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Investigate the effect of resistance spot welding pulsation on dissimilar Al-Ti joint on corrosion behavior and mechanical properties

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ABSTRACT

Aluminum AA2024-T4 and titanium G2 sheets were joined by resistance spot welding successfully. Welding parameters used are; current 60 amps, holding time 3 seconds, and with three different pulsations. One pulse, three pulses, and five pulses with pulsation time being one second. Mechanical (tensile, microhardness, and microstructure) and chemical (corrosion) tests were carried out and compared for each welded plates with different pulsations (1, 3, and 5 pulses) for the same conditions aluminum-aluminum, titanium-titanium, and aluminum-titanium for a complete and comprehensive comparison. Through the results obtained, the optimum results were obtained for spot welded Al-Ti (Al-Ti 603) with (3) pulses, where a maximum tensile strength value of 135 MPa, a corrosion rate of 0.00308 mm/y, and a microhardness between (215–198 HV). A spot welded joint was obtained with partial fusion, clear overlapping vertical granular areas, and no cracks compared to other joints, which show cracked areas, lower strength and microhardness values, and a higher corrosion rate.

Keywords: spot welding, dissimilar Al/Ti, corrosion, mechanical properties.

INTRODUCTION

As a result of the development of industry and the expansion of applications, the need to use welding processes between different materials emerged. The welding processes for different metals showed many characteristics and advantages that in turn contributed to solving many problems in the field of aviation, space, and automobiles, and the applications that fall within the field of weight reduction [1, 2]. Also, in the areas of the environment, energy saving and costs which requires the use of lightweight and low-cost metals such as Titanium, Aluminum and Magnesium, in addition to the requirements for connecting and welding them when manufacturing [3–7].

Both titanium and aluminum alloys are considered as the most widely used because of the advantages that can be obtained from their use, such as high formability, excellent mechanical properties, and high resistance to corrosion [8–10]. Resistance spot welding is considered as one of the important joining methods which is used in the process of joining dissimilar metals and in the areas mentioned above. However, car manufacturers suffer from the difficulty of dealing with spot resistance welding due to the complexities resulting from its use. For example, the diameter of the block is considered one of the most substantial criteria for the quality of spot welding. The microstructure of spot welds also has a significant influence on the mechanical properties of welds [11, 12].

Fusion welding has been applied to both aluminum and titanium on a large scale. It was not the ideal method for welding dissimilar aluminum and titanium alloys due to the presence of a large amount of variances in the melting point, thermal conductivity, coefficient of expansion, and specific heat capacity. This may result in a significant deformation, internal stresses, the grain size, and a decrease in bonding during the welding process.

For instance, the melting point of aluminum alloy is 660 °C, while Titanium alloy is 1650 °C. This large variance in melting points between the two alloys leads to difficulty in joining them by traditional welding methods as well. In addition, the difference in melting points may lead to the evaporation of some aluminum elements at temperatures higher than its melting point, which causes the loss of chemical composition of the weld joint [13–15].

Researchers have improved the quality of welding by improving welding parameters. Mezher *et al.* [6] examined welding factors (welding current, welding pressure, welding time, holding time, squeezing time, and pulse welding) effect on shear force, hardness, and failure mode of spot welding for Titanium sheets (grade 2). They used design of experiments and artificial neural network models to find the optimal results. Wang *et al.* [16] investigated the use of Aluminum foil as an interlayer to join magnesium alloy (AZ31B) and titanium (TA2) using resistance spot welding. Welding current and welding time were changed during welding process while microstructure and tensile shear were observed. They found that increasing welding current or welding time led to an intial increase then a slight decrease in tensile shear. Al-Kinani and Alali [17] studied the parameters of welding and coating type effect on Al 6061 and steel AISI 1006 joint by spot welding. They found that the max. shear force increased with the use of coating, Vickers microhardness varies in the welding joint, corrosion resistance increased with welding current. Ulbrich *et al.* [18] used ultrasound waves to investigate the effect on spot welding joint with different welding parameters. They showed that surface waves can be used accurately to assess weld nugget diameter. Fatmahardi *et al.* [19] studied resistance spot welding quality of titanium alloy (Ti-6Al-4V). The physical and mechanical properties by Taguchi L9 method to find the optimum value of the weld joint strength were sudied. The optimum sample was analyzied in terms of failure mode, microstructure, and hardness. Zhou *et al.* [20] examined mechanical and microstructure properties of AA6061Al and commercial pure Ti sheets spot-welded with ultrasonic waves under a welding time of 0.6s to 1.4s. No intermetallic compounds were found at the joint interface. Moreover, as the welding time increased, the maximum joint load first increased with the expansion of the bonding area, and then decreased due to fatigue crack in the Aluminum side. The peak temperature increases with increasing welding time. Zhang *et al.* [21] investigated shear, hardness, fracture energy, and microstructure for AA2139 and TiAl6V4 spot welding by ultrasonic waves. They found that with increasing welding time, strength and fracture energy have increased. Li *et al.* [22] researched the effect of electromagnetic stirring (EMS) on the mechanical and microstructure properties of aluminum/titanium resistive spot welding. It was noted that the microstructure in the traditional Aluminum/Titanium joint consists of a partially molten region, a columnar granular region, and a transitional structure. While under the influence of (EMS) a fine spherical granular structure was formed with appearance of a larger bond diameter and higher tensile shear strength. Zhang and Senkara [23] noted that an appropriate second pulse current can increase the maximum resistance load for spot weld. Maria and Jayden [24] discovered that an elevated current, a long welding time, and a high weld strength help reduce shrinkage voids.

The current research studied joining AA2024-T4 and Ti G2 by using spot welding with fixed parameters (current, holding time, and pressure) and different number of pulsation. Mechanical and chemical tests were carried out and compared for each welded plates with different pulsations for the same conditions aluminum – aluminum, titanium – titanium, and aluminum – titanium for a complete and comprehensive comparison.

EXPERIMENTAL WORK

Materials used

Aluminum type AA2024-T4 and titanium type G2 were used. Before used, both plates were cleaned and dried using Acetone to remove any dust or oxidation layers. The chemical composition for both are shown in Tables 1 and 2.

Classification of specimens and machine setup

A specimen thickness of (0.5 mm), width (16 mm), and length (76 mm) in contact with an overlap of (16 mm) was made according to AWS C1.1M/C1.1:2012 standard. Spot welding of aluminum – aluminum with (1) pulse at (holding time: 3 seconds, DC 60 Amps.), and then welding at the same joint parameter with different pulsations (3 and 5). Under the same welding conditions

Table 1. Chemical composition of AA2024-T4

Element wt. %	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al
Actual	0.5	0.5	4.9	0.6	1.8	0.1	0.05	0.25	0.15	94.7
Standard	0.112	0.352	4.6	0.533	1.6	0.002	0.014	0.049	0.020	92.6

Table 2. Chemical composition of Ti G2

Element wt.%	Ti	Fe	O	N	C	H
Actual	Balance	≤0.3	≤0.25	≤0.03	≤0.08	≤0.015
Standard	Balance	0.055–0.060	0.11–0.12	0.018–0.020	0.016–0.016	0.001–0.0013

as before, titanium – titanium, and aluminum – titanium welding was performed. The classification of the specimens employed is provided in Table 3, which will be utilized throughout the rest of this paper. In order to check test results repeatability, 3 samples were done for each sample type in Table 3, the total are (27) samples.

Tensile test

Tensile testing for the welded samples specified above was performed using a (50 tons) United Tester type tensile testing device. The tests were conducted at a speed of 0.2 mm/min. The stress-strain curves were obtained for the samples, as shown in Figure 1. The maximum tensile stress values were determined as shown in Table 4.

Corrosion test

The corrosion test was carried out using Tafel method to calculate the corrosion rate of each weld with a specimen of exposed area of (1 × 1 cm^2). A Wenking Mlab multi-channel powerful dynamic and SCI-Mlab system from Bank Electronics-Intelligent control GmbH, Germany was used for tests. The corrosion rate was calculated for each weld with a scan rate of (10 mV/ sec), as shown in the Table 5. The obtained corrosion curves are shown in the Figure 2.

Microhardness measurement

Vickers microhardness test using a Digital Microhardness Tester HVS-1000 was used to conduct the tests according to ASTM E384 standards. Load testing used was 100 g. The microhardness for the welded structure areas were measured along a straight line (an axis from the beginning of the weld to the end), with four readings for each weld. The readings were repeated (3) times for each reading to insure test repeatability. The results are shown in Table 6, and are represented in Figure 3.

Microstructure test

The microstructure was tested by a scanning electron microscope (SEM) to recognize the structure of the weld zone. Only aluminum - titanium joints were shown as an example for the microstructure tests for the three pulses joints (1, 3, and 5), since other types (Al-Al, Ti-Ti) will show the same material structure itself. Microstructure tests are shown in Figure 4.

Table 3. The specimens classification

Name of sample	Welded metals	Current (Amps.)	No. of Pulses	Sample
A	Al-Al	60	1	Al60
B	Al-Al	60	3	Al603
C	Al-Al	60	5	Al605
D	Ti-Ti	60	1	Ti60
E	Ti-Ti	60	3	Ti603
F	Ti-Ti	60	5	Ti605
G	Al-Ti	60	1	Al-Ti60
H	Al-Ti	60	3	Al-Ti603
I	Al-Ti	60	5	Al-Ti605

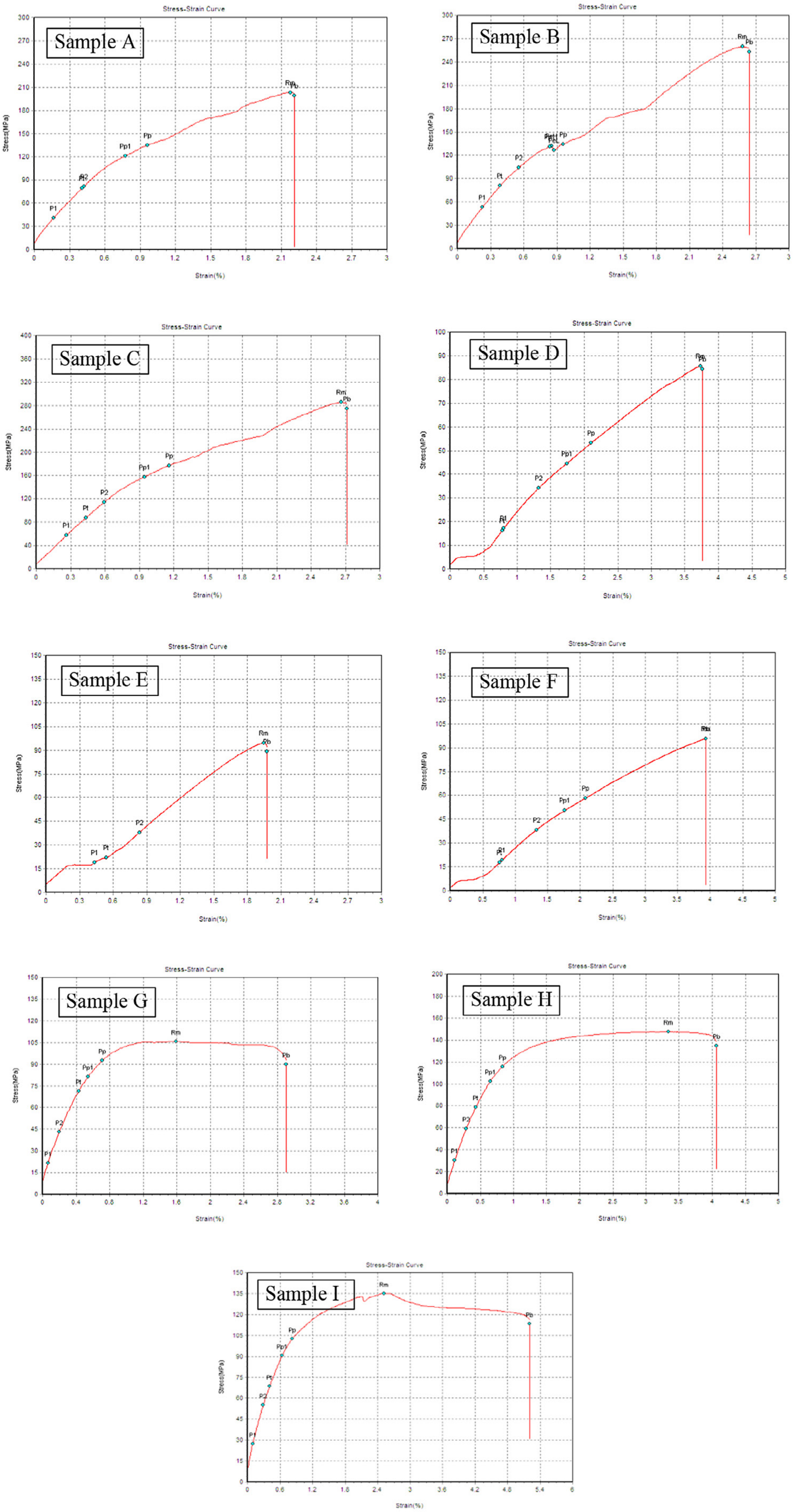


Figure 1. Stress-strain curves for welded specimens

Table 4. Ultimate tensile strength values for the welded specimens

Specimen	U.T.S (MPa)
Al60	191
Al603	260
Al605	284
Ti60	86
Ti603	97
Ti605	93
Al-Ti60	106
Al-Ti603	135
Al-Ti605	148

Table 5. The corrosion rate for the welded specimens

Specimen	Corrosion rate (mm/y)
Al60	0.00629
Al603	0.0084
Al605	0.0244
Ti60	0.0102
Ti603	0.0154
Ti605	0.0133
Al-Ti60	0.0131
Al-Ti603	0.00308
Al-Ti605	0.00604

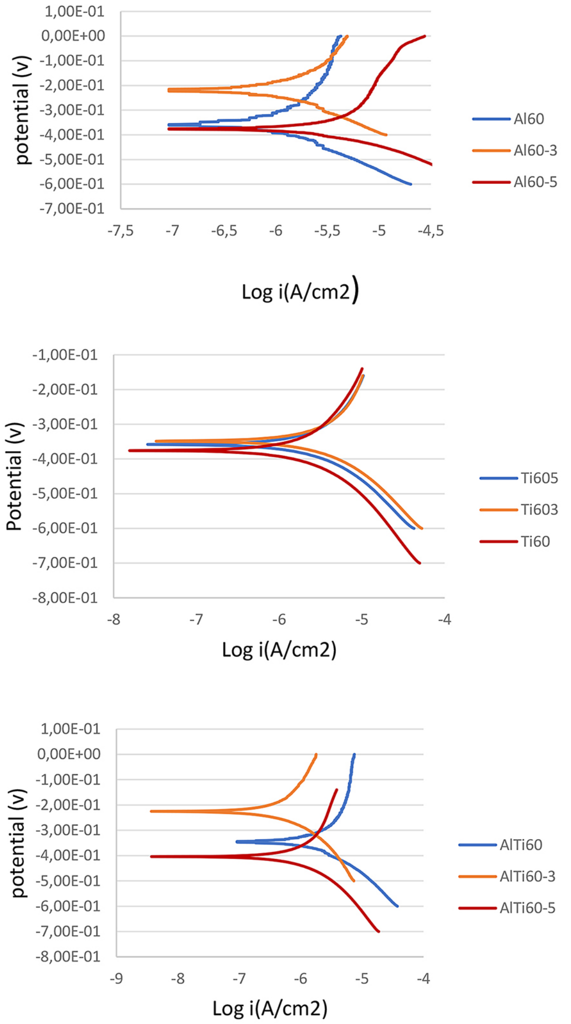


Figure 2. Corrosion tests

DISCUSSION

Aluminum AA2024-T4 and titanium G2 sheets were joined by resistance spot welding successfully with welding parameters (current 60 amps, holding time 3 seconds, and three different pulsations 1, 3, and 5). Through the results obtained from conducting the tensile test, it was discovered that the failure of spot welds of Al-Al and Al-Ti welds was in the base metal around the joint area (the interaction zone between HAZ and base metal) and not in the joint area itself. This indicates that the structure in the joint area was more resistant than the base structure due to a good diffusion, grain refinement, and a good bonding during the adopted welding conditions. While the failure of Ti-Ti weld was in the joint area itself, which indicates that the structure obtained in the

Table 6. Vickers microhardness values

Specimen	T1	T2	T3	T4
Al60	185.6	213.4	190.4	180.7
Al603	180.2	204	191.3	171.6
Al605	184.8	215	198	184.4
Ti60	158.8	171.3	170.5	164.4
Ti603	139.7	161.6	159.3	141.3
Ti605	157	167.2	164.7	156.9
Al-Ti60	155.5	194.4	191.7	183
Al-Ti603	153.2	201.8	210.9	182.1
Al-Ti605	160.2	205.2	220.4	180.2

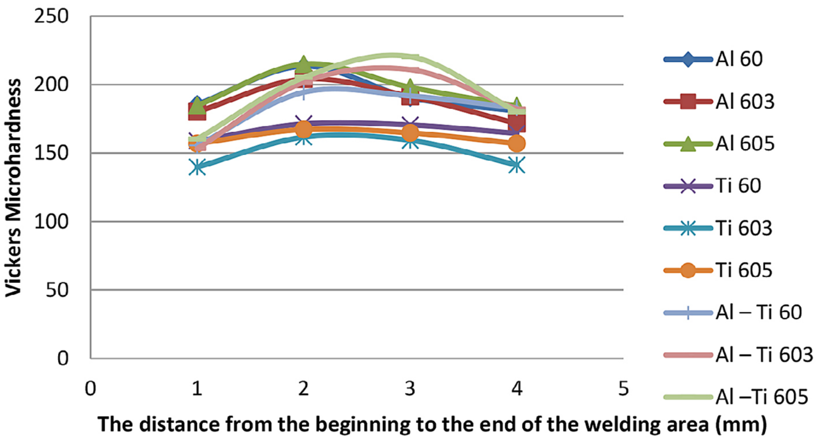
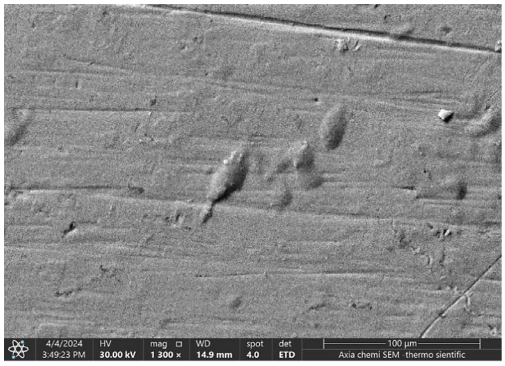


Figure 3. Microhardness measurements for the welded specimens

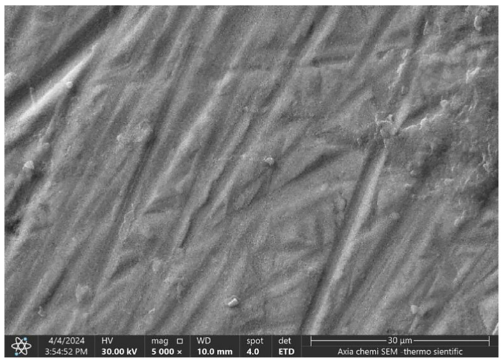
weld area was weaker and less cohesive than the base metal unlike previous welds, knowing that the welding current was constant for all (60 amperes) with different pulses, suggesting that current welding parameters are not suitable for Ti-Ti welding due to huge difference between Al and Ti thermal properties. The obtained results are consistence with literatures [6, 18, and 20].

The corrosion test was conducted using Tafel method. It is obvious from the obtained results that the lowest corrosion rate was for spot welds of Al-Ti with three pulses (0.00308 mm/y), while the value of the corrosion rate for Al specimens welded with one pulse was (0.00629 mm/y). For Ti welds in one pulse, the rate is (0.0102 mm/y). These values are the best corrosion rate values for each type of welding that was performed, as shown in Table 4. For comparison, Ti (G2) base metal corrosion rate is in the range of (0.01 mm/y), and for AA2024-T4 is in the range of (0.0001 mm/y). The obtained results show that with the welding pulses increase for both Al and Ti each one alone, corrosion resistance decrease due to change in the structure in base metal. This is consistent with what was mentioned regarding the welded structure of Al-Al and Al-Ti in terms of the bonding strength and correct diffusion during the welding process and under the conditions that were adopted. Unlike the Ti-Ti welds, they have less bonding strength under the same conditions.

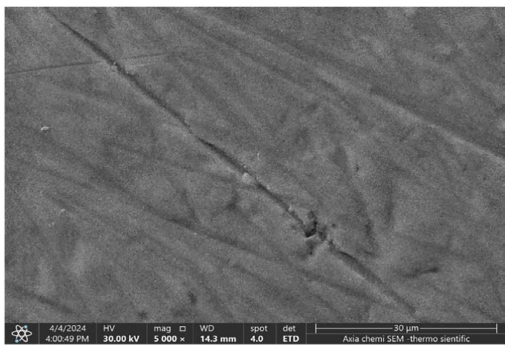
From the results obtained for Vickers microhardness, by taking four readings along an axis from the beginning to the end of the welded joint area representing base metal, HAZ, fusion, and base metal at the other side. It was found that the highest value of microhardness was for welds of Al-Ti, specifically for (Al-Ti 605 joint)



a) (Al – Ti 60)



b) (Al – Ti 603)



c) (Al – Ti 605)

Figure 4. SEM for aluminum - titanium joints for welding pulse (1, 3, and 5)

with values between (205.2–220.4 HV). While in Al welds, specifically for sample (Al 605), values were between (215–198), this is due to grain refinement with more heat input. The values for Ti welds, (Ti 60) samples were lower than the rest values (171.3–170.5 HV). This is also consistent with what was indicated regarding the more homogeneous bonding and diffusion process in Al-Al and Al-Ti welds under the welding conditions adopted for Ti-Ti welds for the same conditions [6].

By examining the structure of (Al-Ti 603) joint, it contains a region of partial relief and overlapping vertical granular regions that are clearer and more structured than the rest of the weld joints, which shows that the coordination fulfills the conditions for this [6, 18, 20].

CONCLUSIONS

Resistance spot welding has a good potential for joining similar and dissimilar metals, like aluminum and titanium, which can be used in wide range industrial applications.

1. Al-Ti (Al-Ti 603) welds gave the best results in terms of high tensile strength, low corrosion rate, and acceptable microhardness values.
2. Al-Ti (Al-Ti 603) welds have a clean, longitudinal overlapping, and crack-free grain structure.
3. The results were not good enough for Ti-Ti welds, because the melting process was not sufficient enough using the introduced welding conditions, due to the huge difference between melting points of Al and Ti and other thermal properties. This is the main challenge in the current study.

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