Strength of resistance spot welding of aluminum alloy AA6061 to carbon steel using different filler materials

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Abstract. Resistance spot welding is a process in where contacting metal surfaces for similar or dissimilar materials are joined by heat generated from resistance to electric current. Carbon steel and aluminum alloy A6061 sheets were welded by using resistance spot welding method in two stages with and without filler materials where copper and zinc were implemented as fillers, where those two materials, particularly the former, has acceptable affinity, therefor better wettability, to both welded metals. The characteristics of weld joint were investigated by measuring the effect of welding current and time on the nugget size and tensile shear strength of the weldment. The results showed that the welding current has an incremental influence on both the nugget size and tensile shear strength for the two cases studied. Also, the results revealed that the copper filler increases the strength of the weldments more than the zinc filler, which is attributed of higher affinity of the copper to both metals. The joint with the maximum tensile shear strength of 47 kN/m² is obtained at the condition of 15 kA welding current for copper filler and 40 kN/m² is obtained at the condition of 13 kA. The thickness of interfacial reaction layer decreased from central joints region to the surrounding area.

1. Introduction

In automotive industry, aluminum alloy and steel is the most reliable materials for its lightweight. Mostly for the importance of this topic, current work had been conducted, to investigate a more reliable procedure to join aluminum to steel that would give a higher strength joints, and shed light on the main factors affecting the welding process. The joining of two dissimilar materials namely aluminum alloys to steel using different techniques is indispensable [1]. On the other hand, the joining between two types of materials have some difficulties, because of the big differences in mechanical and thermal properties between aluminum alloy and steel [2]. For that reason, many works have been performed using different developed welding techniques, for instance, solid state welding methods, such as ultrasonic spot welding [3], friction stir welding FSW [4], and friction stir spot welding [5,6], where used for welding dissimilar joint of Al alloy to steel. However, fusion welding methods including laser [7], Tungsten Inert Gas (TIG) [8], Metal Inert Gas (MIG) [9,10] and resistance spot welding (RSW) [11-13] that are used extensively to join Al alloys to steel have been documented.

For RSW welding, Sun et al. and Oikawa et al. [14,15] have used aluminum alloy to weld with alloy steel by resistance spot welding with transition material sheet and investigated the static and dynamic properties of the welded joint. Mohammad J. Zedan and Qasim M. Doos [16] used the electrodes force of 2100-2700 N, current of welding 7.5-10.5 kA, and welding period of 10-20 cycle to join aluminum alloy 5052 to low carbon steel alloy 1008. The maximum shear load of the Al alloy carbon steel was found to be 2860 N for a weld nugget size of 9 mm. Arghavani and Kokabi [17] explored the effects of zinc layer on mechanical and microstructure of aluminum carbon steel joint in resistance spot. They found that the present of zinc reduced the tensile strength of the weldment. Also
they obtained a superior mechanical properties of intermetallic layer with thickness smaller than 5.5 µm at high welding currents. Chen et al. [18] studied the microstructure and physical properties of RSP of aluminum and DP600, they concluded that the maximum shear load of the weld joint was 5.5 kN, accompanied with molten nugget diameter of 6.3 mm.

2. Theory of resistance spot welding
The welding method uses fusion heat generated at contact part due to metal’s peculiar resistance, and at the same time applies pressure as shown in figure 1.

Figure 1. Electrical Circuit and configuration of welding in Spot Welding Machine

Heat at the resistance (in joules) [19]

\[ Q = I^2 R t \]  

Where :  
\( I \) : welding current [A], \( R \) : resistance of work [Ω], \( t \) : welding time [sec]

2.1 Factors of spot welding:
The main factors that influence the reliability of spot welding are Resistance \( R \), Welding time \( t \), Welding current \( A \) and welding force \( P \). Figure 2 shows the temperature distribution during spot welding and the molten area (nugget) position and shape [20]

Figure 2. Heat gradient from the resistance spot up to the top of the electrodes

Weldability according to Resistance\( W \) [19]:

\[ W = \frac{\rho}{F_K} \]  

Where : \( F \) = Melting point °C, \( K \) = Thermal Conductivity cal.cm.cm\(^{-2}\).°C, \( \rho \) = Resistance µΩ.cm
3. Experimental Procedure

The materials used in this study were 1.5 mm thick plates of aluminum alloy A6061 and mild steel (AISI-SAE 1005). The specimen geometry is 100mm × 25mm × 1.5mm. Their chemical compositions are listed in tables 1 and 2.

Table 1. Carbon steel composition

| Composition wt% | C%  | Mn% | P%  | S%  | Si% | Cr% | Mo% | Ni% | Al% | Cu% | Fe%  |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Measured values | 0.05 | 0.347 | 0.0116 | 0.016 | 0.025 | 0.0247 | <0.002 | 0.0196 | 0.025 | 0.0546 | Bal. |
| Standard values* | 0.06 | 0.35 | 0.40 | 0.05 | N/A | N/A | N/A | N/A | N/A | 0.02 | Bal. |

* ASM Handbook, vol. 1, table 12, pp 249, 2005

Table 2. Aluminum alloy AA6061 composition

| Sample wt% | Si%  | Fe%  | Cu%  | Mn%  | Mg%  | Zn%  | Cr%  | Ni%  | Pb%  | Ti%  | Al%  |
|------------|------|------|------|------|------|------|------|------|------|------|------|
| Measured value | 0.693 | 0.518 | 0.257 | 0.128 | 0.935 | 0.033 | 0.181 | 0.0033 | 0.015 | 0.06 | Bal. |
| Standard values* | 0.4-0.8 | 0.7 | 0.15 – 0.15 | 0.15 | 0.8 – 1.0 | 0.25 | 0.04 – 0.05 | 0.05 | 0.15 | Bal. |

* ASTM B308/B308M – 10, Standard Specification for Aluminum-Alloy 6061-T6

Figure 3. Schematic diagram of resistance spot welding configuration

Figure 3 shows a schematic diagram of the configuration of the work to be carried out and the heat concentration.

The shape and size of joint according to (EN ISO 14273 – 2000), is illustrated in figure 4.

Figure 4. Sample dimensions

The following points summaries the main steps to prepare and test the specimens:

1. Preparation of the specimens (preliminary cleaning, cutting, marking the welding point and trimming the filler strips to the size of the welding zone).
2. Thorough mechanical cleaning directly before welding.
3. Performing the welding process according to the preset variables, for the two stages of the research (with and without filling materials).
4. Conducting the shear test.
5. Calculating the nugget area.
6. Determining the welding strength values.
3.1 Samples Preparation
The samples were cut to the required dimensions of (100×25) mm via hydraulic press, with three samples for each case (set of variables) for more reliability of results. Then the welding lap zone were marked ( 25 × 25) for each sample as well as the welding points ( at the centre of the lap joint) . For the second stage (with filler materials) slices of pure copper and zinc in the dimensions of ( 25 × 25 mm) were also prepared to be but between the specimens at the marked lap regions (see figure 5).

![Figure 5. Spot welding process](image)

3.2 Welding Procedure
The welding was carried out in two steps for each stage, the first was carried out at fixed current value and change the welding time, while the second was performed at fixed welding time and vary the current. Figure 6 shows a sample resulted from spot welding process which used in this research.

![Figure 6. Samples after welding](image)

The samples were thoroughly cleaned (in addition to the preliminary cleaning) by mechanical rubbing with emery cloth right before welding to eradicate the oxide layer from the surface of the samples then they were directly welded as shown in figure 7. The squeezing and holding times were also kept fixed as well as the pressure (force).

![Figure 7. Welded samples (a) from the aluminum alloy side. (b) from the steel side](image)
3.3 Tensile Shear test
The main test was tensile shear test to investigate the strength of the joints, and it was carried out in two groups, the first in the Technical College / Laboratory of Metallurgy. The other set of samples were tested in the Department of Mechanics / Institute of Technology – Baghdad, using a universal tester. The results of the two sets were correlated and processed.

4. Results and Discussion
To calculate the strength of spot weld, the area affected by the force (Nugget) needed to be measured accurately and this was a problem as the spot or nugget area was not of a regular shape, so the nugget was pictured then the image of each one was meshed to calculate the number of squares corresponding to each nugget area. With a scale (ruler) at the edge of the welded zone, the dimensions of the squares were determined, so the total nugget’s area could be obtained which made it possible to calculate the strength as illustrated in figure 8.

![Figure 8. Calculation of the nugget area](image1)

Taking the welding time as constant, figure 9 was plotted between the stress and the power introduced in each case instead of the current as it is of the same trend, besides that the power can be converted to heat which is the most important factor in welding. So, the first diagram was obtained, in which that the increase in strength is directly proportional to the power injected, but to certain extent (not linear) as too much power would damage the joint.

![Figure 9. Stress – Power in the case of no](image2)

The second stage the time was varied against a constant current of (about 16000 Amps.) as this current value was the optimum from the first stage and the results are shown in the figure 10.
It is obvious that the welding current and the welding time are the essential contributors in the input heat generation, so the strength of the weldment is affected almost by these two factors. Figure 1 shows the relationship between stress and current for different times in the case of copper filler. It can be seen that for a current of 9100 Amp the highest strength was obtained for all durations except for the longest welding time of 5 second. The causes for that different trend can be explained by the fact that when the input heat is less the filler strip kept most of its thickness. So, the joint is stronger as a result of the thicker interphase. On the other hand, the higher input heat affected the filler more with higher temperature and get diffused into the welded metals to become a thinner interphase and the strength decreased till the point where all the joint is burned out and fail. In the second case (zinc filler) as illustrated in figure 12, at welding time (5 sec.), the situation is relatively the same except that the heat input is higher from the start for the heat as the interlayer captured all the input heat. However the interphase get more diffused into the joined steel and aluminum alloy almost the same degree of the other combination of current and time and that leads to the values be relatively less than the others. More heat increases the depth of melting in the two main metals to be joined, so more amount of the filler material would be diffused into each of them till the depletion of it then reaching the point of welding area being burnt out.
Figure 13 shows the relationship of stress with time, and except for (9100 Amp.), the rest current values have close magnitudes, so the current is more effect on the strength than the welding time. It is clear that for the (9100 Amp.) the input heat is the lowest in comparison to other current values, its impact is apparent on the interphase, which is still relatively thick, so result in lower strength.

The zinc has less affinity to be diffused, particularly in steel than copper, so it needs more heat and that explain why at current of (9100 Amp.) it requires more time for the stress to be at its highest value as pointed in figure 13. The reason for that, the zinc acts as a third layer in the joint so there are two interfaces, one between zinc and steel and the other is zinc with aluminum alloy. As the heat increase further the opposite occurs where the mid-layer (zinc) become thinner for the higher amount diffused in the thicker molten surface layer of the two main metals. For higher temperature of the joint, almost all the zinc is diffused in the metals to be welded so stronger interphase developed leading to a stronger joint at the (9100 Amp.). It would have been apparent that the joint got burned off if it withstood longer time at higher current, so only at (2 sec.) the welding point was destroyed later than the others.

As previously was stated, the combination of welding time and current is the major factor in the strength of the joint, thus the stress time relationship was also studied to figure out whether current or welding time plays a relatively bigger role in the magnitude of stress.

Figure 12. Stress – welding current in the case of Zinc filler

Figure 13. Stress – welding time in the case of copper filler
In figure 14 for the zinc filler, also at the lower current the strength increased with time while the current of 10616 Amp. gave the lowest stress for all welding periods. At the highest current (12133 Amp), the case is relatively different where the stress is decreased then increased steeply. That can briefly attributed to the filler being a third layer, then get thinner to become an interphase weaker in strength. Stronger interface was achieved when the mid layer becomes thinner and less attached to the steel part, and with higher heat input it got diffused into both metals.

**Figure 14. Stress – welding time in the case of Zinc filler**

5. Conclusions

1- Resistance spot welding of steel to aluminium alloy without filler is not practical and gives very low strength in comparison to the using of suitable filing material in between.

2- The copper filler gave higher strength for the weldments than the zinc filler, which is attributed to the higher affinity of the copper to both metals while for zinc it needs higher current for longer time to overcome the weaker affinity of zinc to steel

3- The trend of stress strength for copper is to decrease with higher current for the same time period, while for zinc there is magnitude of current that gives the lowest stress due to the change in filler strip thickness.

4- It was shown that the welding current has greater impact on the strength of the joint than welding time.

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