

## Article

# Constraint Effect on Tensile and Fatigue Fracture of Coach Peel Specimens of Novel Aluminum–Steel Resistance Spot Welds

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**Abstract:** In response to the growing demand for fuel economy and the imperative to reduce greenhouse gas emissions, the automotive industry has embraced structural lightweighting through multi-material solutions. This poses challenges in joining dissimilar lightweight metals, such as aluminum alloys to steels. The effects of the diameter of a weld nugget have been well documented, particularly in relation to its effects on the tensile strength, tensile fracture modes and fatigue behavior. For tensile shear specimens, various methods have been developed over the years to predict fracture modes by deriving the critical nugget diameter. However, these methods have proved inadequate for coach peel specimens, where a noteworthy observation is the occurrence of pull-out fracture modes with smaller weld nugget diameters than the critical diameter. In the present study, aluminum alloy sheets and steel sheets were resistance spot welded, achieving a deliberately reduced weld nugget diameter to induce an interfacial fracture mode in the tensile testing of coach peel specimens. Intriguingly, it was noted that fatigue fracture modes in the same coach peel specimens transitioned from pull-out to interfacial with decreasing applied loads, challenging conventional expectations. Furthermore, finite element analysis was performed, and the findings indicated that the fracture modes of the coach peel specimens were influenced not only by the diameter of the weld nugget but also by local stress states, specifically the stress triaxiality at the tips of the spot weld notches.

**Keywords:** Al–steel resistance spot welding; weld nugget diameter; fracture modes; tensile and fatigue properties; finite element analysis



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## 1. Introduction

Facing the increasing demand for fuel economy and greenhouse gas emission reductions, multi-material solutions have been widely accepted as a common practice for structural lightweighting in the automotive industry. However, multi-material solutions present challenges in joining dissimilar metals, e.g., aluminum alloys and steels. Resistance spot welding offers a viable solution, as it is the predominant welding technique for steel car bodies in the automotive industry. Aluminum alloy sheets and steel sheets have been successfully resistance spot welded by using a multi-ring domed (MRD) electrode and multiple-solidification welding schedules [1,2].

Generally speaking, there are two typical fracture modes during mechanical testing for aluminum to steel RSWs: interfacial fracture and pull-out fracture. The interfacial fracture mode should be avoided due to its unpredictability, resulting from brittle fracture. For the tensile shear configuration of dissimilar aluminum-to-steel RSWs, achieving a weld nugget with a sufficiently large diameter is crucial in obtaining a desirable pull-out

fracture mode during tensile tests [3–5] and when aiming to achieve a long fatigue life [6]. Until now, numerous techniques have been devised to calculate the critical diameter of weld nuggets to prevent interfacial fracture in tensile shear specimens [7–12]. The leading author and her colleagues [4] recalculated the critical weld nugget diameter for Al–steel RSWs considering material inhomogeneity and successfully predicted the fracture modes in aluminum-to-steel specimens with tensile shear configuration. However, these methods were only suitable for tensile shear configuration and inadequate for coach peel specimens, where a noteworthy observation was the occurrence of pull-out fracture modes even when the weld nugget diameters were smaller than the critical diameter [13].

The stress state in coach peel specimens is complex, involving shear stresses, tensile stresses and bending moments. Our previous work verified that the fracture mode of these specimens is also influenced by the sheet thickness [13]. Chen et al. pointed out that defects at the periphery of the aluminum fusion zone, aluminum thinning, the aluminum nugget size and the thickness of the intermetallic compound (IMC) are primary factors affecting the tensile properties of coach peel specimens [14]. Therefore, the constraint effect should be considered in coach peel specimens when predicting the fracture mode. Since Bridgeman's seminal work on hydrostatic stress impacts on material fracture [15], it has been well recognized that stress triaxiality not only reflects the stress conditions under various complex loads effectively, but also enables the development of material fracture models by quantifying the relationship between stress triaxiality and strain. Utilizing this method, Bao et al. [16] performed shearing and tensile tests and simulations on 2024-T351 aluminum alloy, deriving a quantitative relationship between the fracture equivalent strain and stress triaxiality. They discovered that the correlation between stress triaxiality and fracture strain is not linear. Similarly, Kang et al. [17] developed a fracture failure criterion for AA6060 aluminum alloy based on this stress–strain model. The definition of crack tip constraint parameters currently falls into two categories: stress-based and plastic-deformation-based [18]. Yang et al. [19] introduced the equivalent plastic strain parameter  $A_p$ , which unified the description of in-plane and out-of-plane constraint effects. Qian found that  $A_p$  could fit critical fracture toughness values for samples with different crack lengths, loading conditions, and materials onto a single master curve [18].

Until now, it remains unclear that how these factors affect the fracture modes of coach peel specimens. In our previous research, all fracture modes for coach peel specimens were pull-out, even though the diameter of the weld nugget was small. Therefore, the diameter should be deliberately reduced within the usable range to observe whether there is a sufficiently small size to induce interfacial fracture. One of the challenges in welding practice was the difficulty of producing Al–steel RSWs in coach peel configuration with a small enough weld nugget size, as the load capacity would be too low to handle in testing. To explore the effect of the weld nugget diameter and constraint parameters on the fracture behavior in coach peel configurations of aluminum–steel RSWs, this study aimed to develop a predictive model incorporating these factors. To achieve this, aluminum alloy sheets and steel sheets were resistance spot welded using multi-stage welding schedules and multi-ring domed (MRD) electrodes. In addition to achieving a large enough weld nugget size that ensured pull-out fracture, a deliberately reduced weld nugget diameter was also produced to induce an interfacial fracture mode during the tensile testing of coach peel configuration. The macrostructure and microstructure of the specimens were characterized. A recently created mini-shear test was employed to determine the shear strength of the IMC layers. Tensile tests and fatigue tests were performed to determine the maximum tensile load capacity and fatigue life, with a particular focus on fracture modes. Furthermore, finite element analysis was carried out, and the stress triaxiality was calculated for the aluminum to steel stack-ups. Stack-ups with various sheet thicknesses

were also simulated in ABAQUS to reveal the fracture mode mechanism of the coach peel configuration.

## 2. Material and Testing Methods

### 2.1. Materials and Welding Process

This study employed 1.2 mm thick AA6022 alloy sheets and 2.0 mm thick low carbon steel (LCS) sheets, with the steel sheet being hot-dip galvanized. The chemical composition (in weight percent) was measured using the optical emission spectrum (Thermo Scientific ARL 3460, Thermo Fisher Scientific, Waltham, MA, USA). The results are presented in Table 1. The basic mechanical properties of the sheets are outlined in Table 2.

**Table 1.** Chemical composition (wt %) of sheets.

| Materials     | C     | Cr    | Ti    | Mg    | Cu    | Mn    | Si    | Al    | P     | Fe     |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
| 1.2 mm AA6022 | -     | -     | -     | 0.510 | 0.240 | -     | 0.750 | Bal.  | -     | 0.170  |
| 2.0 mm LCS    | 0.026 | 0.021 | 0.032 | -     | 0.011 | 0.130 | 0.003 | 0.033 | 0.016 | Remain |

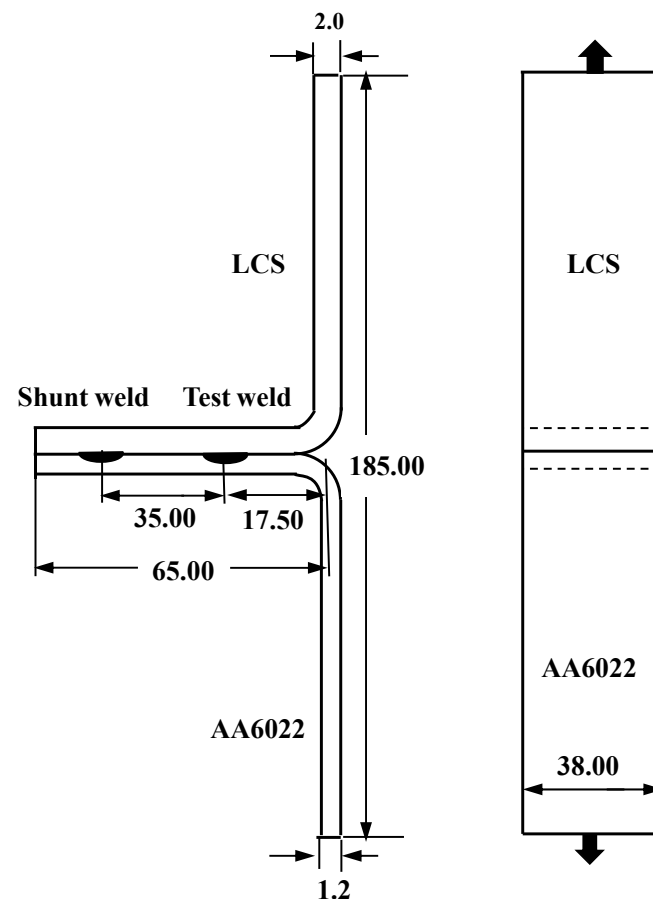
**Table 2.** Tensile properties of AA6022 and LCS sheets.

| Materials     | Elastic Modulus, E (GPa) | Yield Stress, $\sigma_y$ (MPa) | Ultimate Tensile Stress, $\sigma_u$ (MPa) | Elongation (%) |
|---------------|--------------------------|--------------------------------|-------------------------------------------|----------------|
| 1.2 mm AA6022 | 69                       | 202                            | 297                                       | 22             |
| 2.0 mm LCS    | 213                      | 161                            | 292                                       | 53             |

A Medium-Frequency Direct Current (MFDC) machine was used to resistance spot weld the aluminum alloy sheets to themselves and the LCS. Coach peel configurations, as depicted in Figure 1, were produced using multi-ring domed (MRD) electrodes made of CuZr alloy, with the welding parameters outlined in Table 3. To compare the effect of the weld nugget diameters on the mechanical properties of AA6022-LCS RSWs, the stack-ups with weld nugget diameters of 8.0 mm and 8.6 mm were included here, and had been studied in our previous research [6,13]. The welding schedules are also listed in Table 3. The AA6022 alloy sheet was spot welded to LCS by varying the weld current and weld time to achieve large and small weld nugget diameters. After welding, the samples were baked at 175 °C for 35 min in an oven to replicate the bake process of the Electrode position Paint Operation (ELPO) used in vehicle production, which helps to cure adhesives and sealers.

**Table 3.** Schedules for welding aluminum to itself and aluminum to LCS RSWs.

| Stack-Ups ID          | Welded Sheets               | Force (N) | Preheat                      | Weld Time (ms) | Hold Time (ms) | Root Mean Square (RMS) Weld Current (kA) |
|-----------------------|-----------------------------|-----------|------------------------------|----------------|----------------|------------------------------------------|
| AA6022-AA6022         | 1.2 mm AA6022               | 3114      | 10 ms at 16% voltage setting | 151            | 250            | 23.3                                     |
| AA6022-LCS-6.7mm      | 1.2 mm AA6022 to 2.0 mm LCS | 3892      | 40 ms 7.5 kA, 10 ms cool     | 1615           | 250            | 10.9                                     |
| AA6022-LCS-8.0mm [6]  | 1.2 mm AA6022 to 2.0 mm LCS | 4003      | 40 ms at 7.5 kA, 10 ms cool  | 1705           | 250            | 11.3                                     |
| AA6022-LCS-8.6mm [13] | 1.2 mm AA6022 to 2.0 mm LCS | 3781      | 40 ms 6 kA, 10 ms cool       | 1670           | 250            | 11.0                                     |



**Figure 1.** Dimensions of aluminum to LCS RSWs.

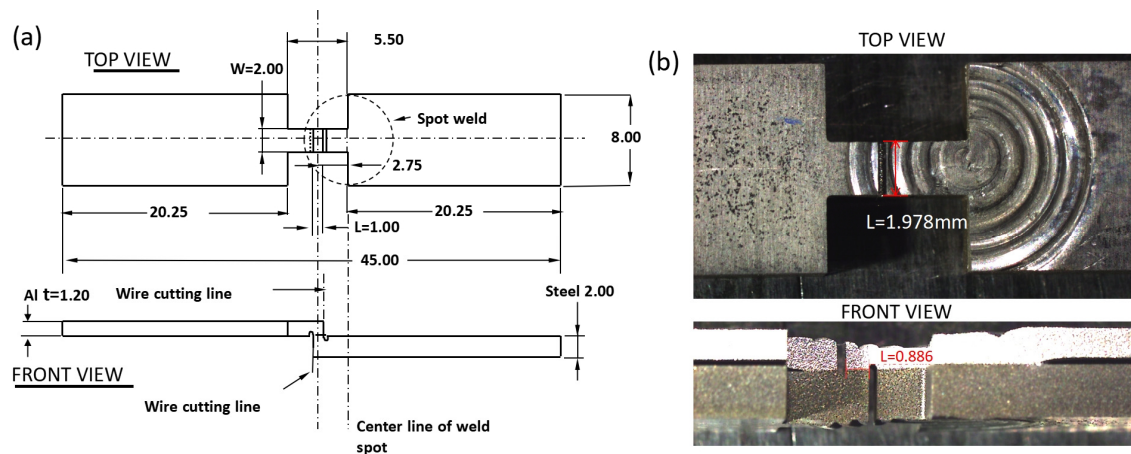
## 2.2. Microstructure Characterization

The coach peel weld specimens were cut and sectioned along the midline of the sheet width. The weld samples were mounted, polished, and etched by using 4% Nital following standard metallography procedures. Optical microscopy was used to characterize the nugget diameter. Scanning electron microscopy (SEM) was used to characterize and measure the IMC thickness.

## 2.3. Mechanical Testing and Fatigue Life Estimation

The mini shear specimens (Figure 2) were used to determine the shear strength of thin IMC layers in both large and small size Al–steel RSWs. The mini-shear test specimens were loaded onto an MTS with a load cell of 5 kN. The loading rate was set as 0.3 mm/min. The displacement–force curve was recorded until the fracture occurred. At least five specimens were conducted for each stack-up. The average shear strength was calculated and reported.

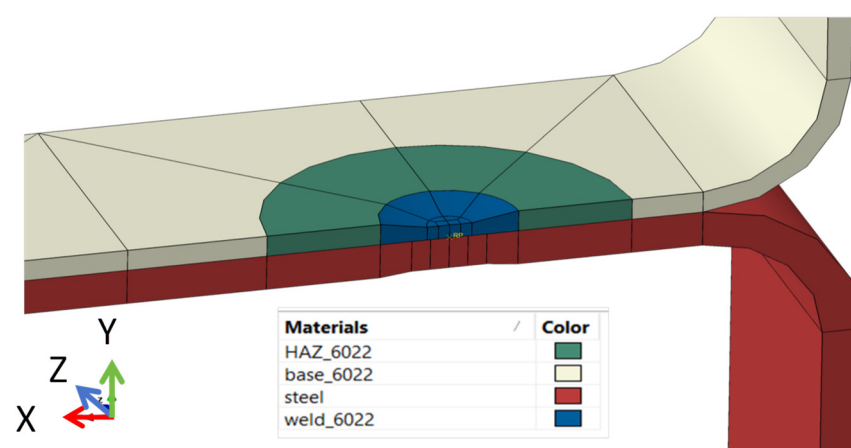
The tensile experiments were conducted using an MTS servo-hydraulic system. Load–displacement data were recorded throughout the process. The tensile rate was 3 mm/min. Following the tensile tests, the tensile fracture modes were analyzed. Similarly, fatigue tests were carried out on the same MTS system at room temperature, with a load ratio ( $R$ ) set to 0.1 and a testing frequency of 5 Hz. The fatigue load was chosen to be between 20% and 60% of the peak tensile load, aiming for a fatigue life ranging from tens of thousands to a million cycles. Following fatigue testing, the fracture modes related to fatigue were also examined.



**Figure 2.** Configuration of mini shear specimen in a (a) schematic diagram and (b) actual object diagram.

#### 2.4. Finite Element Analysis

The local stress state was analyzed using finite element analysis software in ABAQUS 2020. A three-dimensional model of the coach peel specimen was created using C3D8R brick elements with reduced integration. The model included the fusion zone, heat-affected zone (HAZ), and base metal regions (Figure 3). The material properties for these regions, determined from shear tests [4], were incorporated into the simulation. Boundaries were applied at both ends of the model. The Y displacement of the bottom surface was tied to the reference points, which were fixed in the loading direction, i.e., the Y direction. To prevent movement in the horizontal plane, the X direction was constrained for both the top and bottom-back edge, ensuring the vertical alignment of the top and bottom parts throughout the experiments. The local stress, i.e., the shear stress and tensile stress at the interface, was calculated. In addition to the AA6022-LCS RSWs with varying weld nugget diameters, the stack-ups studied in previous work (Table 4) [4,13] were also simulated. The stress triaxiality and  $A_p$  were calculated and plotted against the weld nugget diameter of the coach peel specimens to reveal the mechanism behind the tensile fracture modes.



**Figure 3.** Coach peel model in Abaqus software.

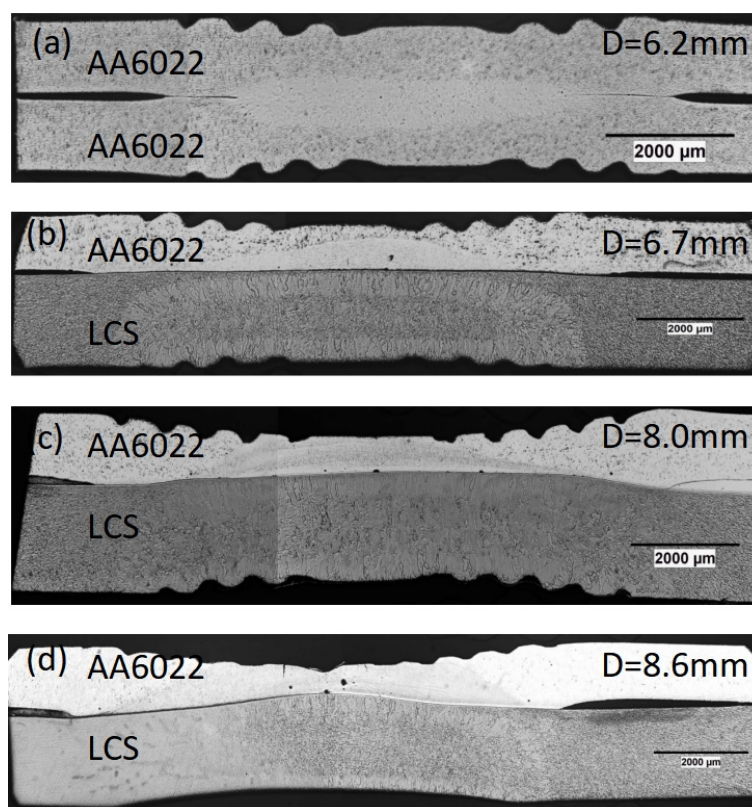
**Table 4.** The list of stack-ups researched in this study.

| Stack-Ups                | Weld Nugget Diameter (mm) |
|--------------------------|---------------------------|
| 1.2 mm AA6022-2.0mm LCS  | 8.6                       |
| 1.2 mm AA6022-2.0mm LCS  | 8.0                       |
| 1.2 mm AA6022-2.0mm LCS  | 6.7                       |
| 1.2 mm AA6022-1.2mm LCS  | 8.2                       |
| 1.2 mm AA6022-0.9mm LCS  | 7.9                       |
| 1.2 mm AA6022-1.2mm HSLA | 7.8                       |
| 1.2 mm AA6022-2.0mm HSLA | 7.1                       |

### 3. Results

#### 3.1. Features of Spot Welds

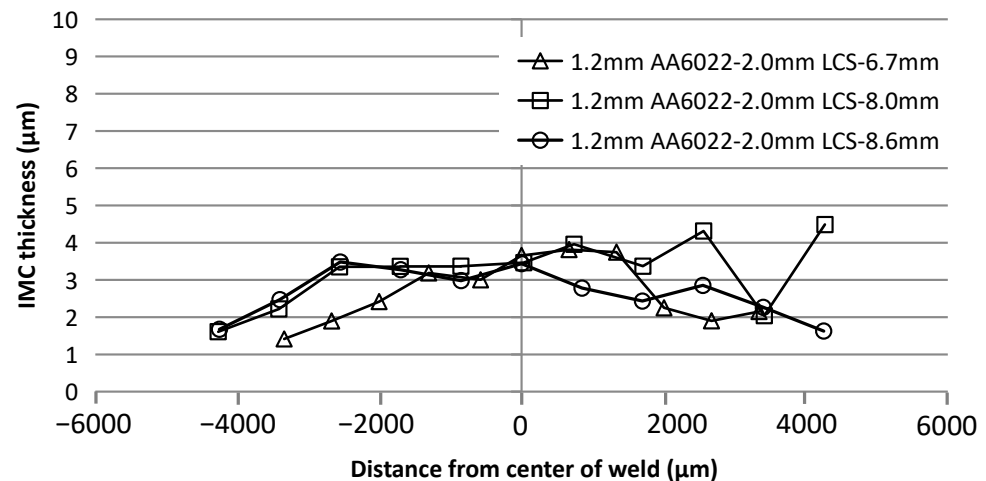
The macrostructure of the resistance spot welds is displayed in Figure 4. The weld nugget diameter of AA6022-AA6022 RSW was 6.2 mm. For AA6022-LCS, the weld nugget diameters were 6.7 mm (Figure 4b), 8.0 mm (Figure 4c) and 8.6 mm (Figure 4d). For the sake of clarity, the three AA6022-LCS stack-ups with different nugget diameters are now named AA6022-LCS-6.7 mm, AA6022-LCS-8.0 mm and AA6022-LCS-8.6 mm. Regardless of the weld nugget size, defects were minimal and centrally located within the aluminum weld nugget, distant from the notch (Figure 4).



**Figure 4.** Macrostructure of (a) AA6022-AA6022 and (b) AA6022-LCS RSWs with a small weld nugget diameter and (c,d) AA6022-LCS with larger weld nugget diameters.

Maintaining the uniformity of the IMC layer thickness during resistance spot welding with varying weld nugget diameters was challenging. A thicker IMC layer usually formed in RSWs with larger weld nugget diameters due to the greater heat generated during welding. In the present study, the 1.2 mm AA6022 sheet and LCS sheet were resistance

spot welded using a higher weld current to create aluminum weld nuggets with a larger diameter (Figure 5). The IMC layer thickness profiles in all stack-ups were found to be similar (Figure 5). More specifically, the average IMC layer thickness at the periphery (within 1 cm from the weld nugget edge) was 2.0  $\mu\text{m}$  for AA6022-LCS-6.7mm, and 2.2  $\mu\text{m}$  for AA6022-LCS-8.0mm and AA6022-LCS-8.6mm. At the center of the weld nugget, the IMC layer thickness was slightly greater than 3  $\mu\text{m}$ .



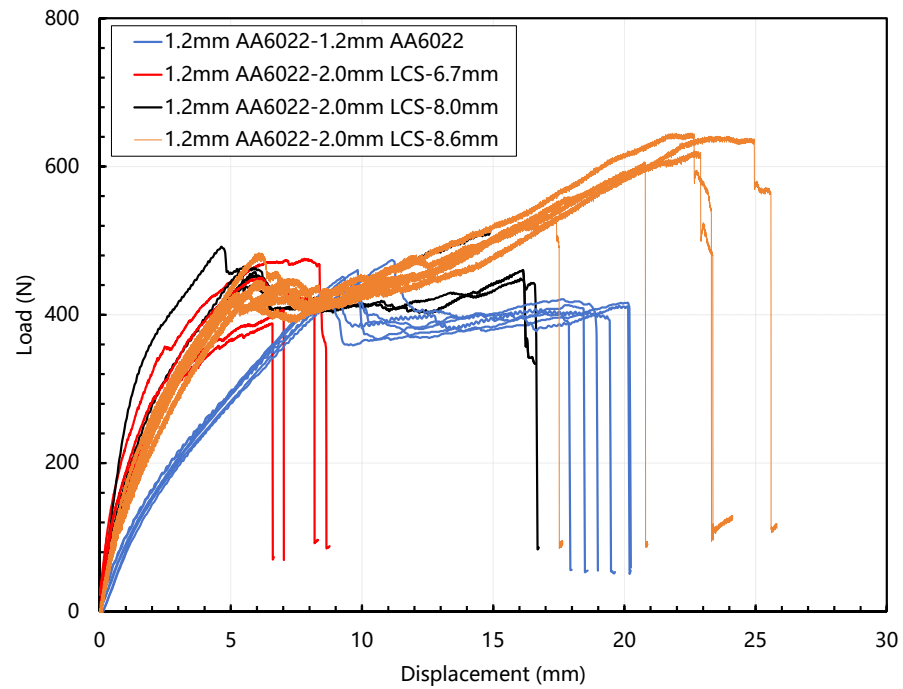
**Figure 5.** The thickness of the IMC layer in the 1.2 mm AA6022 to LCS RSWs with a small and large aluminum weld nugget diameter.

### 3.2. Shear Strength of IMC and Tensile Properties of Joints

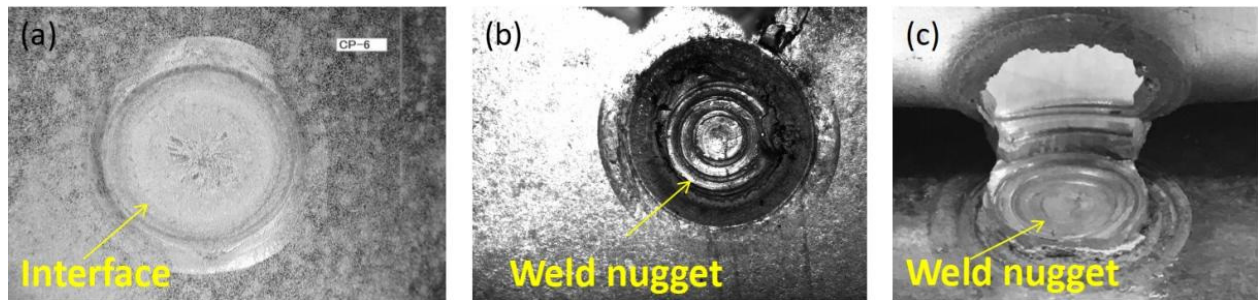
For the IMC layer, the average shear strength obtained from the mini-shear tests was 74 MPa for AA6022-LCS-6.7mm, 90 MPa for AA6022-LCS-8.0mm, and 98 MPa for AA6022-LCS-8.6mm. The average tensile peak load for the coach peel specimens of AA6022-LCS-6.7mm was 419 N, which was less than that of the AA6022-AA6022 stack-ups (451 N) (Figure 6). There were two peak loads in the AA6022-AA6022, AA6022-LCS-8.0mm and AA6022-LCS-8.6mm stack-ups. For the first peak load, the average tensile peak loads were 464 N and 460 N for AA6022-LCS-8.0mm and AA6022-LCS-8.6mm (Table 5). Except for the higher tensile peak load, the fracture displacement for AA6022-LCS-8.0mm and AA6022-LCS-8.6mm was longer than that for the AA6022-LCS-6.7mm stack-ups (Figure 6). This was due to the pull-out fracture mode in the AA6022-LCS stack-ups with larger weld nugget diameters (Figure 7). The first peak load was induced by the cracks formed in the weld nugget, which then propagated along the aluminum alloy sheet, resulting in a ductile fracture (Figure 7b,c). The small fracture area in the tensile curves for the AA6022-LCS-6.7mm stack-ups was due to the interfacial fracture mode, which was more inclined towards brittle fracture (Figure 7a).

**Table 5.** Shear strength of the IMC and tensile peak load of all stack-ups.

| Stack-Ups        | Shear Strength of IMC (MPa) | Tensile Peak Load of Coach Peel (N) |
|------------------|-----------------------------|-------------------------------------|
| AA6022-AA6022    | -                           | 451                                 |
| AA6022-LCS-6.7mm | 74                          | 419                                 |
| AA6022-LCS-8.0mm | 90                          | 464                                 |
| AA6022-LCS-8.6mm | 98                          | 460                                 |



**Figure 6.** Tensile curves of AA6022-AA6022 and AA6022-LCS stack-ups in coach peel configurations.



**Figure 7.** Fracture modes of (a) AA6022-LCS-6.7mm, (b) AA6022-LCS-8.0mm and (c) AA6022-LCS-8.6mm stack-ups.

### 3.3. Prediction of Tensile Fracture Modes Based on Stress Triaxiality

#### Calculation of Stress Triaxiality

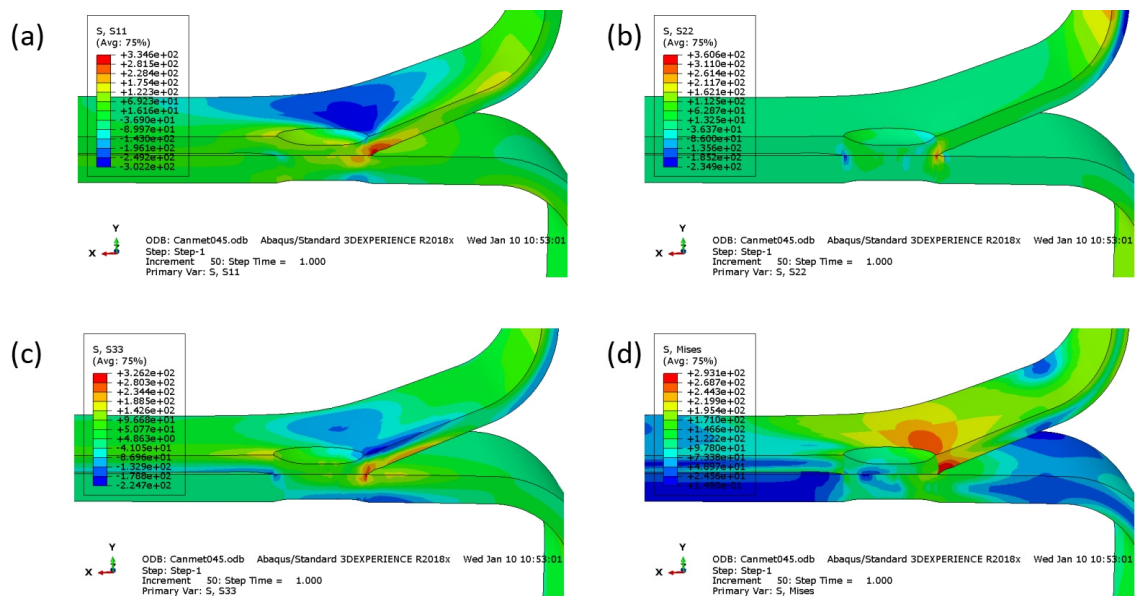
The complex stress state in coach peel joints resulted in multi-axial stresses. Stress triaxiality, combined with strain intensity, plays a crucial role in governing the onset of ductile fracture [16]. The equation of stress triaxiality is presented as Equation (1), which equals the ratio of hydrostatic pressure to the equivalent von Mises stress (Equation (1)) [15,16].

$$\sigma^* = \frac{\sigma_m}{\sigma_e} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) / \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}{2}} \quad (1)$$

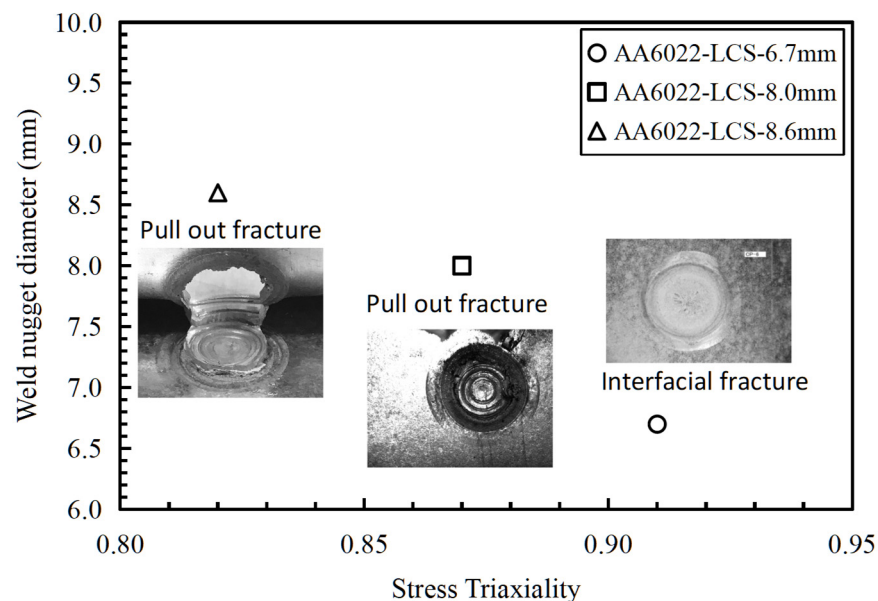
where  $\sigma_m$  is the hydrostatic pressure, and  $\sigma_e$  is the equivalent von Mises stress.  $\sigma_1$ ,  $\sigma_2$  and  $\sigma_3$  are the principal stresses in three directions, respectively.

Taking the 1.2 mm AA6022-2.0mm-thick LCS specimens as a representative, the required parameters in Equation (1), namely the principal stresses in three directions and the equivalent von Mises stress, were calculated. The stress contour plots are shown in Figure 8. From the contour results, it was observed that the highest stresses occurred near the notch at the interface between the aluminum and steel sheets. Therefore, the stress values at this location were extracted and used in Equation (1) to calculate the stress triaxiality.

The stress triaxiality and weld nugget diameter of the coach peel specimens in the present study are plotted in Figure 9. The results show that the stress triaxiality increased with a decreasing weld nugget diameter. For the AA6022-L



**Figure 8.** Stress contour of (a) tensile stress S11, (b) tensile stress S22, (c) tensile stress S33 and (d) von Mises stress of 1.2 mm-thick AA6022-2.0mm-thick LCS specimens.

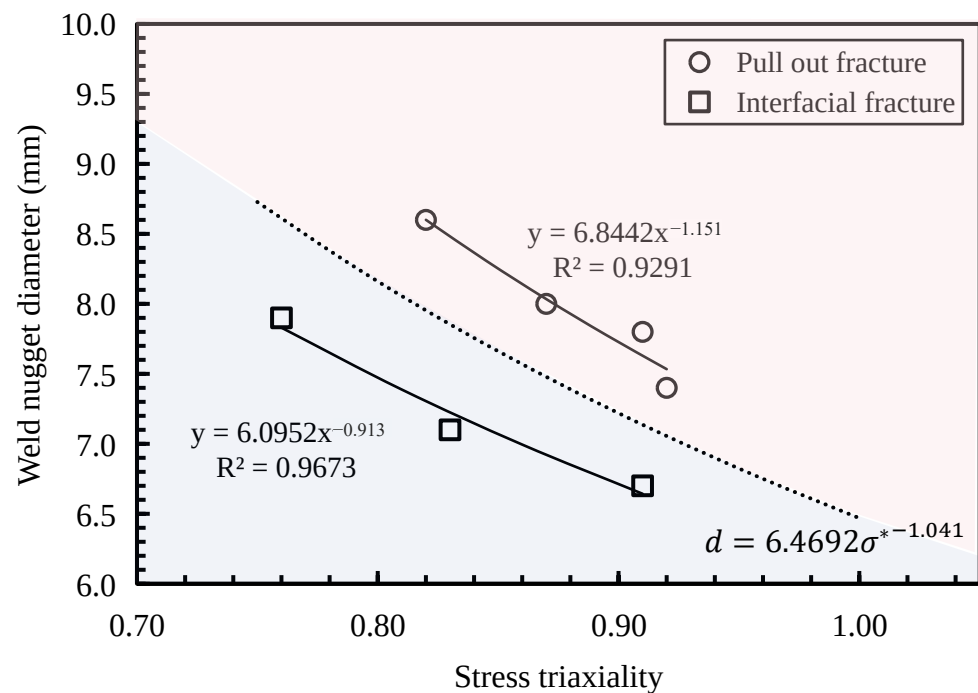


**Figure 9.** The relationship between the stress triaxiality and weld nugget diameter in the coach peel specimens from this study.

CS-6.7mm stack-up, the stress triaxiality was 0.91, in which the fracture mode was interfacial (Figure 9). The stack-ups with a larger weld nugget diameter had smaller stress triaxiality. The fracture mode was pull-out (Figure 9).

The stress triaxiality of all stack-ups listed in Table 4 were calculated and plotted in Figure 10. The pull-out fracture modes and interfacial fracture modes are represented by circle and square symbols, respectively. Interestingly, two distinct trend lines for the pull-out and interfacial fracture modes are evident in Figure 10. When the stress triaxiality and weld nugget diameter were larger, the fracture mode tended to be pull-out. Conversely,

when these factors were smaller, the fracture mode was interfacial. Therefore, the fracture mode of the coach peel stack-ups was affected by both the weld nugget diameter and the stress triaxiality. The trend line in the middle of the pull-out and interfacial lines (dotted line) is plotted in Figure 10 with the fitting equation of  $d = 6.469\sigma^{*-1.041}$ .

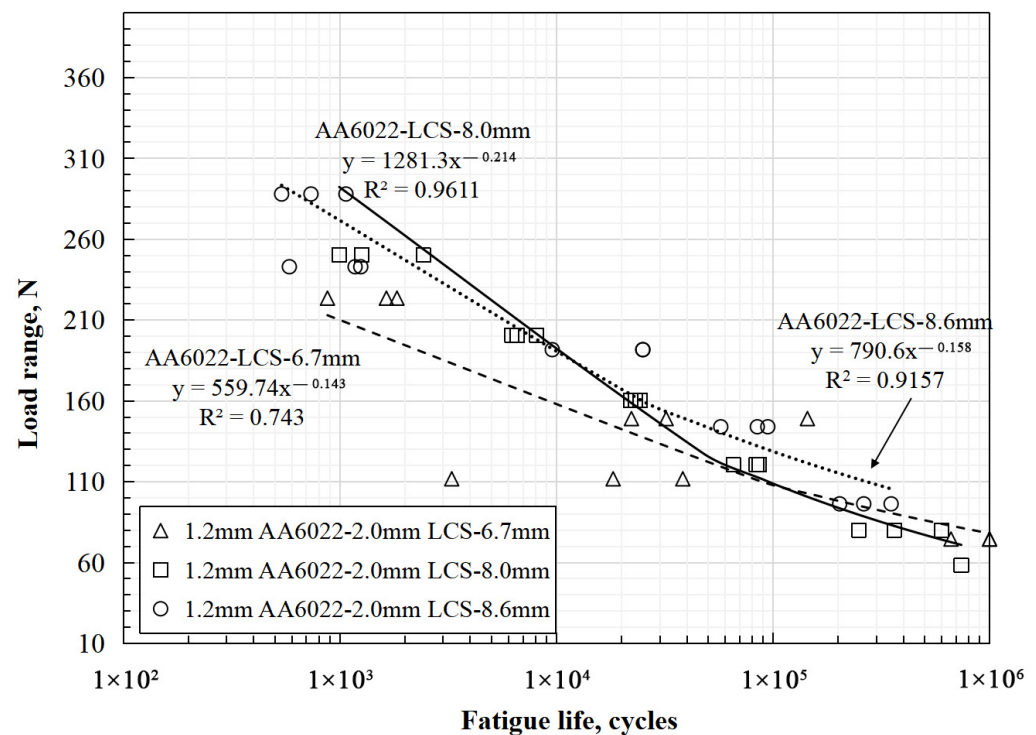


**Figure 10.** The effect of the weld nugget diameter and stress triaxiality on the fracture modes of the coach peel specimens in Table 4. The pink area represents the pull-out fracture mode, and the blue area represents the interfacial fracture mode.

### 3.4. Fatigue Properties

#### 3.4.1. Fatigue Life

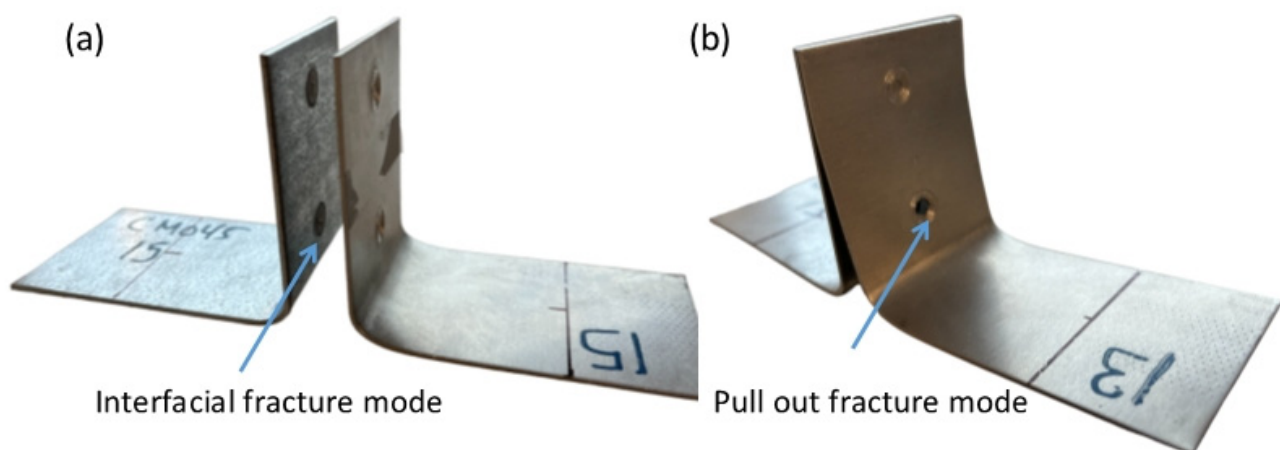
A comparison of the fatigue life of the AA6022-LCS-6.7mm, AA6022-LCS-8.0mm and AA6022-LCS-8.6mm stack-ups in coach peel configurations is presented in Figure 11. It was observed that the fatigue life of AA6022-LCS-6.7mm, with a smaller weld nugget diameter, was the shortest. Increasing the weld nugget diameter to 8.6 mm resulted in the longest fatigue life for the stack-ups. At lower load ranges, there was little variation in the fatigue life between the AA6022-LCS-6.7mm and AA6022-LCS-8.0mm stack-ups. However, a decrease in the weld nugget diameter led to greater variability in the fatigue life. For the AA6022-LCS-6.7mm stack-ups, the fitting coefficient was found to be 0.743.



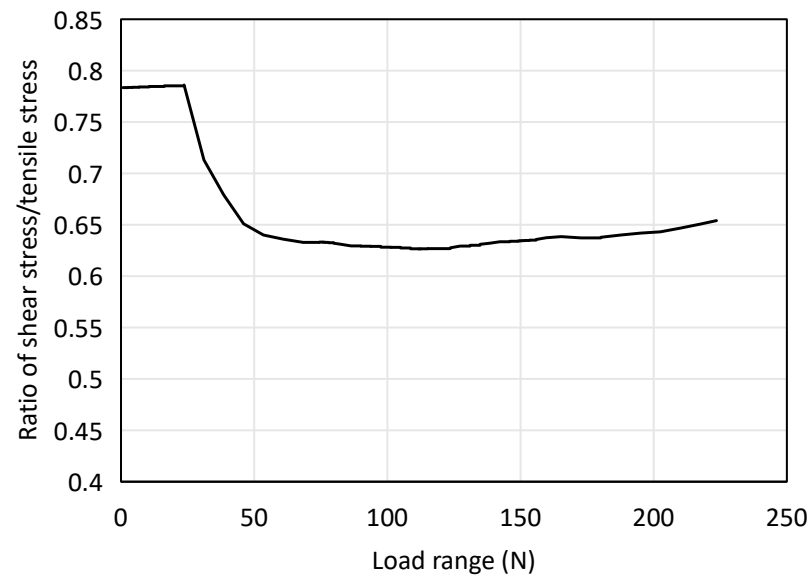
**Figure 11.** Load range vs. fatigue life of AA6022-LCS RSWs with different weld nugget diameters.

### 3.4.2. Fatigue Fracture Modes

Notably, the fatigue fracture modes for the AA6022-LCS-8.0mm and AA6022-LCS-8.6mm stack-ups were pull-out. Intriguingly, for the 1.2 mm AA6022-2.0mm LCS-6.7mm, the fatigue fracture modes transitioned from pull-out (Figure 12b) to interfacial (Figure 12a) with a decrease in the loads applied, challenging conventional expectations. This could be attributed to changes in the local stress state (Figure 13). At high load levels, the ratio of shear stress to tensile stress was low (0.65), leading to pull-out fracture even with a small weld nugget diameter. At low load levels, the ratio increased to 0.78, causing the fracture mode shift to interfacial for the same weld nugget diameter.

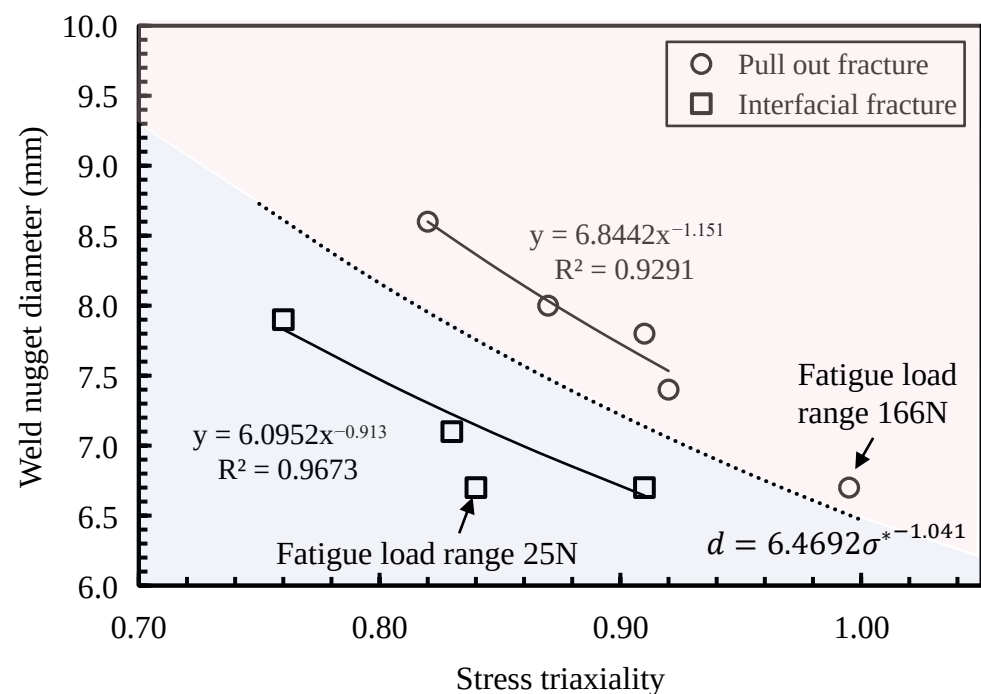


**Figure 12.** Fracture modes of fatigue specimens of AA6022-LCS RSWs with a smaller weld nugget diameter. (a) Interfacial fracture mode when the load range was 75 N. (b) Pull-out fracture mode when the load range was 224 N.



**Figure 13.** Ratio of shear stress to tensile stress at different load ranges for the 1.2 mm AA6022-LCS-6.7mm stack-up.

Additionally, the stress triaxiality was calculated to be 0.84 at a low fatigue load range (80 N) and 0.99 at a high fatigue load range (166 N) for the AA6022-LCS-6.7mm stack-ups with a nugget diameter of 6.7 mm. The fatigue fracture mode for the load range of 80 N was interfacial. The fatigue fracture mode for the load range of 166 N was pull-out. The calculated stress triaxiality under both load ranges is plotted in Figure 14. The two points are located at the two sides of the trend line, which indicates that stress triaxiality is also an effective constraint parameter in predicting the fracture modes for fatigue testing.



**Figure 14.** Predicting fatigue fracture modes using weld nugget diameter and stress triaxiality. The pink area represents the pull-out fracture mode, and the blue area represents the interfacial fracture mode.

#### 4. Discussion

Chao et al. predicted the fracture modes of tensile shear and cross tension configurations based on the theory of fracture mechanics [10]. Distinguishing between the two fracture modes was achieved through an analysis that yielded a critical weld nugget diameter. The equation for deriving the critical weld nugget diameter incorporated two material properties, namely the shear strength  $\tau_f$  and fracture toughness  $K_c$  (Equation (2)).

$$d_{cr} = 0.86 \left( \tau_f / K_c \right)^{2/3} t^{4/3} \quad (2)$$

where  $d_{cr}$  is the weld nugget diameter,  $\tau_f$  is the shear strength,  $K_c$  is the fracture toughness and  $t$  is the sheet thickness.

The fracture toughness in Equation (2) neglected the constraint effect presented in various configurations, which led to its inability to accurately predict the fracture modes of the coach peel configuration. In our earlier work, the fracture mechanism of coach peel specimens was elucidated. It was found that the fracture modes of the coach peel specimens were greatly affected by the ratio of shear stress to tensile stress within the weld nugget [13]. Consequently, the constraint effect must be taken into account when predicting the fracture modes in coach peel specimens.

In summary, the results from the tensile and fatigue testing of the coach peel stack-ups, which had a small weld nugget diameter, demonstrated that the weld nugget diameter alone did not determine the fracture modes. The constraint parameter, namely stress triaxiality, was calculated and used to predict the fracture modes of these specimens. The unusual fracture patterns observed in the fatigue tests further underscored the importance of accounting for the constraint effect.

#### 5. Conclusions

Aluminum alloy sheets and steel sheets were resistance spot welded with a deliberately reduced weld nugget diameter to induce an interfacial fracture mode in tensile experiments on coach peel stack-ups. Concurrently, the thickness of the IMC layers remained consistent across RSWs with varying weld nugget diameters. Tensile and fatigue tests were performed. The main novelty of this study lies in the introduction of a method for predicting the tensile and fatigue fracture modes of coach peel specimens based on the stress triaxiality and weld nugget diameter, particularly when the critical nugget method is not applicable. The conclusions are summarized as follows:

- (1) For coach peel specimens, when the weld nugget diameter was sufficiently small, the interfacial fracture mode occurred at the interface during tensile testing.
- (2) The tensile fracture modes of the coach peel specimens were not solely influenced by the diameter of the aluminum weld nugget, but also by local stress states, particularly the stress triaxiality.
- (3) The fatigue fracture modes in the same coach peel specimens shifted from pull-out to interfacial with a decrease in the applied load, which was attributed to changes in the local stress state, i.e., shear stress dominated when the load was high, while tensile stress took precedence when the load was low. At the same time, the fatigue fracture modes were predicted successfully based on weld nugget and stress triaxiality.

Building upon the current findings, future research will further explore the influence of stress triaxiality on fracture mode prediction in specimens with more complex loading conditions, such as cross-tension and KSII specimens. These configurations introduce additional stress states that may affect the fracture behavior, requiring a more refined assessment of failure mechanisms. Additionally, further investigations will be conducted on the effects of other constraint parameters, such as the  $A_2$  constraint parameter and

the Q parameter obtained from the HRR solution (crack-tip singularity field proposed by Hutchinson, Rice and Rosengren), on fracture mode prediction under complex loading conditions. These efforts aim to enhance our understanding of the predictive capability of fracture behaviors in the resistance spot welding of aluminum–steel joints.

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## Nomenclature

|                                            |                                        |
|--------------------------------------------|----------------------------------------|
| RSW                                        | Resistance Spot Welding                |
| IMC                                        | Intermetallic Compound                 |
| MRD                                        | Multi-Ring Domed (Electrode)           |
| LCS                                        | Low Carbon Steel                       |
| MFDC                                       | Medium Frequency Direct Current        |
| ELPO                                       | Electrodeposition Paint Operation      |
| SEM                                        | Scanning Electron Microscopy           |
| MTS                                        | Material Testing System                |
| AA6022                                     | Aluminum Alloy 6022                    |
| HSLA                                       | High-Strength Low-Alloy (Steel)        |
| HRR                                        | Hutchinson–Rice–Rosengren (Solution)   |
| FEA                                        | Finite Element Analysis                |
| $A_p$                                      | Equivalent Plastic Strain Parameter    |
| $Q_{HRR}$                                  | Q Parameter from HRR Solution          |
| $E$                                        | Elastic modulus                        |
| $\sigma_y$                                 | Yield stress                           |
| $\sigma_u$                                 | Ultimate tensile stress                |
| $R$                                        | Load ratio                             |
| $\sigma^*$                                 | Stress triaxiality                     |
| $\sigma_m$                                 | Hydrostatic pressure                   |
| $\sigma_e$                                 | Equivalent von Mises stress            |
| $\sigma_1, \sigma_2 \text{ and } \sigma_3$ | Principal stresses in three directions |
| $d$                                        | Weld nugget diameter                   |
| $d_{cr}$                                   | Critical weld nugget diameter          |
| $\tau_f$                                   | Shear strength                         |
| $K_C$                                      | Fracture toughness                     |
| $t$                                        | Sheet thickness                        |

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