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The electrical and mechanical aspects of aluminum and copper resistance spot weld joints

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HIGHLIGHTS

- Copper and Aluminum 1050, with 1 mm thickness, were joined by RSW.
- Metallurgical properties for RSW joints change in three areas: BM, HAZ, and FZ.
- Electric resistance during tensile tests was investigated for similar and dissimilar RSW joints.
- Resistivity increases as the deformation increases.
- The deformation reducing electrical conductivity.

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ABSTRACT

Resistance spot welding (RSW) is widely used in the automotive industry, particularly for copper-aluminum alloys in electric cars. RSW joint conductivity is crucial for electric vehicles. Welded parts may fracture due to tension, altering conductivity. The study examines resistance spot post-weld joint metallurgy and deformation-induced conductivity changes. The electric resistance of similar and dissimilar RSW joints was examined during tensile tests. Metallurgical tests for RSW joints revealed an increase in grain size from the base metal (BM) to the heat-affected zone (HAZ) and finally the fusion zone (FZ). Satisfactory shear tension strength results were obtained for dissimilar joints (Al-Cu) at 690 N and similar joints (Al-Al) at 780 N, exceeding the minimum limit of 643 N. However, weld strength in similar joints (Cu-Cu) only achieved 933 N, less than the required strength of 1528 N. Furthermore, the relationship between deformation rate (i.e., applied stress) and electrical resistance has been shown. It was found that resistivity increases with increasing deformation stress, resulting in decreased electrical conductivity with a high percentage, representing 99.8, 99.66, and 99.49% for Al-Cu, Al-Al, and Cu-Cu RSW joints, respectively. The electrical resistance was measured at the maximum force of 650 N and maximum stress of 33.1 MPa. The results show (15.7 Ω, 5.9 Ω, and 1.99 Ω) and the electrical conductivities (0.063 IS, 0.169 IS, and 0.502 IS) for the joints (Al-Cu), (Al-Al), and (Cu-Cu), respectively.

1. Introduction

RSW is the most prevalent welding method in the automotive industry. It creates weld nuggets with the desired shape and size, ensuring they can withstand mechanical deformation and provide the necessary toughness. RSW is one of the greatest techniques for sheet metal manufacturing because of its simplicity, flexibility, and ability to offer features in the form of a workpiece [1-8]. RSW is a technique for joining two pieces of metal using an electric current to weld the lap joints in the interface surfaces [1,2,6-11]. The structural strength and integrity mainly depend on the condition of the welded area [1,8,12-16]. However, certain applications require a balance between toughness and electrical conductivity. In line with the automotive industry's objectives to reduce weight, enhance safety, and improve fuel efficiency, carefully considering material cost and mechanical properties has led to the use of Cu and Al-alloys. These materials possess high electrical conductivity, making them advantageous for electric automobiles [3,6,17]. It is still challenging to weld metals with higher thermal conductivity, lower resistance, and high conductivity, such as non-ferrous group metals. The tensile shear test is a common method used to evaluate the strength and integrity of resistance spot welds [18]. The metallurgical process investigates resistant spot-welded joints' microstructural changes and mechanical behavior. The findings can aid in optimizing the resistance spot welding process for

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different material combinations and enhance the overall performance and reliability of welded structures in various industrial applications [19]. Copper and aluminum alloys have very low electrical resistance (approximately 20 ohms) [3,20,21]. Hence, electrical power can flow very easily.

Different mechanical stresses are applied to the welded structures. Tensile testing is an important mechanical test as a result.

In previous studies, researchers have focused on microstructural changes, mechanical behavior, hardness, failure modes, mechanical properties, and the HAZ of RSW joints [1,10,11,22]. The electrical resistance in copper and aluminum alloys is well-known. Still, there is a lack of investigation into the effect of applied mechanical stresses on the weld nugget's electrical conductivity [23,24,25]. The present work aims to fill this research gap by measuring the electrical resistance of specimens under deformation to determine their conductivity This study will focus on electrical connectivity in terms of resistivity for RSW joints and investigate the metallurgical properties of different zones within the weld joint.

To the author's knowledge, the effect of the applied stresses (deformation) on the RSW electrical conductivity has not been investigated. Therefore, this study measured the electrical resistance of the specimen under deformation to indicate the conductivity values. Electrical resistance is the physical characteristic that opposes the current flow, and its measurements are a non-destructive technique that may be used in the field or lab. If electricity can flow through a material with ease, it has low resistance. A material is highly resistant if electricity flows through it significantly [26].

The present study focuses on electrical connectivity in terms of RSW joints' resistivity and the RSW joint's metallurgical properties. The mechanical deformation affects the conductivity of the metal. Therefore, the measurements during the tensile test have been carried out. In addition, the joint that represents the highest strength was determined for dissimilar and similar joints with copper and aluminum.

The increase in deformation (i.e., tensile or shearing) will increase the electrical resistivity while reducing the conductivity of any RSW joint. Hence, this investigation gives insight and recommends avoiding overloading the RSW joints that conduct the current.

2. Experimental procedures

2.1 Materials

Materials were chosen for being well-suited for both electrical conduction and RSW processes. As a result, applications that demand electrical conductivity also necessitate weld strength and quality. In the automotive sector, there is growing attention to non-ferrous metals due to the imperative of reducing vehicle weight. Automotive materials are required to meet various criteria, such as a favorable strength-to-weight ratio, toughness, formability, weldability, resistance to corrosion and fatigue, successful performance in crash tests, and cost-effectiveness [27]. Electrical conductivity is one of the selection criteria for an electric automobile. Investigations involving both similar and dissimilar resistance spot welding (RSW) joints have been conducted on materials of interest. Specifically, T2 grade commercially pure copper sheet and aluminum AA1050, both possessing a 1 mm thickness, were subjected to these welding experiments, as shown in Figure 1. Due to their remarkable electrical conductivity, these materials hold extensive applications in various industries, particularly electric cars [28].

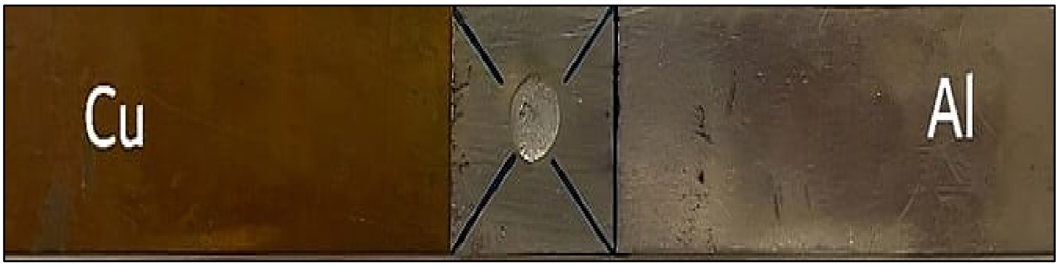


Figure 1: RSW joint (Al-Cu)

The chemical composition was investigated using an optical emission spectrometer (spectroscopy). The chemical elements are shown in Table 1.

The electrical properties, including the electrical resistivity and the electrical conductivity of the metals (Cu and Al), are shown in Table 2 [29].

Preparation before spot welding or any welding process is crucial for achieving strong joints, high-quality welds, and safety. This involves essential steps such as surface cleaning to remove dirt or rust and ensuring the surfaces are flat, smooth, and devoid of any imperfections.

2.2 RSW parameters

This study aims to investigate the effect of deformation on the electrical conductivity of resistance spot-welded (RSW) joints. The most favorable weld joints were created to achieve this goal using optimal welding parameters tailored for the specific metals and thicknesses involved, as outlined in Table 3. The weld energy was established based on the chosen weld current and time, ensuring the formation of the desired weld nugget [1-3,7,8,21].

Table 1: Chemical composition analysis

	Element %									
Aluminum 1050	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**	**AL**		
Actual [test]	0.047	0.4	0.048	0.0033	0.0012	0.0027	0.021	99.5		
Nominal [Stand.]	0.25	0.4	0.05	0.05	0.05	0.05	0.03	99.5		
	Element %									
Copper	**Zn**	**Pb**	**P**	**Mn**	**Fe**	**Ni**	**Si**	**Mg**	**AL**	**Cu**
Actual [test]	0.003	0.0003	0.0008	0.0004	0.007	0.0002	0.0008	0.0001	0.002	100
Nominal [Stand.]	0.01	0.005	-	-	0.007	0.005	-	-	-	> 99.95

Table 2: Electrical Properties of Aluminum 1050 and Copper [29]

	Electrical Properties	
Metals	**Electrical Resistivity (Ω x cm)**	**Electrical Conductivity (Ω^{-1} x cm^{-1})**
Copper	0.034 x10^{-5}	29 x 10^5
Aluminum	0.03 x 10^{-5}	33.3 x 10^5

Table 3: RSW parameters

Joint type	Current (Amp.)	Squeeze time (sec)	Weld time (sec)
Al-Cu [30]	14000	0.65	1
Al-Al [31]	14000	0.2	0.8
Cu-Cu [32]	14000	0.2	0.5

2.3 Metallurgical investigation

Resistance spot welding (RSW) of copper to aluminum joints is challenging due to the significant differences in the metallurgical and mechanical properties of these two materials. Copper and aluminum have different crystal structures and thermal expansion coefficients, which can form brittle intermetallics compounds at the joint interface. These intermetallic can weaken the weld and reduce its mechanical properties [33].

The cross-section of the RSW sample is prepared to show the different zones, including the FZ, HAZ, and BM, under an optical microscope. The etching stage began after the polishing and grinding stages; see Figure 2 (a and b). The etching stage included putting the specimen in the etching solution, which was very important to modify according to the concentration. The etching solution of 5g $FeCl_2$, 50 mL HCl, and 100 mL H_2O has been used by Zare and Pouranvari [34].

The previous studies investigated the intricate details of Al/Cu dissimilar joint formation using resistance spot welding, focusing on the melting phenomena, joining mechanisms, microstructure evolution, and mechanical properties. The metallurgical bonding between Al and Cu through a reaction-diffusion process involving the interaction of liquid Al with solid Cu was achieved by Zare and Pouranvari [34].

(a) (b)

Figure 2: a) Embedded sample, b) Microscopic device

2.4 Tensile-shear test

The single-spot weld nugget samples were prepared for tensile shear testing according to EN ISO 14329 [35]. Two sheets with a length of 100 mm, a width of 25 mm, a thickness of 1 mm, and an overlap of 25 mm in width were welded. The length of the welded sample was 175 mm; see Figure 3. The weld nugget in the center of the overlap distance has been determined to ensure uniaxial loading.

At room temperature, a specimen of 175 mm in length and 25 mm in width was subjected to a shear strength test using universal testing equipment (Tinius Olsen H50 KT) with a 100 KN maximum load capability. It was done at a speed rate of 1 mm/sec. Shims with the same thickness as the specimens were used to hold the tensile specimens in place.

2.5 Electric resistance determination

The joints are supposed to be used in some high-conducive applications under mechanical loading. Consequently, during the tensile test, the electrical resistance was computed; see Figure 3. Physically property, electric resistance is a force that prevents the flow of electricity. The resistance (R) of a workpiece is determined by Ohm's law, which represents a relationship between the current (I) flowing through a material and the voltage (V) applied across it:

$$V = IR \tag{1}$$

The calculation of the electrical resistance for similar and dissimilar RSW joints during the tensile test is shown in Figure 4 (a-d). By connecting the ohmmeter electrodes on the welded sample from two sides with the computer, the impact of the force and stress on the conductivity of the welding joints during the tensile shear test will be measured.

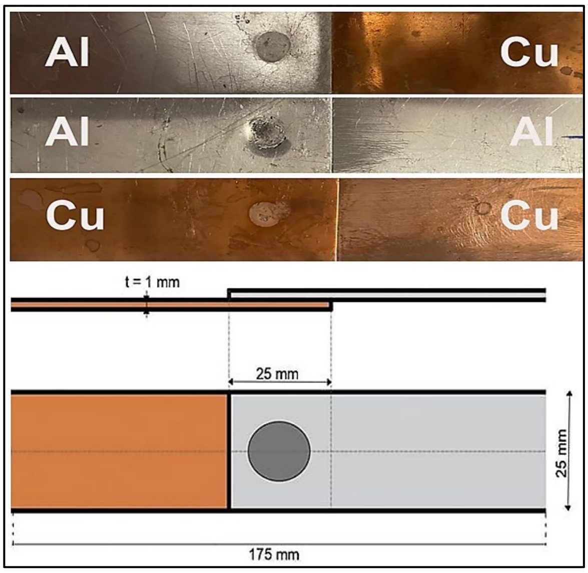
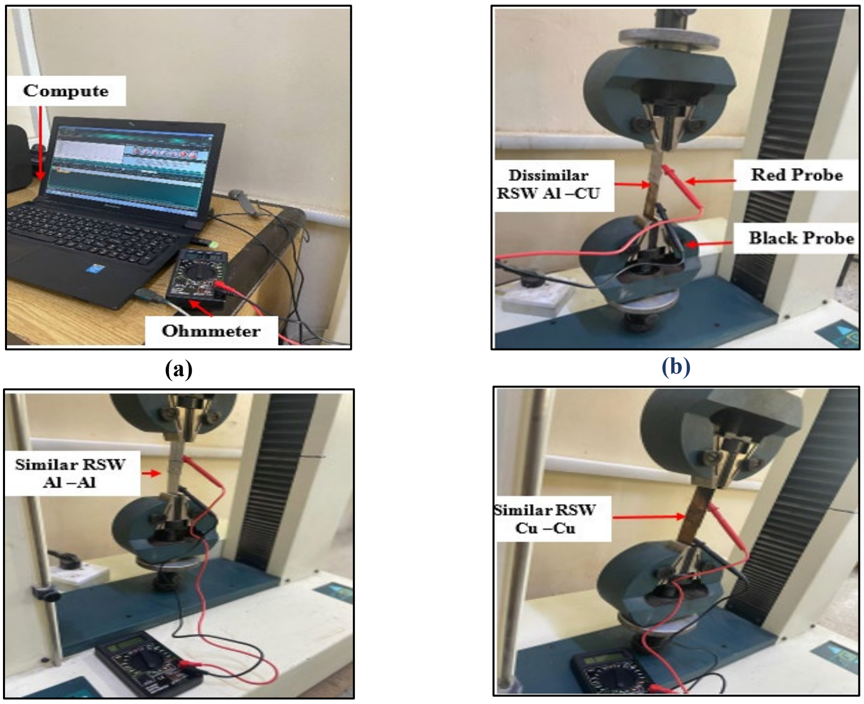


Figure 3: Specimen dimensions for RSW joint



(a) **(b)**

(c) **(d)**

Figure 4: Electric resistance measurement, a) Ohmmeter, b) Al-Cu, c) Al-Al, d) Cu-Cu

2.6 Electrical conductivity determination

The measured resistivity will be used to determine conductivity [36]. The relationship between conductivity Б and electrical resistance, R, is presented in Equation 2 [37]. Equation 3 represents the unit of electrical conductivity [37]:

$$Б = \frac{1}{R} \tag{2}$$

$$\text{Siemens } (1S) = \frac{1}{\text{ohm } (\Omega)} \tag{3}$$

Traditionally, the electrical resistivity and conductivity have been calculated between the electrodes of the welding machine and the workpiece (metals joined by RSW) [38]. This work investigates the electrical resistance of a post-welded joint to show the effect of deformation on electrical conductivity.

3. Results and discussion

3.1 Metallurgical investigation

Metallurgical investigation in RSW involves examining and analyzing the microstructural changes of the welded joints. This investigation aims to understand the effects of the welding process on the materials being joined and to evaluate the quality and integrity of the weld. Three main zones can be observed in the cross-section of resistance spot welding joints. The first zone is FZ, representing the area where the base metals have been melted and fused together during welding. This region exhibits a distinct microstructure due to the solidification of the molten metal. The second zone is the HAZ, surrounding the FZ, where the base metals have been subjected to high temperatures during welding but have not completely melted. In this zone, there are microstructural changes due to thermal cycles, potentially leading to alterations in material properties. Finally, the third zone is the base metal (BM), which refers to the unaffected parent material that has not experienced significant thermal or microstructural changes during welding. The base metal is a reference point for comparison with the FZ and HAZ; see Figure 5.

The increase in temperature caused by current and electrode pressure on the sheet metal shows an observable increase in grain size (see Figure 5). This increase leads to the loss of the granular shape as grains become crowded, particularly in the FZ.

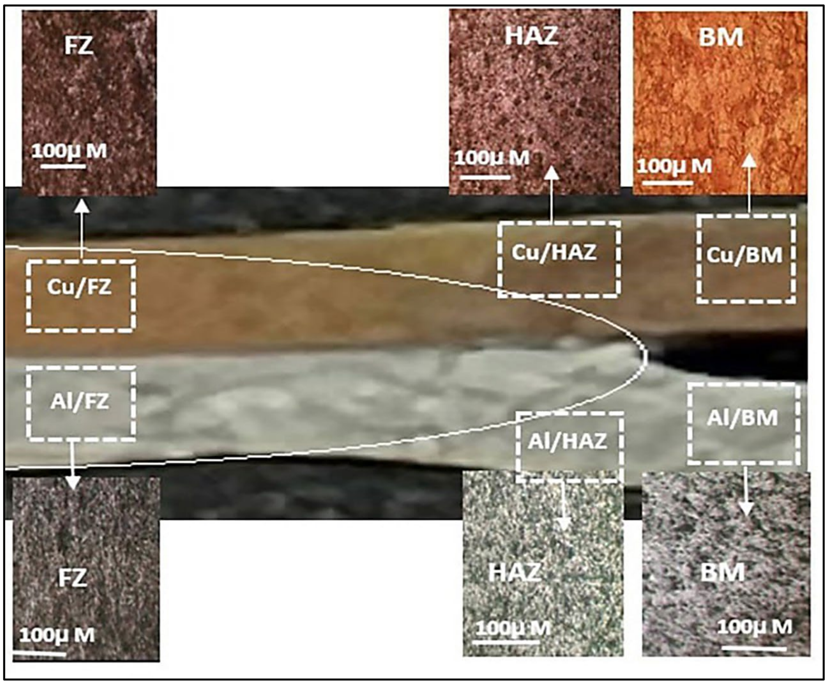


Figure 5: Microstructure of Weldment

3.2 3.2 Tensile shear test

The tensile shear test provides crucial information about the weld's quality, including its load-carrying capacity, shear force resistance, and ability to withstand applied tensile stresses. The test results assess the weld's mechanical strength and compare the performance of different welding parameters and materials.

Tensile shear tests were carried out on the overlapping spot-welded sheets to evaluate the strength of the joints. A specimen was welded to verify the results. The experimental results were compared with the tensile shear value in previous references in addition to the values obtained from Equation 4 after welding, depending on the (American National Standard) AWS C1.1 M/C1.1 [39]:

$$ST = (-6.36^{*}10-7 \times S2 + 6.58^{*}10-4 \times S + 1.674) \times S \times 4\,t1.5/1000 \tag{4}$$

Where ST is the shear tension strength (kN), S is the base metal tensile strength (MPa), and t is the thickness of the material (mm). Equation 4 represents the minimum design strength value (required strength). Table 4 shows the tensile strengths of the base metals aluminum and copper obtained by tensile test. Aluminum has less strength than copper. Therefore, the final nugget failure on the aluminum side was recognized. The cracking behavior of the weld nugget was discussed by Al-Mukhtar ***et al.***. [1,8,40,41].

In the case of similar (Al-Al) and dissimilar (Al-Cu) RSW joints, the value of tensile strength of 93 MPa was used in Equation 4. Because of design aspects and safety, the strength of the softer metal is used to calculate the strength of the joints [42]. For similar joints, Cu-Cu, the strength of 214 MPa was used. All metal thickness is 1 mm; see Equation 4. Table 5 shows the tensile strength for welded joints from Equation 4, previous references, and those measured experimentally.

Table 4: Tensile strength for base metals

Metals	Tensile Strength (MPa)
Al 1050	93
Cu	214

Table 5: Tensile strength (ST) for welded joints

Joint	ST kN (N) Eq. 4	ST kN (N) Experimentally	ST kN (N)
Al-Cu	0.643 (643)	0.690 (690)	0.680 (680) [30]
Al-Al	0.643 (643)	0.780 (780)	0.75 (750) [43]
Cu-Cu	1.528 (1528)	0.933 (933)	1 (1000) [44]

There are differences with the literature because the tensile shear strength of welded joints depends on many factors, including electrode force, electrode geometry, welding time, and welding current, see Table 5. These factors influence the tensile shear strength of the resistance spot weld [45].

Equation 4 represents the minimum values of the shear tensile strength for welded joints. To ensure the quality and strength of the welded joints, the experimental results must be greater than the minimum shear tensile strength values. Table 4 shows the tensile strength from experimental, theoretical, and previous reference shear tensile strength results.

Higher tensile strength indicates a stronger and more durable joint. The welded joint needs to possess adequate tensile strength to ensure that it can withstand the anticipated mechanical stresses and loads without failing. The results represent good values for dissimilar Al-Cu and similar Al-Al RSW joints. However, Cu-Cu RSW joints do not achieve the required strength. It is less than the lowest value required by the Equation 4, see Table 5. Because similar Cu-Cu RSW are unsuitable for spot welding. Copper can be successfully welded with other metals and alloys, as demonstrated in previous work [46].

Figure 6 shows the different values of the tensile strength of RSW joints made of aluminum and copper. The shear tensile strength values from experiments and literature have been compared for each case separately (Al-Al, Cu-Cu, and Al-Cu). The experimental values of Al-Cu and Al-Al joints exceeded the theoretical results by 6.8% and 17.5%, respectively.

Figure 6 shows the difficulties of RSW in such hybrid joints (Al-Cu). Hence, it has a lower shear tensile strength. It was shown that the Cu-Cu RSW has higher strength than other cases due to the higher tensile strength of copper base metals.

The used copper is pure since it's desired for electrically conductive applications. Therefore, the tensile strength of the base metal (copper) is lower than the other types of copper alloys; see Table 1. The literature also shows that the experimental value is lower than the designed value (see Table 5).

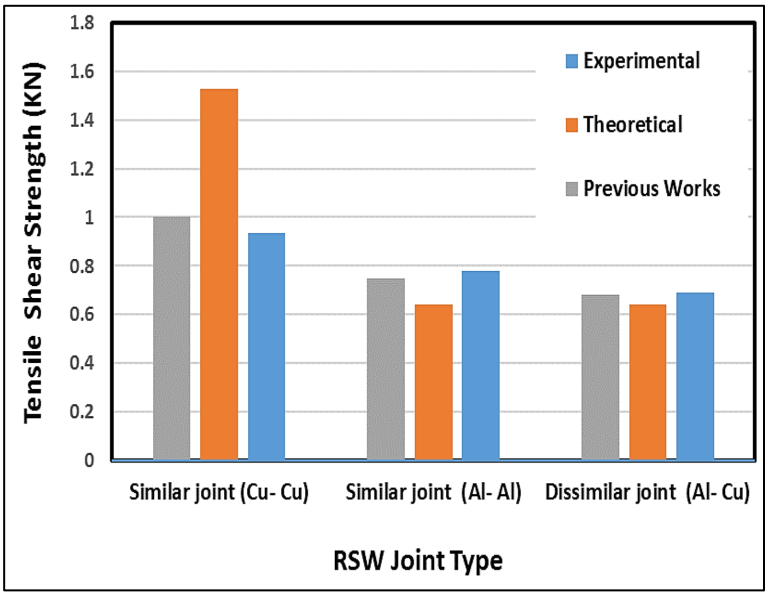


Figure 6: The comparison of the tensile strengths for RSW joints

3.3 Electric resistance measurements

An ohmmeter was utilized to determine the electrical resistance, involving the attachment of two probes on opposing sides of the specimen. The separation distance between these probes remained constant; see Figure 4. Subsequently, a tensile test was conducted on the welded joints, employing a strain rate of 1 mm per minute. During this process, both electrical resistance and the corresponding applied stresses were measured and recorded; see Table 6. The highest force and stress values employed in Table 5 were consistently applied across all tested samples, with values of 650 N force and 33.1 MPa stress.

Figure 7 shows the relationship between force and electrical resistance obtained from Table 6. The force's behavior and stress with electrical conductivity are the same because the cross-sectional areas are the same.

Table 6: Forces (F) and stresses (σ) relation to electrical resistance

F (N)	σ (MPa)	R (Ω); (Al-Cu)	R (Ω); (Al-Al)	R (Ω); (Cu-Cu)
0	0	0.03	0.02	0.01
100	5.10	0.4	0.3	0.2
150	7.65	0.7	0.4	0.25
200	10.20	0.9	0.7	0.4
250	12.75	1	0.7	0.44
300	15.3	1.2	0.9	0.5
350	17.85	1.4	0.98	0.52
400	20.40	2.3	1.5	0.9
450	22.9	7.8	3	1
500	25.51	8.1	3.4	1.1
550	28.06	9	5	1.3
600	30.6	13	5.5	1.7
650	33.1	15.7	5.9	1.99

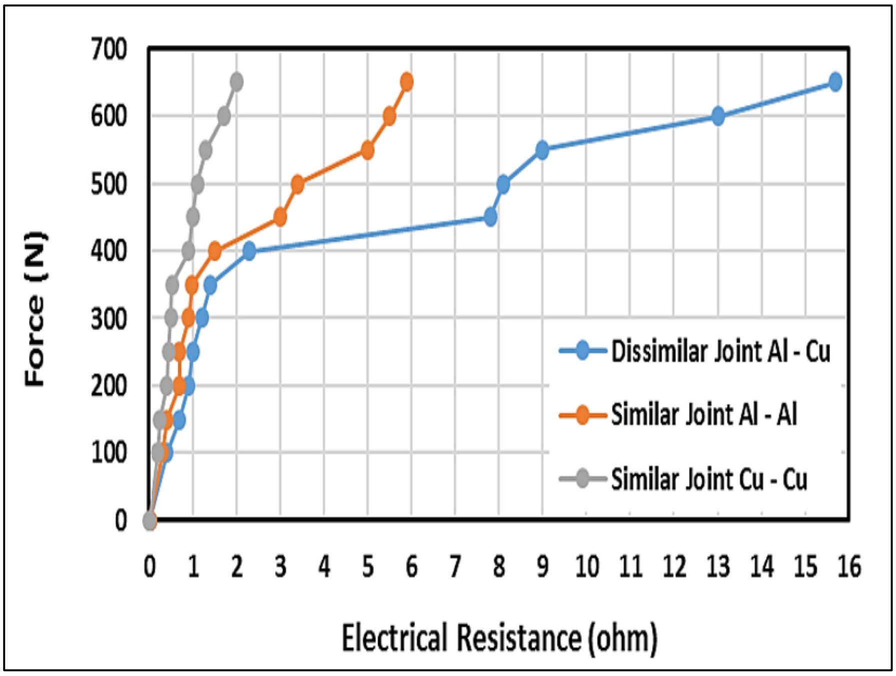


Figure 7: Relationship between forces and electrical resistance

Increasing the forces or applied stresses increases the electrical resistance with ratios of 99.8%, 99.6%, and 99.4% for Al-Cu, Al-Al, and Cu-Cu joints, respectively; see Figure 7. Increasing the forces or applied stresses in a material can lead to an increase in its electrical resistance due to the phenomenon of strain-induced resistance increase. This effect results from the mechanical deformation within the material as it is subjected to higher forces or stresses. When forces are applied to a material, it undergoes strain, a change in its shape or dimensions. The deformation and cold working increased the number of collisions between electrons in metal atoms [47]. Hence, there is an increase in the electrical resistance in all RSW joints. This problem is important to consider in welding applications, as it can affect the quality of joints and the overall electrical performance of post-welded components.

3.4 Electrical conductivity measurements

Electrical conductivity was determined using Equation 2, based on the forces and stresses detailed in Table 7. The obtained conductivity values for each type of resistance spot welding (RSW) joint, whether similar or dissimilar, are presented in Table 6. These conductivity measurements were taken under specific forces and stresses during the tensile testing process.

Figure 8 shows the relation between forces and electrical conductivity obtained from Table 7. The force's behavior and stress with electrical conductivity are the same because the cross-sectional areas are the same.

Table 7: Forces (F) and stresses (σ) relation to electrical conductivity Б

F (N)	σ (MPa)	Б (1S); (Al-Cu)	Б (1S); (Al-Al)	Б (1S); (Cu-Cu)
0	0	33.33	50	100
100	5.10	2.5	3.33	5
150	7.65	1.42	2.5	4
200	10.20	1.11	1.42	2.5
250	12.75	1	1.428	2.272
300	15.3	0.83	1.111	2
350	17.85	0.714	1.020	1.923
400	20.40	0.434	0.666	1.11
450	22.9	0.128	0.33	1
500	25.51	0.123	0.294	0.90
550	28.06	0.11	0.2	0.769
600	30.6	0.076	0.181	0.588
650	33.1	0.063	0.169	0.502

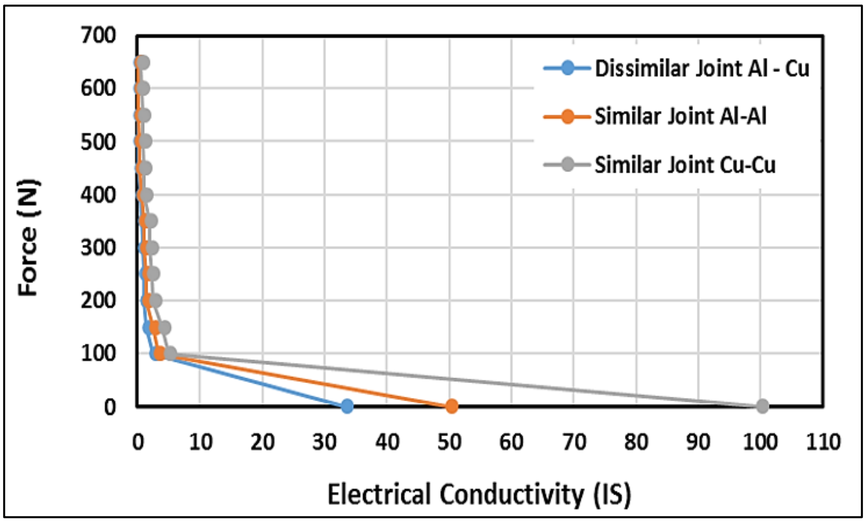


Figure 8: Relationship between force and electrical conductivity

As deformation (stress or force) increases, the electrical conductivity of RSW decreases; see Figure 8. It's been observed that the influence of force and stress on electrical conductivity remains consistent across various welded metal types, showing uniform behavior across all joints. The increasing deformation (stress or force) can decrease the electrical conductivity of joints, such as in resistance spot welding (RSW). When a material is subjected to deformation (the tensile-shear test), there is a crack or defect. The electrons in the metal encounter these defects, and they experience collisions, which hinder their smooth flow and reduce conductivity.

4. Conclusion

The paper investigates resistance spot welding for aluminum and copper joints, focusing on the metallurgical changes occurring after welding. The strength of both similar and dissimilar joints is assessed through tensile shear testing. Furthermore, the electrical conductivity of the RSW joints under tension is studied. The obtained results are compared with findings from other studies. Based on the research, the following conclusions can be drawn:

1) Both the tensile strength of the base metals and the thickness of these materials influence the shear tension strength of resistance spot welds. By increasing the tensile strength of metals, the shear tension strength increases the same way as the condition for thickness.
2) In dissimilar resistance spot welding (RSW), the shear tension strength is calculated based on the strength of the softer metal involved in the joint.
3) The highest shear tensile strength for all the tested joints is observed in similar copper RSW joints; it exceeds 26% for the Al-Cu joint and 16.3% for the Al-Al joint. However, the obtained strength value falls short of the design strength requirement even in this case.
4) The properties of the base metals, namely copper and aluminum, significantly influence the resistance and electrical conductivity values in resistance spot welding (RSW).
5) The electrical conductivity of resistance spot welds decreases as the applied force and stress increase. Therefore, deformation, including tensile force and stresses, substantially impacts the electrical conductivity of RSW joints.
6) With an increase in temperature during welding, the grain size is found to increase from the base metal (BM) to the heat-affected zone (HAZ) and finally the fusion zone (FZ). This phenomenon is a result of the welding-induced heating process.

English Symbols

Notation	Description	Units
RSW	Resistance Spot Welding	
Al-Cu	Aluminum – Copper joint	
Cu-Cu	Copper – Copper joint	
Al-Al	Aluminum – Aluminum joint	
BM	Base Metal	
HAZ	Heat Affected Zone	
FZ	Fusion Zone	
V	Voltage	Volt
C	Current	Ampere
Б	Electrical Conductivity	Siemens (1S)
R	Electrical Resistance	ohm (Ω)
ST	Tensile strength	N

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Author contributions

Conceptualization, M. Fakhri, I. Mahmood, A. Al-Mukhtar; formal analysis, M. Fakhri, I. Mahmood, A. Al-Mukhtar; resources, M. Fakhri, I. Mahmood, A. Al-Mukhtar; writing—original draft preparation, M. Fakhri, I. Mahmood, A. Al-Mukhta. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

Upon request, the corresponding author can provide access to the data supporting the findings of this study.

Conflicts of interest

The authors assert that they have no conflicts of interest to declare.

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