Failure Mode of Spot Welds Under Cross-Tension and Coach-Peel Loads

The failure mode transition of triple-thin-sheet aluminum alloy resistance spot welds under cross-tension and coach-peel loads was investigated

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ABSTRACT

Two analytical models were proposed to predict the critical weld button size (governing the failure mode transform from interfacial failure to pullout failure) in the cross-tension and coach-peel tests, respectively. Three stack-ups, i.e., 1.0/1.0/1.0, 1.5/1.5/1.5, and 2.0/2.0/2.0 mm were tested. The cross-tension joint failed under the combined action of tensile stress and shear stress, while the coach-peel joint almost failed under pure shear stress. The joint design had little effect on the critical weld button size because the stress state was the same at the micro level. The proposed analytical models can be used to predict the critical button size for three-sheet 6061 and 5754 aluminum alloy resistance spot welds under cross-tension and coach-peel loads.

KEYWORDS

• Resistance Spot Weld • Three-Sheet Spot Welding • Aluminum Alloy • Failure Mode • Cross Tension • Coach Peel

Introduction

Economic and environmental considerations are constantly driving the automotive industry to form unique designs and material combinations for both weight reduction and structural integrity (Ref. 1). The automotive industry is actively engaged in engineering lightweight structures to help reduce fuel consumption and improve gas emissions. One approach to reduce weight and therefore enhance fuel efficiency is increasing the usage of aluminum, which has approximately one-third of the density of steel.

Resistance spot welding (RSW) is one of the most practical joining methods for manufacturing sheet metal assemblies in the automotive industry. Although RSW has been extensively applied to welding steel, there has been no significant high-volume production vehicles that have utilized the method as a primary structural joining technology for aluminum construction (Ref. 2). The main barrier to the adoption of RSW for aluminum vehicles is the short life of the welding electrodes and the associated reduction in weld quality as the electrodes degrade (Ref. 3). However, some recently developed electrode maintenance technologies significantly improve the electrode life to 10,000 welds with consistent weld quality (Refs. 4, 5). Consequently, a renewed interest in the RSW of aluminum has emerged.

The present work aims at furthering the fundamental understanding of the failure behavior of three-sheet aluminum alloy resistance spot welds. Although many studies have been performed on the weld growth process (Refs. 6–11), weldability (Ref. 12), and mechanical properties (Ref. 13) of three-sheet spot welds, all of the research has focused on mild- or high-strength steels. There is little work in open literature that has studied the RSW of multiple aluminum alloy sheets.

Experimental Procedures

In this study, 1-mm-thick 6061-T6 aluminum alloy sheets along with 1.5- and 2-mm-thick 5754-O aluminum alloy sheets were used. Table 1 lists the chemical composition of the materials, while Table 2 lists the mechanical properties.

For 6061 aluminum alloy sheets, thickness combinations of 1.0/1.0/1.0 and 1.5/1.5/1.5 mm were examined. For 5754 aluminum alloy sheets, thickness combinations of 1.0/1.0/1.0, 1.5/1.5/1.5, and 2.0/2.0/2.0 mm were investigated. Two types of three-sheet joints for each thickness combination were designed, as shown in Fig. 1. The two left images show the whole coach-peel sample, while the three right images are the cross-tension sample. In the type I joint, only one interface bears the CT or CP load during the test. In the type II joint, both of the two interfaces bear the external load during the test.

Spot welding was performed using a 220-kW direct current (DC) inverter RSW machine. The welding parameters are shown in Table 3. For each stack, six samples were welded per welding condition including three
samples for the complete mechanical test and three samples for the step-by-step mechanical test. The sample dimensions for the CT test were 150 × 50 mm with a 50-mm overlap area, while the dimensions for CP test were 120 × 40 mm with a 30-mm bending area. The CT and CP tests were performed at a cross-head displacement rate of 1 mm min⁻¹ with a CSS-44100 material test system.

The peak load was evaluated using the average value of the three complete mechanical tests. Button size, rather than the nugget size, was measured from the failure surface of the welded joint. It was used to evaluate the weld quality because the button size is easier to measure in industrial production (Ref. 15). The step-by-step mechanical test method has also been described in the authors’ previous work (Ref. 14).

Results and Discussion

Joint Microstructure

Figure 2 shows the microstructures of the 6061-T6 and 5754-O resistance spot weld nuggets and their microhardness distribution. The microstructure of the 6061-T6 resistance spot weld nugget (Fig. 2A–C) has also been discussed in the authors’ previous work (Ref. 14). It showed that the joint microstructure consisted of a partially melted zone (PMZ), columnar grain zone (CGZ), and equiaxed grain zone (EGZ), as shown in Fig. 2A. The authors also found that there are two types of columnar grains, according to its morphologies (Fig. 2B): the columnar grain with large secondary dendrite arm spacing (LCGZ) and the columnar grain with small secondary dendrite arm spacing (SCGZ). Generally, the LCGZ was easier to form when the heat input was not enough (poorly designed weld schedule). When the heat input is high enough (a more suitable weld schedule), less or no LCGZ will form. The hardness test indicated that the lowest microhardness appears in the LCGZ (Fig. 2C), which has a coarser structure and less alloy content. This low-hardness zone has a detrimental effect on the tensile-shear properties of the joint (Ref. 14).

Similar to the microstructures of the 6061-T6 resistance spot weld nuggets, the microstructures of the 5754-O resistance spot weld nuggets also consist of PMZ, CGZ, and EGZ, as shown in Fig. 2D and E.

Failure Mode Transition during the Cross-Tension Test

Interfacial (IF) failure and pullout (PO) failure were observed in joint types I and II. Figure 3 shows the typical load-displacement curves in the CT test. Only 1.5/1.5/1.5 mm stack curves are shown here because of the similarity of all the stacks. The hardness test indicated that the lowest microhardness appears in the LCGZ (Fig. 2C), which has a coarser structure and less alloy content. This low-hardness zone has a detrimental effect on the tensile-shear properties of the joint (Ref. 14).

The authors' previous work (Ref. 14) has shown that the failure location of the IF failure mode was not at the interface, but in the interior of the weld nugget. The joint will fracture through the IF failure mode only when the heat input is very small (nugget size). The insufficient heat input leads to insufficient or uneven melting, which leads to the formation of voids in the weld nugget. An obvious void can be observed on the fracture surface as shown in Fig. 4C. During the CT test, the crack propagated along the voids in the weld nugget and led to the welded joint failing in the IF mode. Generally, large voids are observed near the nugget center (Ref. 15), which is the workpiece/workpiece interface in two-sheet RSW. In three-sheet RSW, the nugget center is no longer the workpiece/workpiece interface. Consequently, the welded joint may fail in the IF mode, whose failure location is not interface but interior. The near equiaxed dimples shown in Fig. 4D indicated that the IF fracture
occurred under tensile stress normal to the fracture.

Figure 5 shows the macrostructures, force analysis, and fracture surfaces of welds that failed in PO mode. Figure 5A1–C1 show the macrostructures of welds that correspond to the stages #1, #2, and #3 in the load-displacement curve as shown in Fig. 3. The upper sheet experienced obvious out-of-plane deformation during stage #1 under the action of CT load. The out-of-surface deformation induced a tensile component and a shear component around the weld edge as shown in Fig. 5A2. The shear component increased with the increase in out-of-plane deformation, as shown in Fig. 5B2. Finally, the welded joint fractured under the combined action of tensile and shear components. It can be inferred that an initial crack was induced by the tensile component, and then the crack propagated rapidly along the thickness direction under the action of the shear component, leading to the fracture of the joint. The fracture surface is shown in Fig. 5D. The spatial locations of the e and f areas are shown in Fig. 5C2. It can be seen that equiaxed dimples were observed at the e area (Fig. 5E), indicating this area was broken by a “tensile.” Elongated dimples along the shear direction (Fig. 5F) indicated that the joint was finally fractured by “shear.” The morphologies of the fracture surface confirmed the above-mentioned inference.

Figure 6 shows the cross-tension peak loads plotted with respect to the measured button size. It shows that the joint design has little effect on the peak load of the welded joint; therefore, one simple linear regression was applied to all of the data obtained from joint types I and II. The data for the 1.0/1.0/1.0 mm stack are quite scattered (relatively low coefficient of determination, R²). Three reasons contributed to this phenomenon. First, the cross-tension strength is more sensitive to peripheral defects (Ref. 16) because the nugget periphery bears the cross-tension load during the test. Second, the nonuniform distributed surface oxide film may lead to unstable weld quality. Third, improper
welding parameters (such as welding time of 300 ms as shown in Table 3) led to over weld (deep indentation). The fitting became better (larger R² value) when the thickness increased because more suitable welding parameters were applied to these samples. Figure 6 also shows the critical button size where the failure mode transferred from IF mode to PO mode. The critical button sizes that guarantees a PO mode for the four stacks were about 2.8, 3.4, 3.5, and 4.0 mm, respectively.

Although welded joint fractures under the combined action of tensile and shear, the tensile action is often neglected to simplify the analysis process. Pouranvari and Marashi proposed a simple model that only considered the shear action to predict the minimum button size required to ensure PO failure mode during the CT test. Considering nugget as a cylinder, failure load at the IF failure mode in the CT test can be expressed as the following equation (Ref. 17):

\[
P_{IF}^{CT} = \frac{\pi d^2}{4} \sigma_{FZ} \quad (1)
\]

where \(d\) is the diameter of the weld nugget, and \(\sigma_{FZ}\) is the tensile strength of the fusion zone. For a three-sheet RSW, \(d\) should be replaced by \(d_{IN}\) which is the weld nugget diameter at the failure interface. However, as shown in Fig. 3A–C, the facture paths did not go along the workpiece/workpiece interface but propagated into the interior of the middle sheet; i.e., the real fracture path/area is longer/larger than the assumed one. The weld nugget, \(d\), in Equation 1 could be replaced by an equivalent weld nugget, \(\alpha d\), where \(\alpha\) is the coefficient, and \(\alpha > 1\). Because the aluminum spot welds are more sensitive to porosity or voids, a porosity factor, \(P\), can be introduced into Equation 1 (Ref. 18). Accordingly, Equation 1 can be rewritten as

\[
P_{IF}^{CT} = P \frac{\pi (\alpha d_{IN})^2}{4} \sigma_{FZ} \quad (2)
\]

where \(P\) is defined as follows.

\[
P = \frac{A_{total} - A_{porosity}}{A_{total}}, \quad 0 < P < 1
\]

where \(A_{total}\) is the total area of the fusion zone on the fracture surface and \(A_{porosity}\) is the projected area of porosity in the fusion zone on the fracture surface of the weld.

In the PO failure mode, it is assumed that failure occurs when shear stress at the circumference of one-half of the cylindrical nugget reaches the shear ultimate strength of the failure position. Therefore, the PO failure load in the cross-tension test can be expressed as

\[
P_{PO}^{CT} = \pi d_{IN}^2 \sigma_{FZ} \quad (3)
\]

Table 4 — Comparison between the Predicted and the Experimental Critical Weld Diameter in the Cross-Tension Test (\(\alpha = 1\))

<table>
<thead>
<tr>
<th>Materials</th>
<th>Stacks (mm)</th>
<th>(t) (mm)</th>
<th>(P)</th>
<th>(f) (Ref. 19)</th>
<th>(P_{FZ}) (HV)</th>
<th>(H_{PFL}) (HV)</th>
<th>Predicted DC (mm)</th>
<th>Experimental DC (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061</td>
<td>1.0/1.0/1.0</td>
<td>1.0</td>
<td>0.9</td>
<td>0.6</td>
<td>65</td>
<td>60</td>
<td>2.89</td>
<td>2.8</td>
</tr>
<tr>
<td>6061</td>
<td>1.5/1.5/1.5</td>
<td>1.5</td>
<td>0.9</td>
<td>0.6</td>
<td>65</td>
<td>60</td>
<td>4.33</td>
<td>3.4</td>
</tr>
<tr>
<td>5754</td>
<td>1.5/1.5/1.5</td>
<td>1.5</td>
<td>0.9</td>
<td>0.6</td>
<td>65</td>
<td>60</td>
<td>4.33</td>
<td>3.5</td>
</tr>
<tr>
<td>5754</td>
<td>2.0/2.0/2.0</td>
<td>2.0</td>
<td>0.9</td>
<td>0.6</td>
<td>65</td>
<td>60</td>
<td>5.78</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Fig. 3 — Typical load-displacement curves in the cross-tension test of 1.5/1.5/1.5 mm stack.

Fig. 4 — Microstructure and fracture surface of welds that failed in IF mode during the cross-tension test: A — Type I joint; B — Type II joint; C — fracture surface; and D — magnification of area d shown in C.
where $t$ is the sheet thickness and $\tau_{\text{PFL}}$ is the shear strength of the PO failure location. The contribution of indentation to the sheet thickness is neglected in the model.

To ensure pullout failure for a spot weld, the failure load for a PO should be less than that for IF failure, i.e., $F_{\text{PO}} < F_{\text{IF}}$. Thus, the critical nugget diameter, $D_{\text{C}}$, can be obtained from Equations 2 and 3:

$$D_{\text{C}} = \frac{4t}{\alpha^2} \frac{\tau_{\text{PFL}}}{\sigma_{\text{FZ}}}$$ (4)

Applying the linear relationship between the strength and hardness, and the linear approximate between shear strength and tensile strength, Equation 4 can be rewritten as

$$D_{\text{C}} = \frac{4t}{\alpha^2} \frac{f \cdot H_{\text{PFL}}}{H_{\text{FZ}}}$$ (5)

where $f$ is the ratio of shear strength to tensile strength, $H_{\text{PFL}}$ and $H_{\text{FZ}}$ are hardness values of the PO failure location and fusion zone, respectively.

For all three stacks, the joints interfacially failed through the interior of the weld nugget, or PO failed at the PMZ. Therefore, the hardness value for the $H_{\text{PFL}}$ and $H_{\text{FZ}}$ should be the hardness value of PMZ and EGZ, respectively. Table 4 shows the predicted and experimental results when $\alpha$ equals to 1. It can be seen that the predicted diameters are larger than the experimental diameters. This is reasonable because the failure load for the IF fail mode is underestimated ($\alpha$ should be larger than 1).

From the experimental data, $\alpha$ approximately equals to 1.0, 1.1, and 1.2 for the sheet thickness of 1.0, 1.5, and 2.0 mm, respectively.

### Failure Mode Transition during the Coach-Peel Test

Similar to the CT test, IF failure and PO failure are observed in joint types I and II. Figure 7 shows the typical load-displacement curves of the CP test. No obvious difference can be observed between the type I and type II joints. Although the CP joint also bears bending moment during the test, the load-displacement curve does not show up two stages in its rising stage, as shown in the CT test. This is because the tensile stress induced by bending moment acts on the same side of the weld nugget during the CP test while it acts on the opposite side of the weld nugget during the CT test (Fig. 5D). Therefore, the joint can move along the tensile direction during the CP test, while it cannot move horizontally during the CT test. Consequently, higher stress concentrated on the edge of the weld nugget in the CT test than in the CP test.

Figure 8 shows the fracture surface welds that failed in the IF and PO modes during the CP test. The near equiaxed dimples shown in Fig. 8A indicates that the IF fracture occurred under tensile stress normal to the fracture. This confirms that the driving force for IF failure mode in the CP test is tensile stress. Elongated dimples are observed both at the root (Fig. 8C) and the side (Fig. 8D) of the fracture surface, confirming the above discussion.

The effect of button size on the CP peak load of joint designs I and II for all the stackups is shown in Fig. 9. The linear regression was only applied to the data from PO failure joints. Han et al. found that the CP load was dominated by the governing metal thickness (GMT) rather than the weld diameter (Ref. 2). This is partly supported by this study. It can be seen that the slope of the linear regression lines was smaller than that in the CT test (Fig. 4) and tensile-shear test (Ref. 14), indicating the weld diameter had less effect on the CP load. Note that the fitting in the CP test was worse (lower $R^2$ value) than that in the CT test. During the CP test, the failure of the sheet initiated at a single point or a very small area. This resulted in more uncertainty in the CP strength. A similar phenomenon was also observed in the work of Han et al. (Ref. 2). A suitable welding schedule and removing oxide film may improve the fitting. The critical button sizes that guarantees a PO mode for the four stackups were about 2.5, 2.4, 2.8, and 4.1 mm, respectively.

Similar to the CT test, during the
CP test, the tensile stress at the work-piece/workpiece interface was the driving force of the IF failure while the shear stress at the nugget circumference was the driving force for PO failure.

A simple analytical model was proposed to predict critical weld diameter during the CP test. Since the critical button size for type I and II joint was the same (Fig. 9), the analytical model was established based on the type I joint. The sheets had little deformation when the joint failed in IF mode. Therefore, the expression of failure load at the IF failure mode in the CP test will be the same as in the CT test:

$$F_{IF}^{CP} = \frac{\pi}{4} \beta d IN \sigma FZ$$  \hspace{1cm} (6)

To derive the expression of the PO failure load, Fig. 10 depicted the failure analysis of the PO failure. Owning to the deformation of CP samples, the CP load decomposed to two components, one was parallel to the work-piece/workpiece interface and the other was perpendicular to the work-piece/workpiece interface. The component perpendicular to the work-piece/workpiece interface, denoted as $F_{peel}$, contributed to the peel failure of the spot weld. As previously mentioned, the PO failure occurs when shear stress at the circumference of one-half of the cylindrical nugget reaches the shear ultimate strength of the failure position. For the CP test, the tearing length was half of the weld perimeter (Ref. 16), as shown in Fig.

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**Table 5 — Comparison between the Predicted and the Experimental Critical Weld Diameter in the Coach-Peel Test**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Stacks (mm)</th>
<th>$t$ (mm)</th>
<th>$\theta$ (deg)</th>
<th>$\beta$</th>
<th>Predicted $D_c$ (mm)</th>
<th>Experimental $D_c$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061</td>
<td>1.0/1.0/1.0</td>
<td>1.0</td>
<td>28</td>
<td>1.0</td>
<td>3.07</td>
<td>2.5</td>
</tr>
<tr>
<td>5754</td>
<td>1.0/1.0/1.0</td>
<td>1.0</td>
<td>28</td>
<td>1.0</td>
<td>3.07</td>
<td>2.4</td>
</tr>
<tr>
<td>5754</td>
<td>1.5/1.5/1.5</td>
<td>1.5</td>
<td>29</td>
<td>1.1</td>
<td>3.69</td>
<td>2.8</td>
</tr>
<tr>
<td>5754</td>
<td>2.0/2.0/2.0</td>
<td>2.0</td>
<td>22.5</td>
<td>1.2</td>
<td>5.24</td>
<td>4.1</td>
</tr>
</tbody>
</table>
10. Therefore, the PO failure load in the CP test can be expressed as

\[ F_{\text{Peel}} = F_{\text{PO} CP} \sin \theta = \frac{\pi d_{\text{CP}} t P_{\text{CP} FL}}{2} \]  

Combining Equations 6 and 7, and applying the linear relationship between the strength and hardness, as well as the linear approximate between shear strength and tensile strength, the critical nugget diameter for the CP test can be expressed as

\[ D_{\text{CP}} = \frac{2t f \cdot H_{\text{FL}}}{\beta P \sin \theta H_{\text{FZ}}} \]  

where \( \theta \) can be measured from the samples as shown in Fig. 10.

The parameters of \( P, f, H_{\text{FL}}, \) and \( H_{\text{FZ}} \) used for calculating Equation 8 are considered the same as those used for the CT test. The coefficient \( \beta \) is assumed to be the same as the coefficient \( \alpha \). The angle \( \theta \) is the average measured from practical samples. The predicted weld diameters are shown in Table 5. It can be seen that the predicted values are still larger than the experimental values. One possible reason is that the tearing length shown in Fig. 10 is overestimated. For the CP test, tearing of the sheet initiates and focuses at a single point or a very small area, which is why the CP load is lower than other quasistatic tests. The tearing area in Equation 7 is overestimated. Accordingly, Equation 7 should be multiplied by a coefficient \( \gamma \) (\( \gamma < 1 \)), and then Equation 8 can be rewritten as

\[ D_{\text{CP}} = \frac{2\pi f \cdot H_{\text{FL}}}{\beta P \sin \theta H_{\text{FZ}}} \]  

According to Table 5, the values of \( \gamma \) for the four cases are 0.81, 0.78, 0.76, and 0.78, respectively. The values are close to each other; even the materials and their thickness are different. This suggests that this value may reflect some intrinsic property during the CP test and need to be further investigated.

### Effect of Joint Design on the Failure Mode Transition

Figure 11 summarizes the effect of joint design on the failure mode transition during tensile-shear (Ref. 14), CT, and CP tests. The joint design has a large influence on the failure mode transition in the tensile-shear test because different lap shear configurations lead to different degrees of weld rotation. The weld rotation will change the stress state around the weld nugget at a micro level. However, the joint design has little effect on the failure mode transition in the CT and CP tests, owing to the stress states around the weld nugget are the same in different joint designs. The CP test has the minimum critical button size when the sheet thickness was smaller than 2 mm. However, the difference between minimum critical button size of CT and CP tests decreased with the sheet thickness increase. More thickness combinations should be tested to further investigate this phenomenon.

### Conclusion and Future Work

This paper investigated the failure mode transition of three-sheet aluminum alloy resistance spot welds during the cross-tension and coach-peel tests. Two types of joints were investigated. The following conclusions can be drawn:

1) The microstructures in both the RSWs of three-sheet 6061 and 5754 aluminum alloys consist of a PMZ, CGZ, and EGZ, where the CGZ is divided into the LCGZ and SCGZ.

2) IF and PO failure modes were observed in both type I and type II joints. The failure location of the IF failure mode was not along the interface but in the interior of the weld nugget,
while the failure location of the PO failure mode was the PMZ.

3) Simple models are proposed to predict the critical nugget diameter required to ensure PO failure mode during the cross-tension and coach-peel tests of three-sheet aluminum alloy spot weld joints:

\[
D_C^{CT} = \frac{4t}{f} \frac{H_{PFL}}{P H_{FZ}}
\]

\[
D_C^{CP} = \frac{2\gamma}{\beta^2 P \sin \theta} \frac{f}{H_{PFL}} H_{FZ}
\]

where \( t \) is the thickness of the sheet; \( P \) is the porosity factor; \( f \) is a constant coefficient; \( \theta \) is the deformation angle during the coach-peel test; \( H_{PFL} \) is the hardness of the PO failure location; \( H_{FZ} \) is the hardness of the fusion zone; and \( \alpha, \beta, \) and \( \gamma \) are coefficients determined from experiments.

4) The joint design has little effect on the failure mode transition in the cross-tension and coach-peel tests. This paper also investigated the failure behavior of triple-thick aluminium alloy resistance spot welds under cross-tension and coach-peel loads. More thickness combinations (include both equal and unequal thickness) should be tested to investigate the critical button size and to verify the proposed analytical model.

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**References**