

Mechanical Testing of Adhesive, Self-Piercing Rivet, and Hybrid Jointed Aluminum Under Tension Loading

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1 Abstract

2 Joining technologies play a crucial role in facilitating vehicle weight reduction, while maintaining
3 structural performance and vehicle crashworthiness. Adhesive and self-piercing rivet (SPR) joining have
4 individually been assessed in joining multi-material structures including aluminum alloys; however,
5 limitations include fixturing requirements for adhesive joints and non-uniform load distribution within
6 SPR joints. Hybrid (adhesive-SPR) joining has been proposed to potentially address these limitations. Yet,
7 there is limited data regarding the strength, stiffness and energy absorption of hybrid joints under
8 tension loading, and a lack of quantitative comparisons between adhesive, SPR and hybrid joints.
9 In the present study, adhesive, SPR and hybrid joints were created in aluminum H-shaped tension
10 specimens and the joint morphologies were quantified. Joint strength, stiffness and energy absorption
11 were compared for two aluminum sheet metal alloys and three sheet thicknesses. Adhesive joints
12 exhibited higher strength (up to 20.5%) and stiffness (up to 422%) than SPR joints, while SPR joints
13 demonstrated higher energy absorption (up to 352%). Hybrid joints in 3 mm sheet exhibited reduced
14 strength and stiffness relative to adhesive joints. Importantly, hybrid joints for 1 and 2 mm sheet
15 thicknesses demonstrated strength and stiffness comparable to adhesive joints (<8% difference), and
16 improved energy absorption compared to adhesive (up to 336%) and SPR joints (up to 53.5%), enhancing

the performance of the individual methods. The study results could facilitate identifying suitable joining method, sheet thickness and alloy type according to structural applications (e.g. intrusion prevention versus energy-absorbing structures), and support future adoption and improvement of hybrid joints.

Keywords: aluminum joining, structural adhesive, self-piercing rivets, hybrid joining, joint morphology, adhesive and SPR

1. Introduction and Background

Weight reduction of future vehicles, including lightweight materials such as aluminum, has a crucial role in meeting increasingly stringent emission regulations and fuel economy standards [1,2]. A comparative study by Tisza and Czinege [2] to produce lighter vehicle components reported an overall vehicle weight reduction of 30% to 40% by adopting aluminum alloys in the vehicle structure. Critical to enabling the adoption of aluminum alloys in the automotive industry are robust joining methods that play a primary role in structural performance and crashworthiness. Adhesive bonding and self-piercing rivet (SPR) joining have demonstrated promising mechanical performance and the potential to enable future materials and multi-material systems needed for vehicle weight reduction [3]. However, barriers remain with respect to the implementation of individual joining methods. Surface treatment, curing time and part fixturing present challenges for adhesive bonding, while a lack of continuous load distribution and generally lower joint stiffness are challenges for SPR joints. To overcome the limitations of individual joining methods, several authors investigated, hybrid joining, augmenting adhesive bonding with another joining method such as SPR riveting [4], friction stir spot welding [5], clinching [6], bolting [7], and mixed adhesives [8]. Hybrid (adhesive-SPR) joining has demonstrated potential when joining aluminum and aluminum-based multi-material structures, enabling further light-weighting opportunities [3,4]. Yet, there is limited data regarding the mechanical performance of hybrid joints, particularly in quantifying joint strength, stiffness, and energy absorption [4].

40 Several studies have been undertaken to assess the shear strength of adhesive, SPR and hybrid joints,
41 using single-lap shear (SLJ) test specimens [3,4,9]. Meschut et al. [3] reported that adhesive joined SLJ
42 specimens, made with aluminum and press hardened steel, outperformed similar hybrid joints in terms
43 of shear strength (16% higher shear strength), owing to the reduced effective bonding area as uncured
44 adhesive squeezed out while applying the SPR rivet. Di Franco et al. [4] compared the strength, stiffness
45 and energy absorption of adhesive, SPR and hybrid joints using SLJ joints, joining aluminum (2024-T6)
46 and carbon fibre reinforced composite. Hybrid joints exhibited the highest shear joint strength (~5 kN)
47 compared to adhesive joints (~4.5 kN) and SPR joints (~3.5 kN). It has been reported that SLJ specimens
48 induce varying degrees of mixed-mode loading, highly depending on the adherend stiffness, and
49 therefore make comparisons between different studies challenging [10].

50 While characterizing joint shear strength is essential, joints in automotive applications experience
51 different modes of loading [11], and adhesive and SPR joints were reported to generally exhibit lower
52 strength under tension loading (i.e., Mode I) [9,12]. Lee et al. [13] compared the crashworthiness of
53 adhesive and SPR joined double hat-section axial crush tubes demonstrating SPR pull-out and adhesive
54 failure due to peel stresses, which were attributed to tension loading.

55 H-shaped test specimens (Fig. 1), comprising two U-shaped adherends joined together, have been used
56 to evaluate adhesive steel joints [14], SPR extruded aluminum joints [15], SPR multi-material joints [9]
57 and hybrid (adhesive-spot welded steel) joints [12] under tension loading. Recently, Ciardiello et al. [11]
58 investigated adhesively joined boron steel H-shaped specimens under various loading orientations,
59 highlighting that the joints under tension loading had 50% lower joint strength compared to shear
60 loading. Cross tension (CT) specimens were used to characterize tension (Mode I) response of adhesive
61 and SPR joints [16,17]; however, the high compliance of these specimens was recently reported to affect
62 deformations and reduce joint strength [12]. Weiland et al. [12] used the LWF-KS2, an H-shaped

specimen, for evaluating adhesive and hybrid (adhesive-spot welded) joints to overcome the compliance and bending stiffness issues of the CT specimens. Importantly, a comparison between joined H-shaped and CT specimens showed that the latter could reduce joint strength by up to 44% (3.4 kN for H-specimen versus 1.9 kN for CT) owing to deformation of the adherends [18].

Sheet thickness and adherend material properties (*e.g.* yield strength and ductility) were reported to have significant effects on the mechanical performance of adhesive and SPR joints, but there has been no detailed investigation on hybrid joints. da Silva et al. [19] highlighted that sheet thickness (*i.e.* adherend thickness) affected the plastic deformation and bending moment of test specimens when evaluating the shear strength of SLJ adhesive joints. In their work, they explained that the influence of sheet thickness on adhesive joint strength changed according to the adherend material yield strength. The influence of steel adherends (yield strength and thickness), adhesive (thickness and toughness), joint overlap, and surface treatment on the SLJ joint strength was assessed using the Taguchi method [20]. Among the parameters they studied, adherend yield strength and thickness had the greatest influence on adhesive joint strength; however, similar work was not extended to hybrid joints under tension loading. Furthermore, Han et al. [17] demonstrated that the increase in sheet thickness increased the SPR joint strength and energy absorption under shear and tension loading using SLJ and CT specimens. The improvement in SPR joint strength and energy absorption with sheet thickness was attributed to the greater mechanical interlock and higher energy stored in the joint. Earlier work on hybrid (adhesive-SPR) joining has been limited to SLJs, but no single study has investigated the tension (Mode I) response of adhesive, SPR and hybrid joints under the same test conditions. Previous hybrid joining studies have reported both strength improvement [4] and strength reduction [3] compared to adhesive-only joints. Two aspects that have not been systematically investigated in hybrid joints are the influence of sheet properties, and joint-level morphology.

86 The aim of the current study was to quantitatively compare the strength, stiffness and energy absorption
87 of adhesive, SPR and hybrid joints using H-specimens under tension loading, considering two aluminum
88 alloys and three sheet thicknesses. Statistical analysis was applied to quantify the effects and
89 interactions of the joining methods, sheet metal thickness, and aluminum alloy type (strength and
90 ductility). The joint-level morphology of adhesive, SPR and hybrid joints was systematically assessed by
91 measuring bonding area, bond line thickness and SPR mechanical interlock of the joints.

92 **2. Experimental Methodology**

93 **2.1. H-Specimen Testing**

94 The H-specimen geometry was used to assess the mechanical performance of adhesive (Fig. 1a), SPR
95 (Fig. 1b), and hybrid joints (Fig. 1c) under tension loading. The H-specimen geometry, also known as KS2
96 [9,12], was tailored with a larger bend radius required for aluminum sheet material for specimen
97 manufacture for a range of aluminum thicknesses. In addition, the width of the specimen was increased
98 to mimic an automotive flange width and to accommodate the SPR setting tool. The test specimens were
99 made from two cold-rolled aluminum alloys (AA6061-T6 and AA5052-H32), used in studies related to
100 joining and weight reduction [21,22]. The AA6061-T6 alloy offered mechanical properties relatively
101 similar to the properties of automotive alloys in service (*e.g.*, AA6111-T6), while the AA5052-H32 alloy
102 offered distinct yield strength (42% lower) and ductility (56% higher), allowing for the effect of yield
103 strength and ductility to be assessed (Table 1). Three sheet thicknesses (1 mm, 2 mm and 3 mm) were
104 used to fabricate the U-sections required to join the symmetrical H-shaped specimens (1+1 mm, 2+2 mm
105 and 3+3 mm). Sheet metal blanks were machined using a water jet cutter to the required dimensions,
106 then bending was carried out using a compact hydraulic press brake to obtain the U-section geometry
107 (Fig. 1d).

108 **Table 1. Mechanical properties for AA6061-T6 and AA5052-H32 aluminum alloys [23].**

Aluminum Alloy	Modulus of Elasticity [GPa]	Yield Strength [MPa]	Ultimate Tensile Strength [MPa]	True Fracture Strain ϵ_f
AA6061-T6	69.6	289	314	0.61
AA5052-H32		167	231	0.95

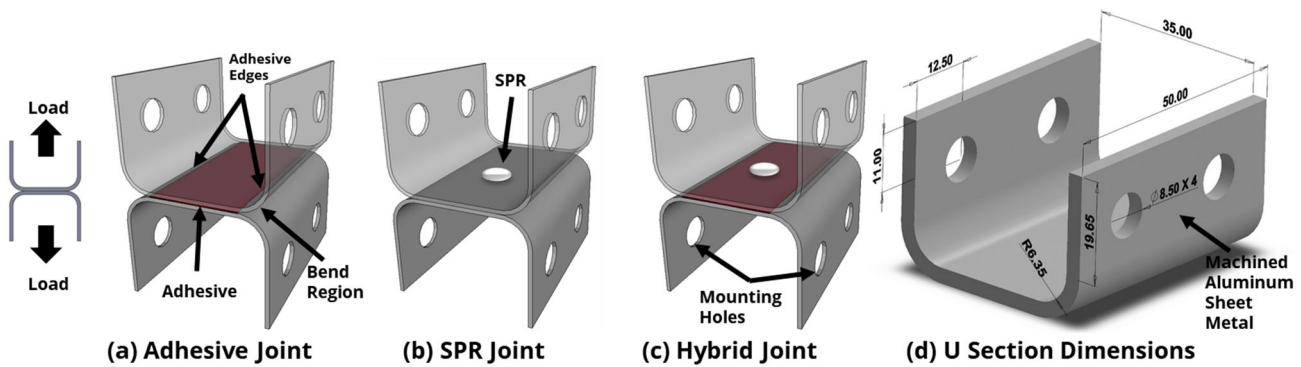


Fig. 1. Adhesive (a), SPR (b) and hybrid (c) joined H specimens, comprising two U-sections (d).

Adhesive, SPR and hybrid joined H-specimens (Table 2) were tested using a hydraulic load frame with a commercial controller (MTS 407; MTS, Minnesota, USA). The quasi-static tests were carried out at room temperature with a constant crosshead speed of 6 mm/min using displacement control and feedback from a linear variable differential transformer (LVDT). The load was measured using a 90 kN load cell (Transducer Techniques SWP 20 k; California, USA). A digital single-lens reflex (DSLR) camera (D3200, Nikon Japan) fitted with a 105 mm macro lens was used to track displacement via markers on each U-section. The load data was acquired using a National Instruments Daqpad-6015 DAC system and LabVIEW software, and specimen displacement was measured from the imaging data using open-source software (Tracker Video Analysis and Modeling Tool, Open Source Physics (OSP) project). The joint performance was assessed using peak load, joint stiffness (slope of the loading curve), and energy absorption (area under the force-displacement curve).

Table 2. Experimental test matrix showing the number of repeats.

Joining Method	Aluminum Alloy Type	Sheet Material Thickness		
		(1+1) mm	(2+2) mm	(3+3) mm

Adhesive	AA6061-T6 Alloy	(3)	(3)	(3)
	AA5052-H32 Alloy	(3)	(3)	(3)
SPR	AA6061-T6 Alloy	(3)	(3)	(3)
	AA5052-H32 Alloy	(3)	(3)	(3)
Hybrid (SPR/Adhesive)	AA6061-T6 Alloy	(3)	(3)	(3)
	AA5052-H32 Alloy	(3)	(3)	(3)

2.2. Adhesive Test Specimen Manufacture

The U-sections (*i.e.* adherends) were bonded using an epoxy-based toughened structural adhesive (07333; 3M, Canada), having a critical strain energy release rate of 3.05 kJ/m² and peak traction of 39.97 MPa under Mode I loading [24]. As reported in previous studies [10], grit blasting was identified to achieve cohesive failure, which was desirable to achieve the maximum performance from the adhesive joint. Teflon-coated fibre-glass spacers were applied at the edges of the bonding area to minimize edge effects, facilitate adhesive spew removal and achieve a nominal bond line thickness of 0.3-0.4 mm. The bond line thickness met the manufacturer requirement (>0.25mm), was within the range reported in automotive applications (0.2 to 0.4 mm) [25], and was the same as the thickness used in a recent study on the same adhesive [26]. A thick, continuous bead of adhesive was applied to the bonding area (18.5 ± 0.5) x (50 ± 0.5) mm²; the U-sections were mated and retrained in a custom fixture, and the joints were cured at 80° C for 90 minutes. The average weights of the 1, 2 and 3 mm specimens were measured as 21.45 ± 0.034 grams, 42.26 ± 0.139 grams and 68.40 ± 0.571 grams, respectively.

2.3. SPR Test Specimen Preparation

SPR joining required precise location of the rivet. This was achieved using a 3D printed template to position the SPR rivet within +/- 0.5 mm of the center of the joining area. To create the SPR joints, an SPR setting tool (Rivlite MK V; Henrob, Atlas Copco, USA) was used with 5 mm zinc-coated semi-tubular steel rivets and domed pip dies (Henrob, Atlas Copco, USA). The SPR setting forces for the 1+1, 2+2 and 3+3 mm were 32 kN, 40 kN and 50 kN, respectively. The setting force for each rivet/die combination was

identified to achieve joints that met the quality guidelines (section 2.5). The weights of the 1, 2 and 3 mm specimens were -3.0%, -0.6% and -0.4% relative to the adhesive joints with similar sheet thickness, highlighting that the test specimens were comparable in terms of weight.

2.4. Hybrid Test Specimen Manufacture

Adhesive and SPR joining were used together to join the U-sections, creating hybrid joints. First, the specimens were joined using the adhesive bonding process (section 2.2) and then, the SPR rivet was applied to the uncured adhesive joint [3,4]. The SPR rivet, die and setting force for each joint thickness were identical in both SPR and hybrid joints, and the hybrid joined specimens were cured at 80° C for 90 minutes, similar to adhesive joints. The weights of the 1, 2 and 3 mm specimens were +4.5%, +1.6% and +1.0% relative to the adhesive joints with similar sheet thickness, indicating that the weight gain with hybrid joining was less than 5%.

2.5. Joint Morphology Assessment

To assess the morphology of the joints, the physical attributes of adhesive, SPR and hybrid joints were measured prior to mechanical testing. High-resolution images under 20X magnification were captured using an Opto-digital microscope (VHX-5000; Keyence, Japan). Adhesive bond line thickness has been reported to influence the mechanical response of adhesives [26,27]; therefore, it was crucial to quantify the bond line thickness variations between adhesive only and hybrid joints. The bond line thickness for bonded and hybrid joints was measured at the edge of the H-specimen from the magnified images using the VHX-5000 Analyzer software (Keyence, Japan) (Fig. 2a). SPR and hybrid joints were sectioned using a water-cooled high-precision cutting wheel (ACCUTOM-50; Struers, USA) to maintain the integrity of the cross-section and retain the physical attributes (Fig. 2b). Each cross-section was assessed for

166 mechanical interlocking (rivet flaring (x) = [deformed rivet diameter (D_f) - initial rivet diameter (D_i)] / 2),
 167 bottom thickness, head height, and leg buckling, bending and fracturing, and sealing [28,29]. Hybrid
 168 joints were qualitatively assessed for adhesive presence in the rivet vicinity and showed an increase in
 169 adhesive thickness away from the rivet (Fig. 2c). Also, variability in bond line thickness was localized to
 170 the location of the rivet, highlighting a limitation that could be addressed in future work.

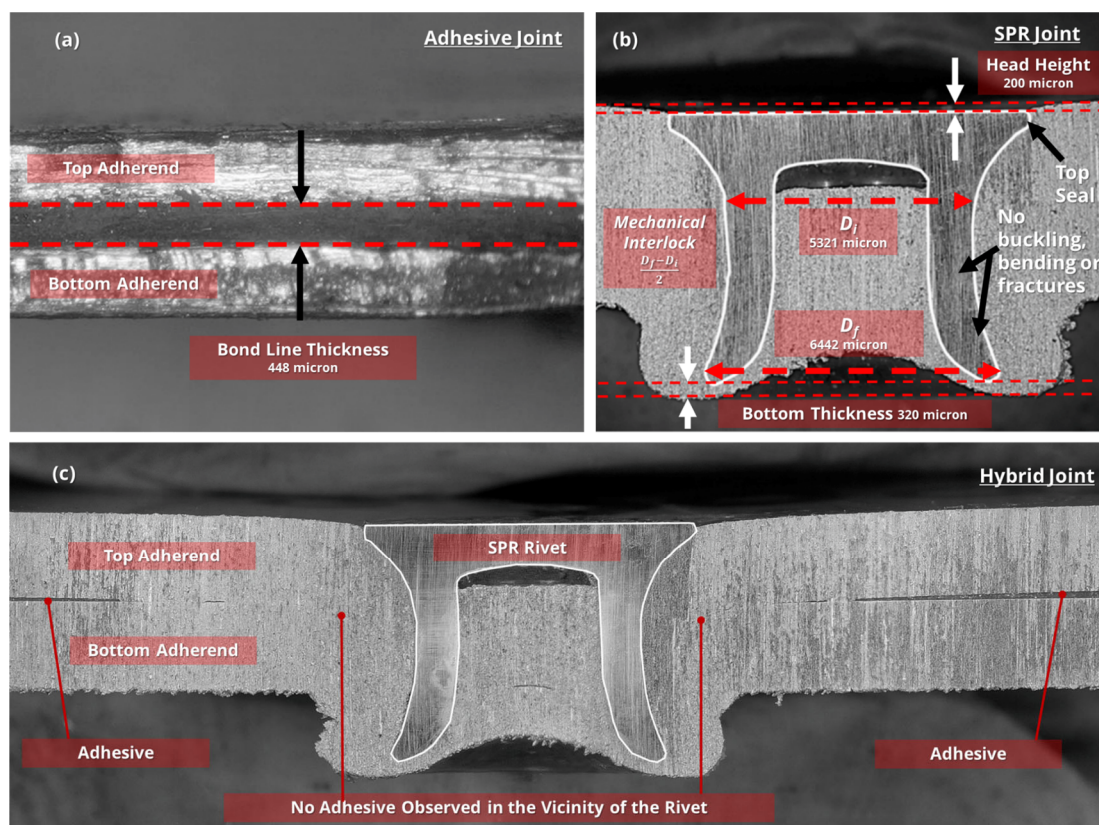


Fig. 2. Joint morphology imaging and measurements for bond line thickness of adhesive (a), physical attributes of SPR (b) and hybrid cross-sections (c).

3. Experimental Results and Discussion

3.1. Adhesive, SPR and Hybrid Joint Morphology Assessment

Imaging and measurements of adhesive and hybrid joints demonstrated that the bond line thickness of the adhesive and hybrid joined specimens was consistent, ranging between 0.406 mm and 0.493 mm for adhesive joints and 0.248 mm and 0.373 mm for hybrid joints (Fig. 3a and b). Adhesive bond line thickness was reported to influence the mechanical response of adhesives [27]; therefore, it was crucial

181 to highlight bond line thickness variability between adhesive and hybrid joints and quantify the influence
 182 of hybrid joining on the adhesive bond line thickness. The average bond line thickness of the hybrid joints
 183 was considerably lower relative to adhesive joints (38% lower for AA6061 joints and 27.5% lower for
 184 AA5052 joints), highlighting the adverse effect of hybrid joining on the adhesive bond line thickness. In
 185 general, controlling bond line thickness using Teflon spacers at the bend radii was influenced by the
 186 preciseness of the fixturing jig and the sheet material thickness after bending process, explaining the
 187 somewhat higher variability in the more ductile AA5052 alloy. Cross-sectional imaging and analysis
 188 demonstrated that the SPR joints met the literature guidelines [28,29], which recommended head height
 189 close to zero, bottom thickness larger than 0.2 mm, mechanical interlock larger than 0.4 mm and a rivet
 190 leg with no bending or buckling. In general, the mechanical interlock measurements of the SPR joints
 191 were relatively consistent for the three sheet thicknesses with a mean value of 0.917 mm and 0.577 mm
 192 for the AA6061 and AA5052 joints, respectively. The AA6061 joints exhibited a 37% higher average
 193 mechanical interlock than the AA5052 alloy (Fig. 4. **Mechanical interlock measurements for SPR and hybrid joints**
 194 **with AA6061-T6 (a) and AA5052-H32 (b) alloys (dashed lines represent the minimum recommended value [28,29]).**a and
 195 b). The higher strength, lower ductility alloy had greater resistance to deformation and penetration,
 196 which could have induced increased rivet flaring during the SPR cold forming process.

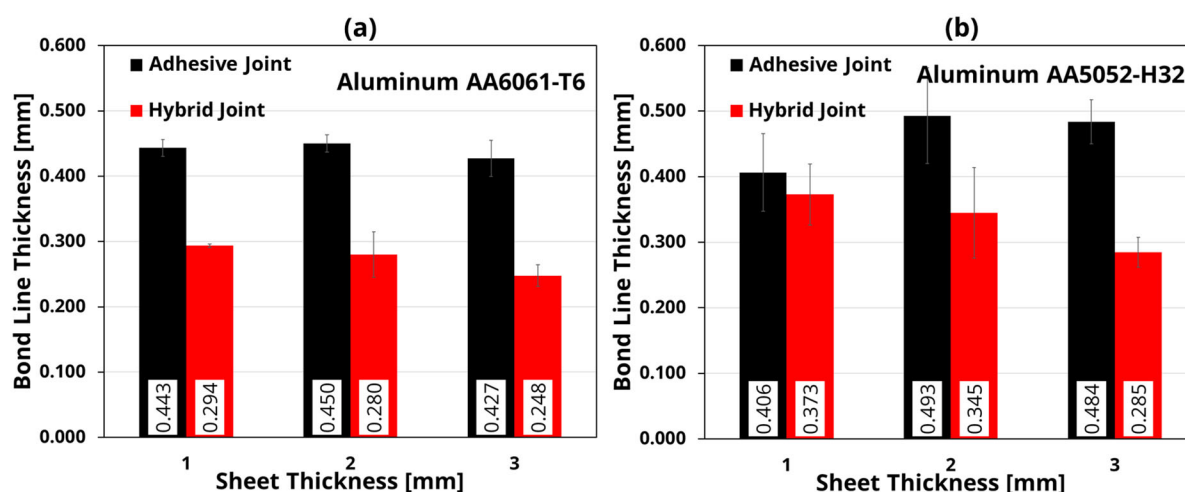


Fig. 3. Bond line thickness measurements for adhesive and hybrid joints made from AA6061-T6 (a) and AA5052-H32 (b) alloys.

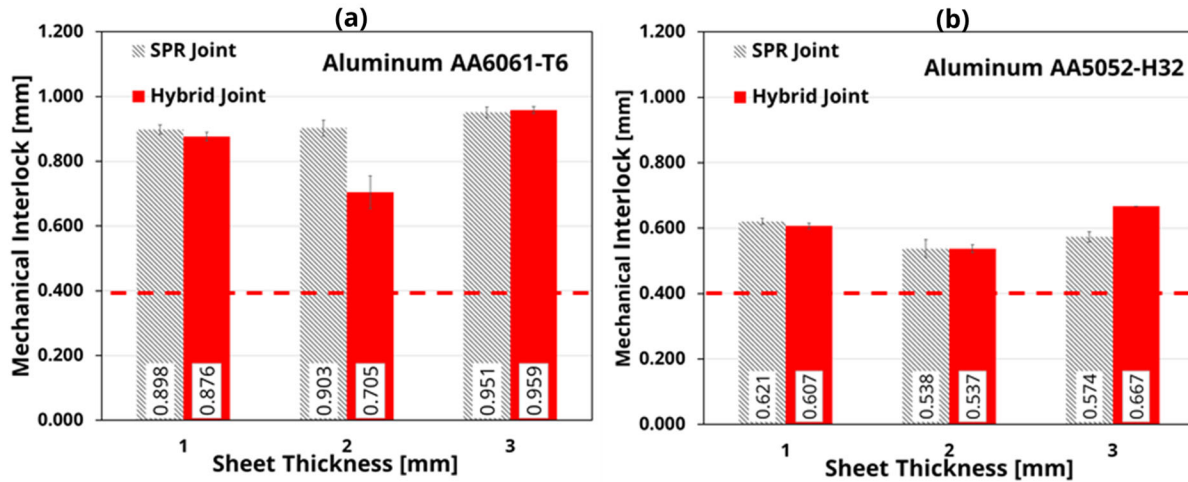


Fig. 4. Mechanical interlock measurements for SPR and hybrid joints with AA6061-T6 (a) and AA5052-H32 (b) alloys (dashed lines represent the minimum recommended value [28,29]).

The riveting parameters, such as insertion force, rivet characteristics, and die material and geometry, were identical for both alloys, so it could be inferred that the difference in mechanical interlock was caused by the mechanical properties of the alloy (*i.e.* ductility and formability). Importantly, the SPR rivets in the hybrid joints did not exhibit cracks, as has been observed in other hybrid joining studies [29]. Also, hybrid joining did not generally reduce the mechanical interlock of the AA6061 and AA5052 joints. A particular case, AA6061 (2+2) mm joints, demonstrated a 22% reduction in mechanical interlock relative to SPR joints, but the interlock was well above the minimum recommended threshold (Fig. 4. Mechanical interlock measurements for SPR and hybrid joints with AA6061-T6 (a) and AA5052-H32 (b) alloys (dashed lines represent the minimum recommended value [28,29])).).

3.2. Mechanical Performance Assessment of AA6061-T6 Joints

The force-displacement response for each joining method, illustrated according to sheet metal thickness, showed good repeatability and consistency (Fig. 5) with somewhat higher variability in the displacement at failure for SPR joints (Fig. 5b) and stiffness for the 3 mm hybrid joints (Fig. 5c). The displacement at failure variability of the SPR joints could be attributed to the progressive change in specimen compliance

as the SPR joint gradually lost the mechanical interlock after reaching the peak load. Hybrid joints with 3 mm sheet material demonstrated mechanical response variability, owing to the adhesive morphology changes (e.g. adhesive squeeze out, bond line thickness reduction, induced adhesive porosity) during the application of SPR rivet with uncured adhesive. The variability in the mechanical response of hybrid joints may explain a limitation and the often high variability in the commonly adopted SPR-adhesive hybrid joining processes.

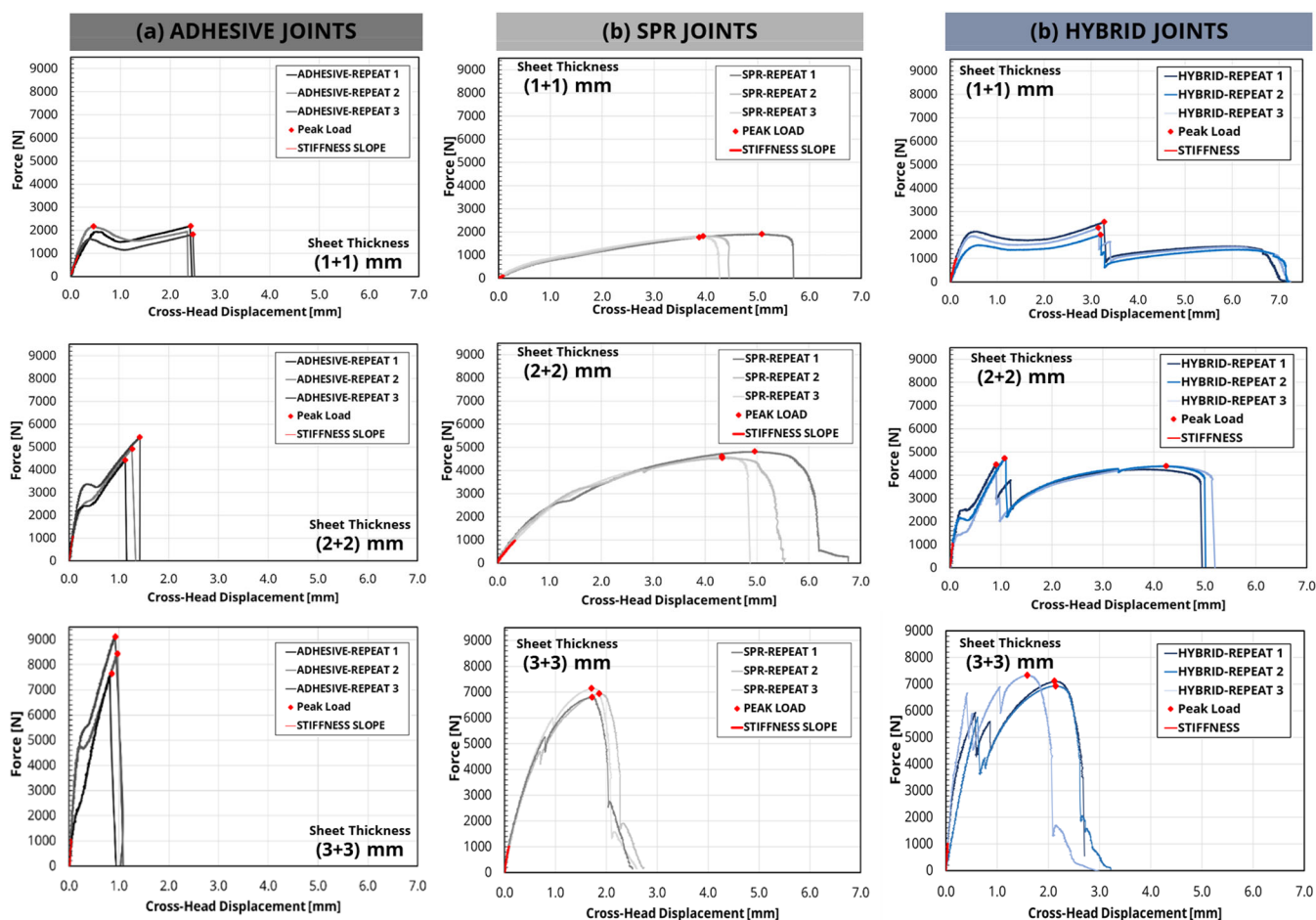


Fig. 5. Force-displacement response measurement of adhesive (column a), SPR (column b) and hybrid (column c) joints for aluminum AA6061-T6 alloy.

3.2.1. Adhesive Joints (AA6061-T6)

Adhesive joints exhibited an average peak load of 2.06 kN for the (1+1) mm joint, 4.92 kN for the (2+2) mm joint (139% increase over 1 mm joints), and 8.39 kN for the (3+3) mm joints (307% and 71% increase over the 1 mm and 2 mm joints, respectively) (Table 3). The load was initially distributed along the two

50 mm adhesive edges, which induced bending deformation at the radii of the section and initiated a crack along the adhesive edges (Adhesive Edges, Fig. 1a). The initial crack extension was followed by a crack arrest, causing the load to increase again. After that, the crack rapidly progressed toward the centerline as the load reached its peak, indicating some adhesive ductility. The joint failed abruptly after reaching the peak load, and cohesive failure was observed for all test specimens. Importantly, adhesive joints generally demonstrated higher peak load and stiffness when compared to SPR and hybrid joints. In contrast, the displacement at failure for adhesive joints was significantly lower than SPR and hybrid joining, attributed to the higher stiffness response and limited specimen deformation prior to failure. Therefore, adhesive joints showed the lowest energy absorption (Table 3), owing to the marginal contribution of specimen deformation and relatively low energy for adhesive crack propagation.

3.2.2. SPR Joints (AA6061-T6)

SPR joints failed at higher displacements relative to the adhesive joints, but generally demonstrated lower average peak loads of 1.84 kN, 4.66 kN and 6.96 kN for the (1+1) mm, (2+2) mm and (3+3) mm joints, respectively (Table 3). The average peak loads were 11%, 5.3%, 17% lower than those of the (1+1) mm, (2+2) mm, and (3+3) mm adhesive joints, respectively. The force-displacement curves (Fig. 5b) demonstrated a smooth, gradual degradation in stiffness up to the peak load, and unloading also continued with gradual softening until ultimate failure. The joints exhibited significant localized plastic deformation around the rivet, and the rivet tail lost the mechanical interlock with the bottom sheet, failing in a tail pull-out mode. While SPR joint stiffness was significantly lower compared to adhesive joints, the plastic strain energy stored during the localized specimen deformation increased the overall energy absorption of the SPR joints relative to adhesive joints (up to 352%).

3.2.3. Hybrid Joints (AA6061-T6)

254 The response of the hybrid joints appeared to follow those of the adhesive joints initially; however, when
 255 adhesive damage extended to the SPR rivet, the load dropped sharply, then the load-displacement
 256 response followed those of the SPR joints. The hybrid joints generally failed at displacement values close
 257 to those of the SPR joints. The average peak load of the hybrid joints made with 1 and 2 mm sheet
 258 material was comparable to the adhesive joints (difference of less than 8%) with no statistically
 259 significant difference (Table 3). The peak load corresponded to adhesive failure, suggesting that the
 260 mechanical interlock of SPR rivet is more relevant to the displacement at failure and energy absorption
 261 of the joint rather than peak load. The load response demonstrated two rapid decreases due to the
 262 discontinuity of the adhesive layer around the rivet, which was caused by adhesive squeeze out during
 263 rivet insertion. Importantly, the hybrid joints demonstrated the highest energy absorption, owing to the
 264 combined energy absorption mechanisms of adhesive and SPR joints. Another important aspect was that
 265 the mechanical performance benefits of hybrid joining were realized with a weight increase of less than
 266 5% (as low as 1%) relative to individual joints (Table 3).

267 **Table 3. Mechanical performance and joint-level morphology summary for the adhesive, SPR and hybrid joints made with**
 268 **aluminum AA6061-T6 alloy.**

Joining Method	Adhesive Joining			SPR Joining			Hybrid Joining		
	(1+1)	(2+2)	(3+3)	(1+1)	(2+2)	(3+3)	(1+1)	(2+2)	(3+3)
	mm	mm	mm	mm	mm	mm	mm	mm	mm
Peak Load (N)	2065 ± 202	4925 ± 507	8397 ± 736	1841 ± 71	4663 ± 143	6966 ± 179	2225 ± 76	4533 ± 180	7128 ± 199
Stiffness (N/mm)	6392 ± 1063	13959 ± 971	22109 ± 4930	1235 ± 252	2674 ± 189	10607 ± 1056	6869 ± 737	14348 ± 1104	13728 ± 3456
Energy Absorption (J)	3.84 ± 0.40	4.20 ± 0.96	4.83 ± 1.06	5.98 ± 1.35	19.00 ± 3.23	11.40 ± 0.59	9.18 ± 0.55	18.33 ± 0.10	13.79 ± 0.80
Bond line Thickness (mm)	0.443 ± 0.022	0.450 ± 0.023	0.427 ± 0.048	-	-	-	0.294 ± 0.005	0.280 ± 0.061	0.248 ± 0.029
Mechanical Interlock (mm)	-	-	-	0.898 ± 0.025	0.903 ± 0.043	0.951 ± 0.029	0.876 ± 0.022	0.705 ± 0.087	0.959 ± 0.018
Bonding Area (mm²)	928	928	928	-	-	-	829 (-10.7%)	809 (-12.8%)	763 (-17.8%)

Specimen Weight (grams) (% relative to adhesive joints)	21.45 ± 0.034	42.26 ± 0.139	68.40 ± 0.571	-3.0%	-0.6%	-0.4%	+4.5%	+1.6%	+1.0%
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3.2.4. Effect of Sheet Metal Thickness (AA6061-T6)

Two-way repeated-measures analysis of variance (ANOVA) revealed that the joining method and sheet thickness had significant effects on joint strength ($p < .05$, $\eta_p^2_{\text{joining method}} = .511$, $\eta_p^2_{\text{sheet thickness}} = .936$), stiffness ($p < .05$, $\eta_p^2_{\text{joining method}} = .849$, $\eta_p^2_{\text{sheet thickness}} = .856$) and energy absorption ($p < .05$, $\eta_p^2_{\text{joining method}} = .936$, $\eta_p^2_{\text{sheet thickness}} = .889$). A significant interaction was reported between the two independent variables, meaning that the effect of sheet metal thickness on joint strength, stiffness and energy absorption changed according to joining method. To isolate the statistical differences, Tukey post hoc pairwise comparison was undertaken. The post hoc comparison showed that the peak load values of the (1+1) and (2 + 2) mm joints were not significantly different among the three joining methods ($p > 0.4$, Fig. 6a). However, the joint strength of adhesive joints was significantly higher for the (3+3) mm joints, achieving 20.5% and 18% higher average peak load compared to SPR and hybrid joints, respectively. Interaction plots showed that adhesive, SPR and hybrid joints exhibited a relatively linear increase in joint strength by increasing sheet metal thickness (Fig. 6d) . A similar relationship was reported for adhesive SLJ joints by da Silva et al. [16], which suggests that the influence of adherend thickness on the strength of adhesive joints is likely linear regardless of loading orientation.

The stiffness response of adhesive joints was significantly higher than those of SPR (108%) and hybrid joints (61%) for the (3+3) mm joints; however, for the (1+1) and (2+2) mm joints, adhesive and hybrid joining were not statistically different ($p_{(1 \text{ mm})} = 0.990$ and $p_{(2 \text{ mm})} = 0.995$) (Fig. 6b), demonstrating significantly higher stiffness (up to 422%) compared to SPR joints. The stiffness of the adhesive joints

289 increased linearly with sheet thickness, which reduced the overall specimen compliance and
290 displacement at failure. Although the load at failure increased, the reduction in specimen deformation
291 and displacement at failure damped the energy absorption capabilities of the adhesive joints. In contrast,
292 SPR joints showed a nonlinear trend with a significant stiffness increase for the 3 mm joints. The SPR
293 joints made with 2 mm sheet material demonstrated significant localized deformation and slower rivet
294 tail pull-out progression, that led to somewhat higher displacement at failure relative to the 1 mm SPR
295 joints. However, when sheet thickness was increased to 3 mm, the SPR joint stiffness was about an order
296 of magnitude larger than 1 mm joints and did not show considerable localized yielding, which led to a
297 rivet tail pull-out at lower displacement at failure. In hybrid joints, an increase in stiffness was observed
298 from 1 to 2 mm, but from 2 to 3 mm, the stiffness was similar (Fig. 6e), highlighting the influence of
299 morphology (*e.g.* bond line thickness) on the mechanical performance of joints with thicker adherends.
300 The energy absorption values of SPR and hybrid joints were significantly higher relative to adhesive joints
301 ($p < 0.05$), demonstrating up to 352% higher energy absorption for the range of sheet thicknesses
302 considered (Fig. 6c). Sheet thickness did not show a statistically significant effect on the energy
303 absorption of the adhesive joints. In contrast, the energy absorption of SPR and hybrid joints changed
304 significantly according to sheet thickness and showed a maximum value for (2+2) mm joints (Fig. 6f). The
305 2 mm material demonstrated significant localized deformation around the rivet and maintained the
306 mechanical interlock with the rivet tail. On the contrary, the 3 mm material did not exhibit considerable
307 deformation prior to failure, leading to a reduction in the overall energy absorption of the joint.

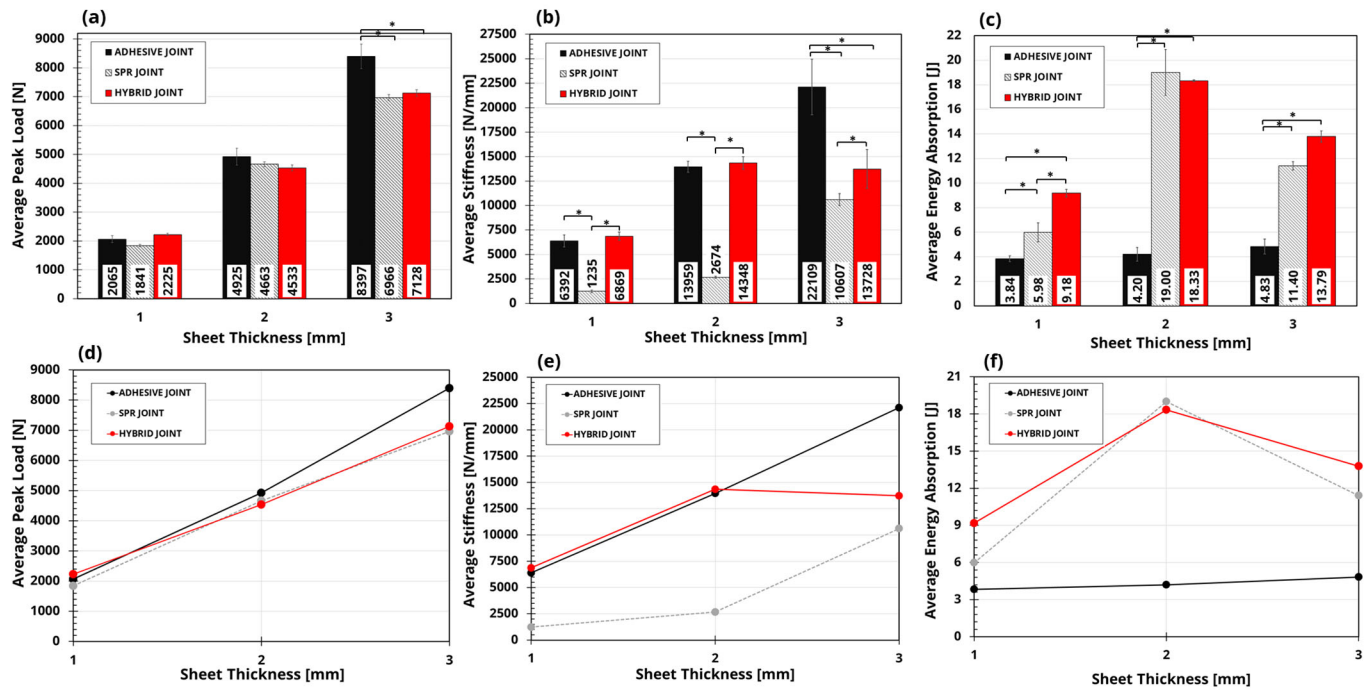
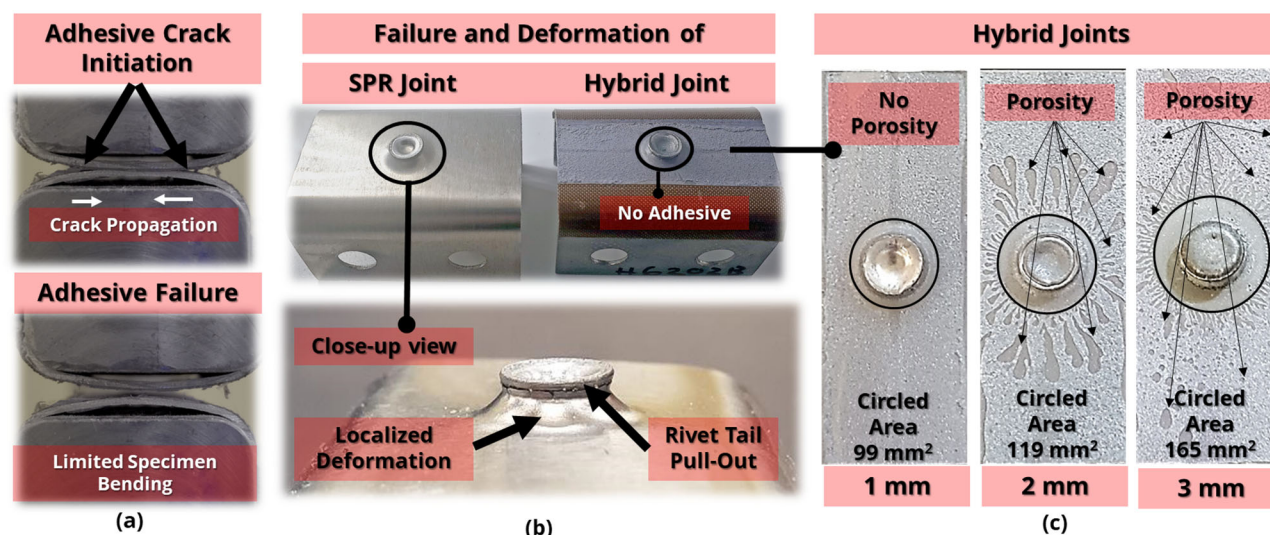


Fig. 6. Comparison charts and interaction plots of average peak load (a, d), stiffness (b, e), and energy absorption (c, f) for adhesive, SPR and hybrid joints made with aluminum AA6061-T6 alloy (* statistically significant different groups are marked and error bars represent standard error)

3.2.5. Failure Surface Analysis (AA6061-T6)

The failure surfaces demonstrated that adhesive specimens achieved a cohesive failure; thus, the strength of the adhesive was maximized for the joints assessed in this study. A crack initiated in the adhesive at the edges along the length of the specimen; then progressed toward the centre leading to joint abrupt separation (Fig. 7a). SPR specimens exhibited tail pull-out failure, indicating that the SPR mechanical interlock had a key role in determining SPR joint strength [17] (Fig. 7b). Hybrid joints exhibited crack initiation and progression similar to adhesive joints, followed by a rivet tail pull-out similar to SPR joints, combining the deformation mechanisms seen in adhesive and SPR joints. The failure surfaces of hybrid joints revealed a reduction in effective bonding area as a circular area around the SPR rivet showed no adhesive, attributed to adhesive squeeze out during SPR rivet insertion (Fig. 7c). The amount of squeeze-out varied according to the sheet thickness. The (1+1) mm joint experienced a 10.7% (99 mm²) reduction in the bonding area, while the (2+2) mm and (3+3) mm joints exhibited an area reduction of 12.8% (119 mm²) and 17.8% (165 mm²), respectively. In addition, the (2+2) mm joints had

325 porosity (air cavities) within the adhesive in the vicinity of the rivet, which was likely induced during the
 326 SPR insertion process. The higher SPR insertion force, required by the (3+3) mm joints, induced higher
 327 porosity in the adhesive, smaller in size but distributed throughout the bonding area. Importantly, the
 328 bonding area reduction did not significantly affect the hybrid joint peak load of the (1+1) and (2+2) mm
 329 joints. However, the (3+3) mm joints experienced a statistically significant reduction in joint strength and
 330 stiffness, which was attributed to the overall effect of reduced bonding area, reduced bond line thickness
 331 below the recommended manufacturer value (0.25 mm), and more extensive porosity closer to the
 332 boundaries of the adhesive. The porosity was likely induced by air pockets entrapped during adhesive
 333 flow (i.e. squeeze out), and increased due to the separation (gap) created between the sheets after
 334 forming the SPR joint. Similar sheet separation was reported for SPR joints applied to ultra-high strength
 335 steel [30]).



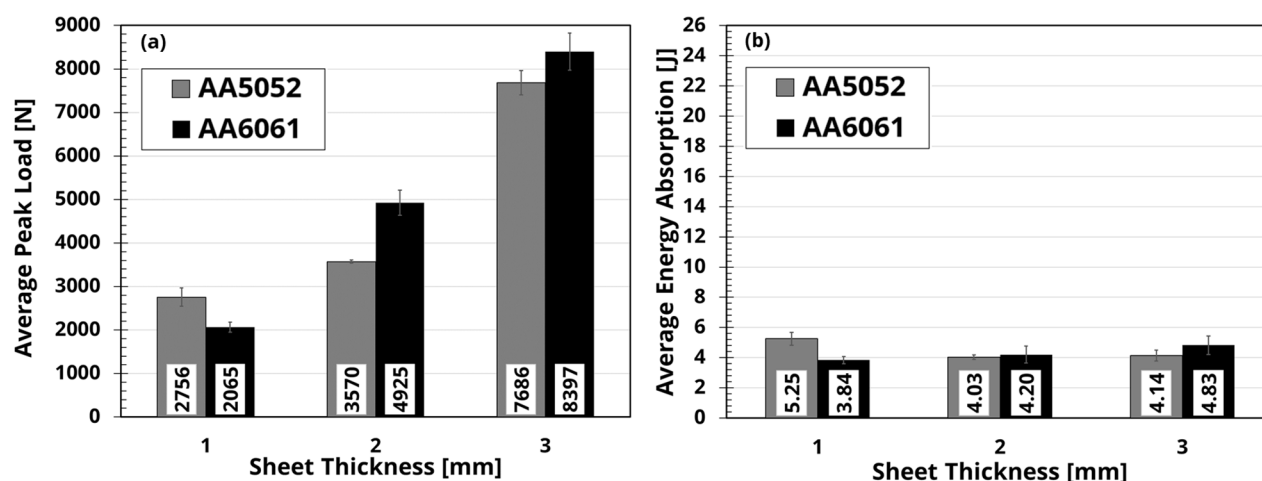
336 Fig. 7. Adhesive crack initiation and progression (a), localized deformation in SPR and hybrid joints (b) and failure
 337 surfaces of hybrid joints with three sheet thicknesses.
 338
 339

340 3.3. Comparison of Peak Load and Energy Absorption for AA6061-T6 and AA5052-H32 Alloys

341 3.3.1. Adhesive Joints

342 Alloy type showed a statistically significant effect on adhesive joint strength (Table 4), and joints with
 343 AA6061 alloy generally exhibited higher joint strength than the AA5052 joints (Fig. 8a). For example, the

344 (2+2) mm joints with AA6061 had a 37% higher peak load compared to AA5052 joints. In the case of 1
 345 mm joints, the AA5052 alloy exhibited yielding in specimen radius damping the edge effects and delaying
 346 adhesive crack initiation, which resulted in increased joint strength relative to AA6061 joints. Alloy type
 347 did not show a statistically significant effect on energy absorption or joint stiffness (Table 4). The energy
 348 was primarily absorbed to create new adhesive fracture surfaces, with limited energy required for
 349 specimen bending or plastic deformation. Therefore, the effects of sheet material properties on energy
 350 absorption were not significant (Fig. 8b). Considering adhesive joints made with both alloys, sheet
 351 thickness showed a strong correlation with joint strength (Spearman's correlation (ρ) = 0.939), moderate
 352 correlation with stiffness (ρ = 0.657) and weak correlation (ρ = 0.376) with energy absorption.
 353 To assess the compliance of H-specimens, the bonded H-specimen data from this study was compared
 354 to adhesive CT test specimens reported in the literature [16]. The (1+1) mm H-specimen made with
 355 AA5052 demonstrated a maximum displacement at failure of ~2.6 mm with a peak load of 2.75 kN, while
 356 similar CT specimens joining thicker sheet thickness (1.6+1.6 mm) failed at ~6.7 mm (more than 2.5
 357 times) with a peak load of 1.77 kN (-35.5%). The CT specimens are known to be more compliant
 358 compared to other geometries due to bending of the adherends [12], which leads to higher loading at
 359 the boundaries of the adhesive and earlier failure.



360
 361 Fig. 8. Peak load (a) and energy absorption (b) for adhesive joints made with AA6061-T6 and AA5052-H32 alloys.

3.3.2. SPR Joints

SPR joints with the AA5052 alloy had a generally lower peak load (-13%, -33% and -16% for the 1, 2 and 3 mm joints, respectively), which in part can be attributed to the lower mechanical interlock of the AA5052 joints. Although the effect of alloy type on the joint stiffness was not statistically significant, there was a significant effect on energy absorption (Table 4). The energy absorbed in SPR joints was attributed to localized plastic deformation of the sheet material around the rivet, where the lower strength and higher ductility alloy allowed for increased deformation prior to joint failure. The AA5052 alloy demonstrated higher energy absorption, relative to the AA6061 joints (Fig. 9), with the largest effect (89% increase) associated with the 3 mm sheet. The AA6061 alloy with 3 mm sheet thickness exhibited significantly lower localized deformation and higher stiffness relative to the other configurations, which led to early loss of rivet mechanical interlock and joint failure, while the AA5052 alloy demonstrated considerably higher energy absorption. Considering SPR joints made with both alloys, sheet thickness showed a strong correlation with joint strength ($\rho = 0.947$) and stiffness ($\rho = 0.913$), and moderate correlation ($\rho = 0.620$) with energy absorption.

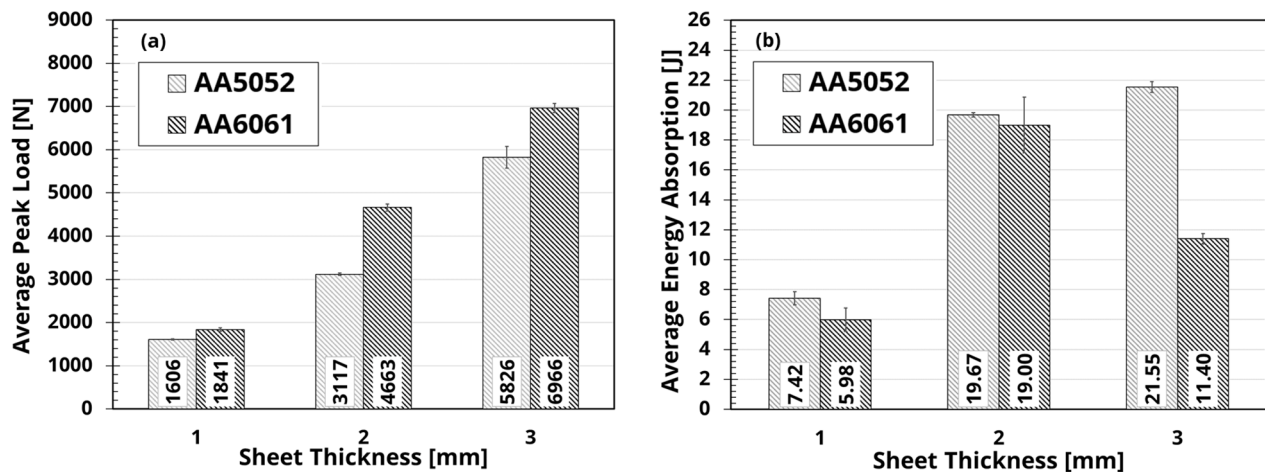


Fig. 9. Peak load (a) and energy absorption (b) for SPR joining of AA6061-T6 and AA5052-H32 aluminum alloys

3.3.3. Hybrid Joints

Alloy type had a statistically significant effect on the peak load, stiffness and energy absorption of hybrid joints (Table 4). Similar to adhesive joints, hybrid joining showed strong interaction effects between sheet thickness and alloy type, and joints made with A5052 alloy generally exhibited lower strength compared to AA6061 joints. Considering hybrid joints made with both alloys, sheet thickness showed a strong correlation with joint strength ($p = 0.982$), stiffness ($p = 0.828$), and energy absorption ($p = 0.737$). Importantly, comparing the strength data of adhesive (Fig. 8a) and hybrid (Fig. 10a) joints highlighted that the effect of alloy type on the strength of hybrid joints was less pronounced compared to adhesive joints. For example, while the 2 mm hybrid joints with AA5052 exhibited 17% lower strength relative to AA6061 joints (3.76 kN versus 4.53 kN, Fig. 10a), similar adhesive joints exhibited 27.5% lower strength for the same alloy. Importantly, the 3 mm hybrid joints with AA5052 exhibited a lesser reduction in strength (-1%), relative to the reduction in adhesive joints (-8.5%). It was evident that the alloy with lower strength damped the strength reduction of hybrid joints, which was observed with thicker sheet material. In addition, the AA5052 joints showed higher bond line thickness relative to the AA6061 alloy (Fig. 3), confirming that the lower strength alloy facilitated maintaining the adhesive joint morphology. The AA5052 hybrid joints demonstrated up to 70% (13.79 J versus 23.46 J) higher energy absorption, relative to the AA6061 joints. The AA5052 joints exhibited increasing energy absorption with sheet thickness and the maximum energy absorption was achieved by 3 mm joints (23.46 J) (Fig. 10b), attributed to increased deformation in the vicinity of the rivet, prior to ultimate failure. In comparison, the AA6061 joints exhibited the maximum energy absorption for 2 mm joints, owing to the reduced deformation and early loss of mechanical interlock in 3 mm joints. In general, hybrid joining improved energy absorption of the joints for both alloys relative to adhesive and SPR joints.

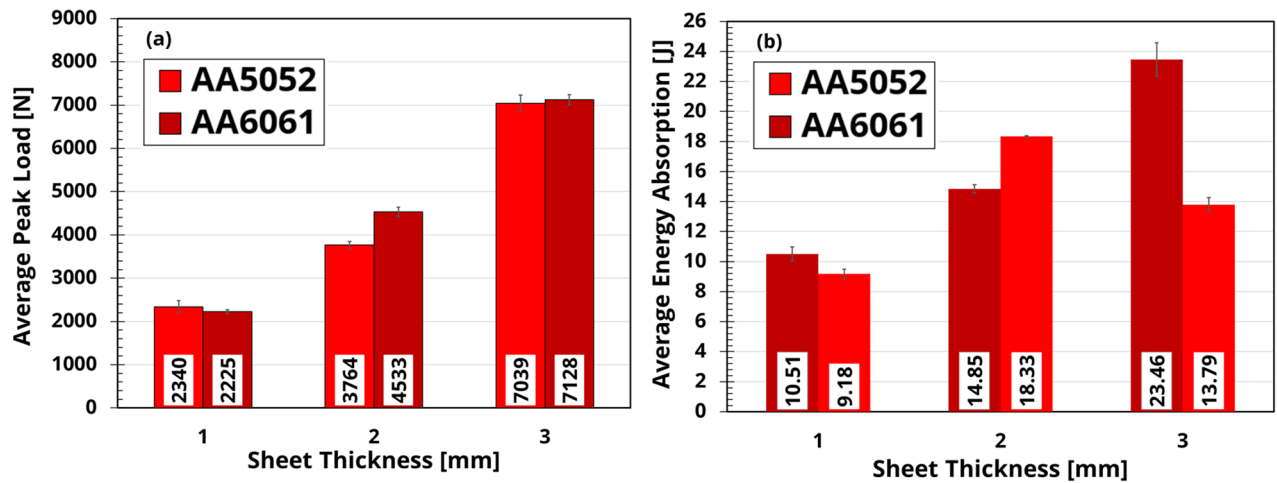


Fig. 10. Peak load (a) and energy absorption (b) of hybrid joints with AA6061-T6 and AA5052-H32 alloys.

Table 4. Two-way ANOVA and Tukey post hoc results testing the effect of sheet thickness and alloy type for each joining method.

Joining Method	Effects (Factors)	Two-Way ANOVA		
		Statistical Significance Effects		
Adhesive	Sheet Thickness	Significant $p < 0.05$	Not Significant $p = 0.223$	Significant $p < 0.05$
	Alloy Type	Significant $p = 0.05$	Not Significant $p = 0.603$	Not Significant $p = 0.136$
SPR	Sheet Thickness	Significant $p < 0.05$	Significant $p < 0.05$	Significant $p < 0.05$
	Alloy Type	Significant $p < 0.05$	Significant $p < 0.05$	Not Significant $p = 0.138$
Hybrid	Sheet Thickness	Significant $p < 0.05$	Significant $p < 0.05$	Significant $p < 0.05$
	Alloy Type	Significant $p < 0.05$	Significant $p < 0.05$	Significant $p < 0.05$

4. Conclusions

The H-specimens redesigned and used in this study provided reduced compliance relative to commonly used CT specimens, enabling the comparative assessment of three joining methods (adhesive, SPR and hybrid) while reducing the influence of adherend deformation. Joint morphology assessment confirmed that hybrid joining considerably reduced the bond line thickness of adhesive but did not have an adverse effect on the SPR joint formation. In general, the mechanical performance gains realized by adopting hybrid joining were dependant on the sheet properties and demonstrated a co-dependence on sheet thickness and aluminum alloy type (i.e. strength and ductility).

419 The study showed that aluminum joined with structural adhesive exhibited higher joint strength than
420 SPR joining, for tension loading. On the other hand, SPR joints demonstrated higher energy absorption
421 capabilities compared to adhesive joints, attributed to the localized plastic deformation in the vicinity of
422 the rivet. Hybrid joints achieved improved overall mechanical performance (strength, stiffness and
423 energy absorption) for joints made with 1 mm and 2 mm sheets, demonstrating peak load and stiffness
424 comparable to adhesive joints and energy absorption equal to, or higher than, the SPR joints. In the case
425 of 3 mm material, hybrid joining adversely affected the adhesive bond area, bond line thickness, and
426 resulted in adhesive porosity leading to a lower joint strength (up to -15%) and stiffness (up to -38%)
427 compared to similar adhesive joints.

428 Increasing sheet metal thickness significantly increased the peak load for all three joining methods. In
429 contrast, the effect of sheet thickness on energy absorption was complex and depended on alloy type
430 and joining method. For example, it was insignificant in adhesive joints, adverse in AA6061 SPR and
431 hybrid joints, when increased from 2 mm to 3 mm sheets, and desirable in AA5052 SPR and hybrid joints.
432 Alloy type had a significant effect on the peak load of adhesive, SPR and hybrid joints. The higher strength
433 alloy (AA6061) improved joint strength for all three joining methods, while the joints with the lower
434 strength and more ductile alloy (AA5052) generally demonstrated higher energy absorption capabilities
435 for SPR and hybrid joints. The alloy type did not have a significant effect on the energy absorption of
436 adhesive joints, attributed to the limited specimen deformation during the test. Importantly, the hybrid
437 joints demonstrated a non-monotonic co-dependence on alloy type and thickness, and the mechanical
438 performance benefits of hybrid joining relative to adhesive joints was inversely related to alloy strength
439 and sheet thickness.

440 Ultimately, the results highlighted important parameters in term of automotive structure design trade-
441 offs (e.g. sheet properties, mechanical performance, joining method and joint morphology) and the

442 statistical results provided evidence that hybrid joining can enhance the strength, stiffness and energy
443 absorption of adhesive and SPR joined structure with relatively thin sheet thickness and low material
444 strength. In longer term, the results from the present study may inform experimental testing and finite
445 element models to investigate complex structures subject to impact loading (e.g. side impact structures).

446

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