for its ability to rapidly form a protective oxide layer when

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exposed to oxygen, formed a corrosion product that is transparent and colorless. While Cu surface tends to turn darker color as a reddish-brown layer. Moreover, the steel tools (bolt, nut, and rivet) are oxidized and chemically changed to produce rust, resulting in the deterioration of the exposed surface of the material.

3.5 Electrical properties

The four-point probe measurement provided a linear V-I graph from which a resistance could be determined from the V-I slope based on the Ohm's law equation (2):

$$V = IR \tag{2}$$

where *V* is voltage between the two inner probes (V), *I* is current through the outer probes (A), *R* is resistance of material. The resistivity was calculated using the resistivity equation [14], as shown in resistivity equation (3):

$$\rho = 2\pi S \frac{V}{I} \tag{3}$$

where ρ = resistivity ($\Omega \cdot m$), *S* = probe spacing (m). This resistivity equation (Equation 3) is valid for the 4-point probe measurement, of which the workpiece's surface area is much larger than the probe spacing (*S*). The average resistivities of the workpieces with steel bolt joining, steel rivet joining, and spot welding, for 0-week and 4-week immersion, are shown in Table 3. Before the immersion test, the resistivities of the three joining methods are comparable. After 4-week immersion in 3.5 wt% NaCl solution, the resistivities of all the specimen increased significantly by at least an order of magnitude. The blind steel rivet specimens exhibited the largest increase of resistivity after the 4-week immersion (increasing by two orders of magnitude). The resistivities of the steel-bolt and spot-welding specimens increased by an order of magnitude after 4-week immersion. The spot-welding specimen exhibited the lowest resistivity after 4-week immersion. The corrosion reaction may form oxide scales between the joints and result in an increase in resistivity on the joints of the metal sheets, as compared to the common resistivity of conductor materials [15]. The standard resistivity of Cu, Al, and steel are 1.68x10^{-8}, 2.82x10^{-8}, and 10x10^{-8} ohm/m, respectively [16]. The resistivity of the three joints were already higher than the standard resistivity of the metals by an order of magnitude, even before immersion test. The higher resistivity will deteriorate the performance of the conductors with higher power loss at the terminal tabs. Normally, the common steel conductor has a higher electrical resistivity than Al and Cu materials. Therefore, the resistivity of the steel-bolt and steel-rivet specimens were higher than that of spot weld specimen. Bolted joints involve threaded connections, which can introduce additional resistance due to the threading and contact interface between the screw and the nut. Whereas, spot welds typically create a more direct and

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continuous electrical path between the joined materials, minimizing resistance at the joint interface.

Table 3 shows Tukey test label letter has confirmed the result were increased more than 10 times with an increased immersion time, from week0 to week4 immersion. In addition, corrosion causes an increase in resistance on metal sheets, moreover, the higher resistance will deteriorate the performance of the conductors. Steel bolt and steel rivet show insignificant difference in their resistivity values for the 0^{th} week. However, after the 4^{th} week immersion, the steel rivet showed the highest resistivity due to the deformation of the tight connection. The deformation may create gaps or surface irregularities which introduce additional resistance to the flow of electric current compared to steel bolt**.** The spot-welding joining exhibited the lowest resistivity as compared to the mechanical bolt and rivet, weld contact is directly bonded the Al and Cu tabs, as opposed to the touching contacts of the mechanical bolt and rivet, which may result in micro gap between Al and Cu tabs.

4. Conclusion

This research reports mechanical, corrosion, and electrical comparisons of three joining methods for Al A1050 and Cu C1100 plates: mechanical steel bolt, steel blind rivet workpieces, and resistance spot welding.

Table 3 The Average Resistivity of workpieces in (a) 0-week, and (b) 4^{th} week immersion test

Joining Methods	Average Resistivity ($\Omega \cdot m$)	
	0^{th} week-immersion	4^{th} week-immersion
Steel bolt	4.27×10^{-7} c	4.11×10^{-6} b
Blind steel rivet	3.66×10^{-7} c,d	2.83×10^{-5} a
Resistance spot weld	1.57×10^{-7} d	1.32×10^{-6} b

The immersion of in a 3.5 wt% NaCl solution, a highly concentrated environment, allowed for the assessment of corrosion over a 4-week duration.

In terms of tensile load, the mechanical bolt joining exhibited the highest strength, while the spot welding showed the lowest strength. The failure analysis showed that, after the tensile test, both heads of steel bolt and blind rivet were struck on the metal sheets with a little bend on the Cu sheets, which helped impede further fracturing. On the other hand, for the resistance spot welding, the fracture occurred along the weld nugget, which was the molten Al on the Cu sheet. Therefore, the fracture mechanism of the spot-welding join was more brittle and weaker than the mechanical joining.

The corrosion from week 0 to week 4 on the workpiece surfaces demonstrated a direct and significant impact on their mechanical strength

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with substantial decreases in the maximum load for all joining methods—steel bolt, blind rivet, and spot weld—approximately 42.62%, 60.06%, and 63.37%, respectively. Spot welds exhibit higher susceptibility to corrosion compared to mechanical joining (bolts and blind rivets) due to the lack of protective coatings in their heat-affected zones (HAZ). These may explain significant drop in the joining strength of the spot welding as compared to the mechanical bolt and blind rivet joining.

The corrosion rates (from Faraday's equation and Tafel analysis) of the three joining methods under 3.5 wt% NaCl environment were relatively high with the corrosion rate of 0.4 – 0.8 mm/year. The high corrosion rates of the three joining specimens are obviously due to the galvanic corrosion under the controlled environment of 3.5 wt% NaCl electrolytes. The concentration of 3.5 wt% NaCl was relatively high and could accelerate the corrosion process, which sodium chloride is a corrosive agent that can be particularly aggressive in breaking the passive oxide films and promoting corrosion.

For the electrical resistivity data, the resistivities of the three joining methods are comparable. After 4-week immersion in 3.5 wt% NaCl solution, the resistivities of all the specimen increased significantly by at least an order of magnitude. The blind steel rivet specimens exhibited the largest increase of resistivity after the 4-week immersion (increasing by two orders of magnitude). The spot-welding specimen exhibited the lowest resistivity after 4-week immersion. The corrosion reaction may form oxide scales between the joints and result in an increase in resistivity on the joints of the metal sheets.

In summary, from a mechanical strength and durability standpoint, the mechanical bolt joining is the best option exhibiting the highest bonding strength even after 4-week immersion in the 3.5 wt% NaCl solution. However, from an electrical power loss standpoint, the spot welding provides the lowest electrical resistivity even after 4-week immersion. So, for the application with low loading demand, the resistance spot welding may be an optimal choice to minimize power loss due to electrical resistance. However, for high loading applications, mechanical joining is recommended.

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