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RESEARCH ARTICLE

Investigating the Structural Strength of Al5052-PVC-Al5052 Sandwich Sheets Using Lap-Shear and T-Peel Testing

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ABSTRACT – The sheet metal forming process stands as a cornerstone in metal forming operations, boasting broad applications across diverse sectors such as automotive, aerospace, and marine industries. With a history spanning over four decades, it remains an irreplaceable method. However, the ongoing emphasis on optimizing strength-to-weight ratios has spurred researchers to explore alternative approaches. Among these, the fabrication of sandwich sheets has emerged as a promising concept, maintaining the desired balance between strength and weight. The present work aimed to fabricate and test Al5052 base sheet material (Lap shear test) and Al5052-PVC-Al5052 sandwich sheets (Lap shear and T-Peel Tests) in various rolling direction combinations. For Lap shear test three different types of test samples were made by riveting such as base material (1 mm thickness), base material with PVC 0.5 and 1mm thickness in lap area. These lap shear test specimens were made in different rolling direction combinations, for instance, with base sheet (0°-0°,45°-45°, 90°-90°, 0°-45°, 90°-45° and 0°-90°).T-Peel test performed with the sandwich material with PVC 0.5mm thickness in different rolling directions. Based on the study, the primary outcomes were identified in terms of the maximum shear strength and pulling force. Additionally, the failure mechanisms were observed, particularly in the rivet zone of both the base and sandwich sheets. Maximum Lap shear strength shown for the base is 2.344 kN (90°-45°), PVC 0.5mm thickness is 2.674 kN (45°-PVC-45°), and PVC 1mm thickness is 2.460 kN (90°-PVC-45°). The maximum peeling force in T-Peel test with PVC 0.5mm thickness is 71.1 kN (45°-PVC-45°). The results indicate a significant enhancement in both maximum shear strength and peeling (pulling force) due to the presence of PVC.

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1. INTRODUCTION

The integration of metals and polymers in sandwich sheets and panels has been increasingly prevalent in the automotive sector. This trend reflects a growing interest in leveraging the unique properties of both materials to enhance various aspects of vehicle design, including weight reduction, structural integrity, thermal insulation and acoustic performance. The combination of metals and polymers offers engineers and manufacturers a versatile solution to meet the evolving demands of automotive applications, contributing to advancements in safety, efficiency and sustainability in the industry [1, 2]. Numerous authors have dedicated their research efforts to the topic of sandwich sheets and panels combining metals and polymers from as early as 1992 up to the present day. Several significant contributions have been identified, each illuminating key advancements in the field. Undoubtedly, their respective studies have collectively advanced the understanding and application of sandwich sheets and panels combining metals and polymers in the automotive industry, providing the way for continued innovation and integration of these materials into new vehicle designs.

Mantel and Descaves (1992) [3] described the T-Peel test using a metal-polymer-metal sandwich sheet to investigate the impact of the metallic substrates' plastic deformation on the peel energy. Their study concluded that, depending on the metal sheets' prior curvature, the peel force is either higher or lower than the initial force. Song and Yu (2002) [4] measured the T-Peel strengths using a copper-chromium-polyimide system with different metallic layer thicknesses and radio frequency plasma pretreatment settings. In contrast to the results of the 90° peel test, the measured peel strength revealed a reversed camel back shape against the thickness of the metal layer. In the year 2003, Kim et al. [5] created a sandwich sheet made of Al5182-polypropylene-Al5182 by using roll bonding at 140°C. The analysis revealed that the sandwich sheet has a lower strain-hardening exponent than the aluminum skin and higher strain rate sensitivity for the sandwich sheet than the aluminum skin. Its higher formability relative to the skin sheet was primarily due to its greater thickness. Kawashita et al. (2005) [6] evaluated the bonding strength of metal-polymer laminates for aerospace applications by analyzing peel tests such as T-peel and fixed-arm peel at three peel angles (i.e., 45°, 90° and 135°). In the year 2010, Balod [7] employed anisotropic yield functions proposed by Hosford (1979) and Barlat & Lian (1989) along with the Marciniak-Kuczynski theoretical analysis to compute the forming limit diagrams (FLDs) of AA5182/poly-(propylene)/AA5182 sandwich sheets. Their study revealed that the limit stress value in the AA5182 skin sheet exceeded that of the sandwich sheets.

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Carradò et al. (2011) [8] commissioned high-quality austenitic steel and aluminum alloy sheets considered to be surface layers in roll bonding and simultaneously press heating processes to produce laminated sandwich sheets. They undertook a few tests and formed operations on their fabricated sandwich sheets, aiming to compare the results with the industrially manufactured materials intended mainly for automotive applications. Another series of experiments by Sokolova et al. (2011) [9] examined the formability of metal-polymer-metal (MPM) sandwich composites with various solid and mesh steel inlays. Comparing sandwiches with round solid inlays to those with mesh steel inlays, there was a slight increase in thinning with the mesh steel inlays. Charde et al. (2013) [10] investigated by changing the welding currents and electrode pressing forces. The experiment was carried out on dissimilar weld joints made of carbon steel and 304L (2B) austenitic stainless steel. One of the main conclusions is that while higher electrode force has a negative effect on weld development, the increasing welding current promotes it. Heat imbalance brought on by varying material characteristics was also noted. To evaluate the quality of the weld, the welded specimens were examined for tensile strength, hardness and metallurgical characteristics. Harhash et al. (2015) [11] fabricated sandwich laminates using a roll bonding technique consisting of 0.49 mm deep-drawing steel skin sheets and a 0.6 mm polypropylene-polyethylene copolymer core. The study examined the laminate's forming behavior, mechanical properties and bonding strength through lap shear tests. The results indicated no significant change in lap shear strength over time.

The mechanical characteristics of quiet aluminum AA6061-T4 skin laminate with non-structural loads were investigated and compared by Ferrari F. (2017) [12]. The sandwich composite's adhesion mechanism was investigated using the T-Peel test, metallographic cross-sectioning technique, self-piercing rivet evaluation and roughness measurements. Satheesh et al. (2018) [13] took a broader approach to see the adhesion mechanism of different material layers (plies). They used the T-Peel test to measure the force needed to separate the layers and compared it to a different method (wedge peel test). They even created a computer model to understand how the friction between the layers affects the results. Aziz Shah et al. (2019) [14] examined the modeling of laser stitch welds in automobile constructions with particular attention to different element connectors such as rigid body, shell, bar and area contact models. Their study highlighted that the inclusion of residual stress and heat-affected zones (HAZs) produced during the welding process has significance to the model's accuracy. Wendel (2019) [15] experimented and suggested that sandwich materials are the best fit as lightweight panels and can be used in automobiles for better efficiency. Using several experiments and theoretical research, Aday (2019) [16] developed the phenomenon to reduce the spring back in rectangular plates of 3105 aluminum alloy and 1020 low carbon steel with 1, 1.5 and 2 mm thicknesses. He experimented with a 50 mm radius die profile to fabricate a laminated sheet, and from the results, it is quite clear that the amount of spring back decreased with increasing plate thickness for low carbon steel and aluminum. In the year 2020, Baptista et al. [17] worked on the efficiency and performance of the lap joints of metal-polymer sandwich composites with the help of a unique joining methodology using inserts in the forming process. They found that the geometry and size of the inserts used played an important role in determining the quality of the joint. Zarei et al. (2020) [18] experimentally studied the failure modes in silicone-based adhesive joints peeling from plastic substrates with varied surface roughness and controlled thickness. They discussed their impact on adhesion energy and failure modes under 90^0 and 180^0 peeling angles. They concluded that the substrate roughness increased the adhesion energy in 90^0 peeling tests. Kazemi et al. (2020) [19] examined the forming characteristics and failure mechanism of AA5754- poly-(ethylene)- AA5754 fabricated sandwich composites with the help of stretch forming, bending and tensile strength. They tried to establish a correlation between them using numerical methods, and with their findings, they suggested replacing pure aluminum sheets with this fabricated composite panel. Redmann et al. (2021) [20] evaluated block shear and single-lap test methods for adhesively bonded composite joints. Their findings indicate that the block shear joint serves as an alternative test method, minimizing normal stresses through compressive-shear loading and a more compact sample geometry. Queiroz et al. (2021) [21] investigated adhesive bonding in natural fiber-reinforced polymer composites, emphasizing cost-effective and sustainable materials for the automotive sector. Their study analyzed hybrid adhesive joints composed of interlaminar hybrid fiber-reinforced composites, integrating both natural and synthetic materials. It examined the influence of interlaminar synthetic layers on joint performance compared to fully synthetic glass fiber-reinforced polymer (GFRP) joints. Their results showed that increasing the number of synthetic layers in hybrid jute/glass-adhered joints improved failure load, with the three-layer hybrid joint exhibiting 28.6% higher failure load than the two-layer joint.

Kella (2022) [22] investigated springback analysis and formability of Al5182/polypropylene/Al5182 sandwich laminates. A comparative study was conducted to determine the polypropylene core's effect on the formability of sandwich laminates with monolithic aluminum sheets and validate predicted forming limit curves with experimental data. Zakki et al. (2022) [23] investigated the mechanical behavior of glass fiber-reinforced polymer (GFRP) composites under tensile loading using finite element analysis (FEA). Their findings demonstrate that FEA effectively captures the specimen's response during tensile testing. When compared to experimental data, the maximum deviation in the calculated stress-strain diagram ranges from 16.5% to 32%, with larger discrepancies observed at greater fiber orientation angles. This deviation is attributed to the increased influence of polymer behavior at higher orientation angles, which leads to nonlinear material responses. Katsivalis et al. (2022) [24] investigated the effects of moisture on glass/steel adhesive joints, which are increasingly used in construction. The study employed cohesive zone modeling in Abaqus 2020 to predict moisture ingress and its impact on bond strength using a multi-physics numerical approach. The model was validated through double lap shear testing and experimental data from the double cantilever beam (DCB). The results indicate that the model effectively predicts critical exposure times for joint degradation, providing valuable insights for lifetime prediction and engineering guidance. In a recent study, Yang et al. (2023) [25] developed a new FLD for electrogalvanized steel/polyamide-6/electrogalvanized steel sandwich composites consisting of 0.6 mm electrogalvanized steel and 1 mm polyamide-6. The study examined the influence of interfacial adhesion on the formability of the sandwich composites, ultimately identifying the optimal conditions for enhanced adhesion. Ibrahim et al. (2023) [26] fabricated five composite designs using various woven fiber types and self-reinforced polypropylene sheets via the hand lay-up technique. Tensile and three-point flexural tests assessed their mechanical properties, revealing that carbon fiber-reinforced plastic (CFRP) exhibited the highest tensile performance with a 33% higher elastic modulus and 46% greater tensile strength than carbon/aramid fiber-reinforced plastic (CAFRP). The study concludes that while self-reinforced polypropylene composites enhance toughness at the cost of stiffness, fiber-reinforced plastics offer high strength and stiffness but have low elongation. The rolling direction can significantly impact the material's structural strength, its effect on the mechanical properties is minimal [27]. Reddy et al. (2024) [28] investigated the formability of AA5052-PVC-AA5052 sandwich sheets, emphasizing the impact of rolling direction on mechanical properties through uniaxial tensile testing with significant implications for lightweight structural design, later the same group (2024) [29] investigated and highlighted the effect of anisotropy on the strength, ductility and failure mechanisms in both monolithic and sandwich structures. Glaser et al. (2025) [30] investigated the joint strength and forming of a polymer-metal composite - polyamide 6 and stainless steel (X5CrNi18–10) using reactive Al/Ni multilayer foils for optimizing the surface structuring to know the possible causes of crack initiation at the interface.

From the existing works and published papers, it has been noted that the significance and applicability of aluminum sandwich sheets in various industries are increasing day by day. Simultaneously, further investigation on strength and load-carrying capacity is needed to evaluate them. Moreover, the adhesive strength of materials using the anisotropic behavior (with respect to rolling direction) of Al5052-PVC-Al5052 sandwich sheets in the lap shear and T-Peel tests is not attempted much in the literature. Hence, the present work aimed at determining the structural/mechanical strength of Al5052-PVC-Al5052 sandwich sheets through T-peel and Lap shear tests.

2. MATERIALS AND METHODOLOGY

In order to fabricate the base sheet and Al5052-PVC-Al5052 sandwich composite sheets, Al5052 skin sheets with a 1mm thickness (base sheet and sandwich sheet), for the sandwich sheets polyvinyl chloride (PVC) as a core with a 0.5mm and 1mm thickness were chosen for Lap shear and 0.5mm PVC chosen for the T-Peel tests. The manufacturer confirmed that the PVC core has a hardness range of 35-55 parts per hundred resin (PHR). During fabrication, base sheets and Al5052-PVC-Al5052 sandwich sheets for the testings are produced using a conventional method. The process involves mixing equal volumes of resin and hardener (Araldite Standard) until a uniform color is achieved. As per the guidelines, the surfaces of the skin sheets of Al5052 were deeply cleaned to remove any impurities on the surface. The adhesive mixture was then applied thinly onto both surfaces of the Al5052 sheets. The required pressure was applied; hence, proper clamping was used to consistently adhere to the excessive adhesive between them, thus allowing proper bonding. The applied pressure was maintained for 6-8 hours to facilitate adequate bond formation. The assembled sandwich sheets were then stored for a full day at room temperature after the idle time before their use in testing. The chemical composition of the specimen was analyzed using a Spectromax spectrometer (Make: Ametek), revealing the composition of the base metal, an Al5052 alloy sheet with a thickness of 1 mm, as presented in Table 1. Table 2 provides details on the thickness considerations for Lap Shear and T-Peel tests, and Figure 1 illustrates the adopted work methodology.

Table 1. Chemical composition of base metal Al5052

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
Wt.%	0.059	0.28	0.004	0.074	2.26	0.23	0.005	Remaining

Table 2. Details of thickness consideration during Lap shear and T-Peel tests

Type of tests ⇩	Base metal Al5052-Al5052 (Al5052 1mm)	Sandwich material Al5052- PVC-Al5052 (Al5052 1mm, PVC 0.5mm	Sandwich material Al5052- PVC-Al5052 (Al5052 1mm, PVC 1mm)
Lap shear test	2mm	2.5mm	3mm
T-Peel test	-	2.5mm	-

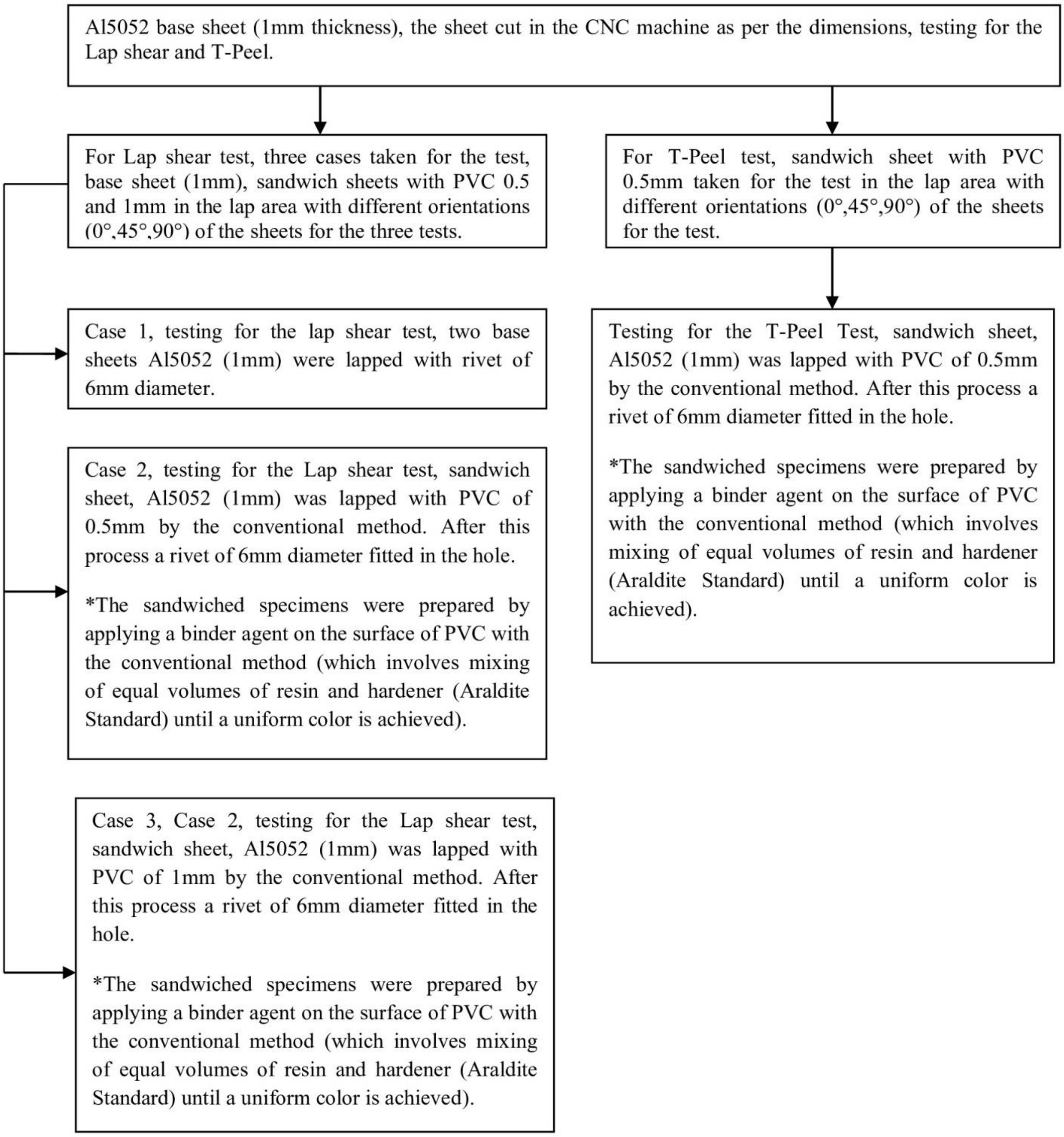
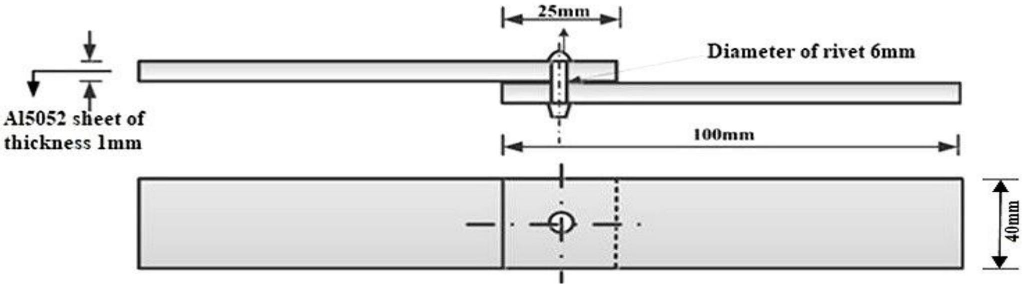


Figure 1. Work methodology

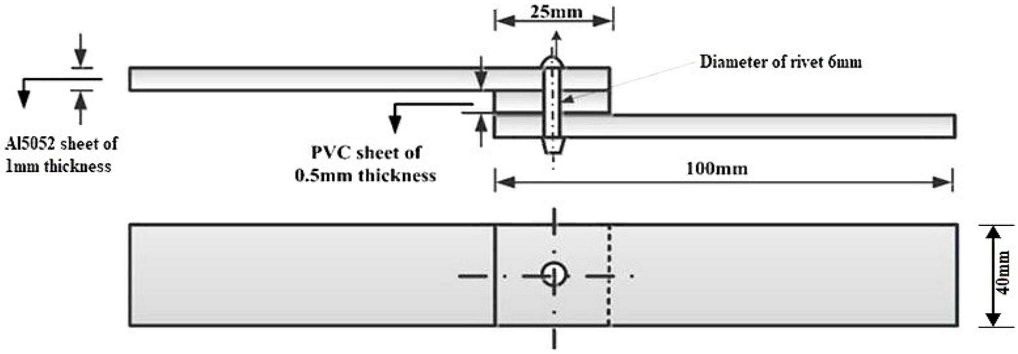
2.1 Lap Shear Test with Single Riveting

Samples were fabricated from the Al5052 sheet using a CNC machine by rolling it in three different directions: 0° (parallel to the rolling direction), 45° (diagonal), and 90° (perpendicular). Additionally, sandwich sheets were produced using various combinations of rolling directions with Al5052, such as 0°-P-0°, 45°-P-45°, 45°-P-0°, 45°-P-90°, 0°-P-90°, and 90°-P-90°, where "P" represents PVC. The bonding strength of these samples was then evaluated through lap shear testing following ASTM D3165 standards. The schematic representation of the samples used for lap shear tests with a single riveting system is depicted in Figure 2.

Three types of test samples were prepared for riveting: (1) samples made solely of the base material, (2) samples incorporating a 0.5 mm PVC layer in the lap area, and (3) samples with a 1 mm PVC layer in the lap area. Lap shear test specimens were fabricated using various rolling direction combinations for the base material, including (a) 0°-0°, (b) 45°-90°, (c) 45°-0°, (d) 45°-45°, (e) 90°-0°, and (f) 90°-90° (refer Figure 3). For sandwich materials, rolling direction combinations were applied as follows: (a) 0°-P-0°, (b) 45°-P-45°, (c) 45°-P-0°, (d) 45°-P-90°, (e) 0°-P-90°, and (f) 90°-P-90° for sandwich sheets with PVC thicknesses of 0.5 mm (refer Figure 4) and 1 mm (refer Figure 5). Subsequently, the samples were taken for testing on an MCS dual columnar universal testing machine (UTM) with an attached crosshead speed of 1 mm/min, where one (bottom) end of the specimen was fixed, and the other (upper) end was subjected to pulling force in the vertical direction.

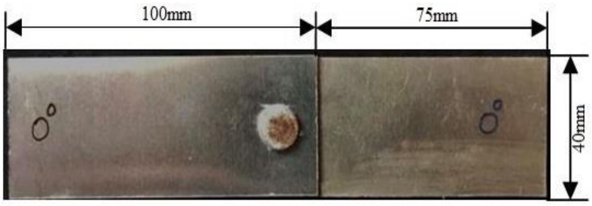


(a)

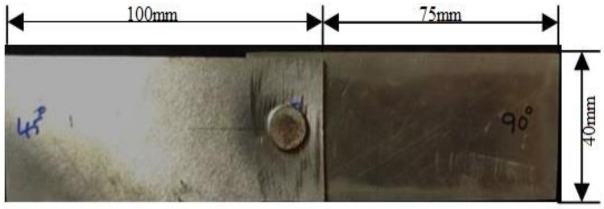


(b)

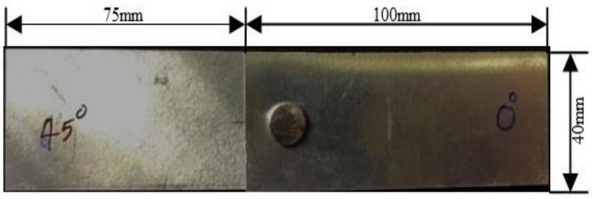
Figure 2. Schematic representation of lap shear tests with a single riveting system (a) without PVC; (b) with PVC



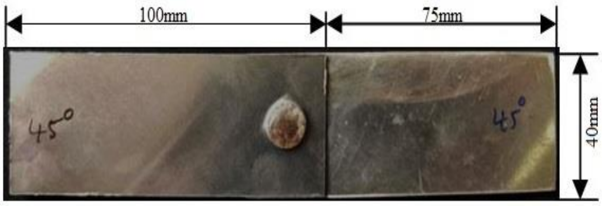
(a) 0°:0°



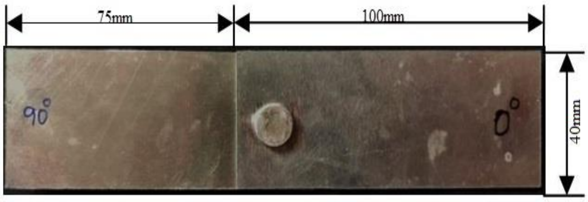
(b) 45°:90°



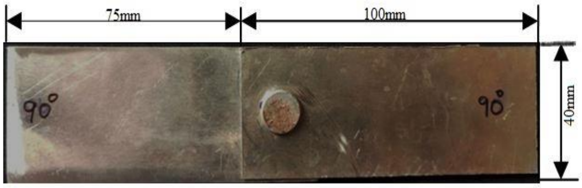
(c) 45°:0°



(d) 45°:45°

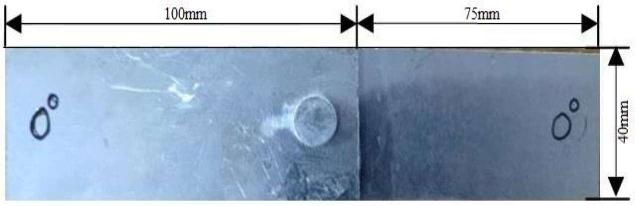


(e) 90°:0°

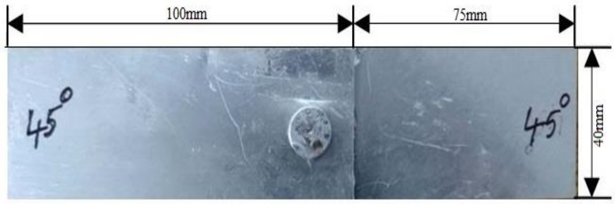


(f) 90°:90°

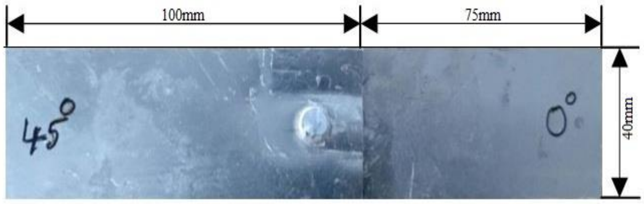
Figure 3. Lap shear testing specimens of base Al5052 sheet



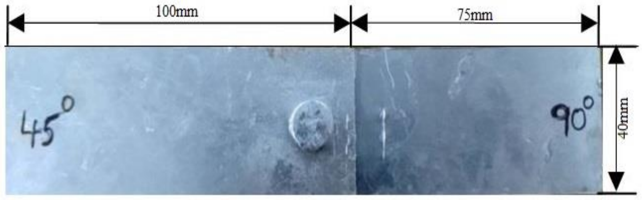
(a) 0°:P:0°



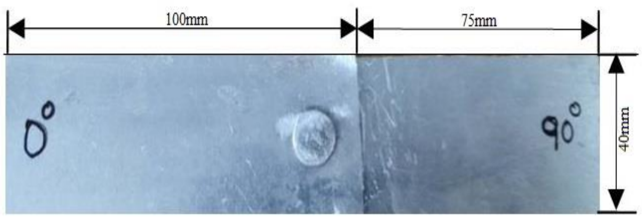
(b) 45°:P:45°



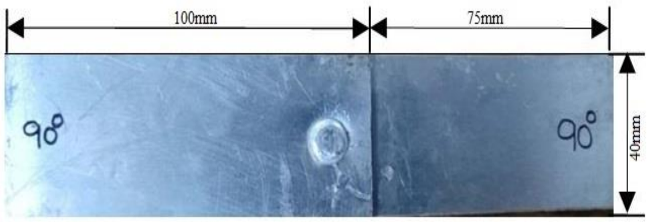
(c) 45°:P:0°



(d) 45°:P:90°

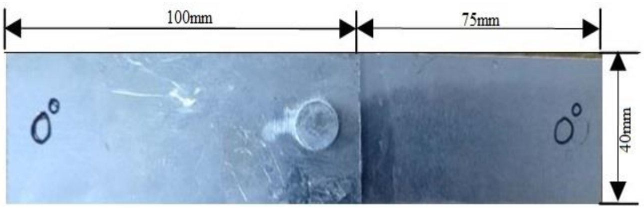


(e) 0°:P:90°

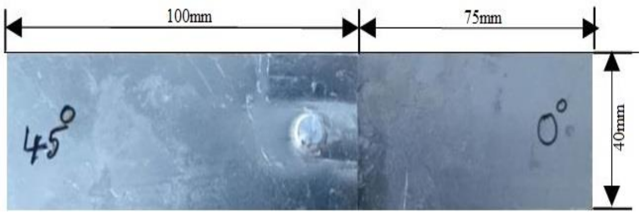


(f) 90°:P:90°

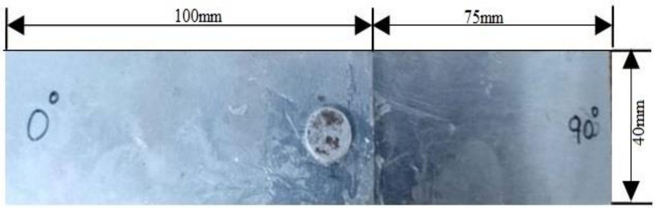
Figure 4. Lap shear testing sandwich sheet specimens with 0.5mm thickness PVC



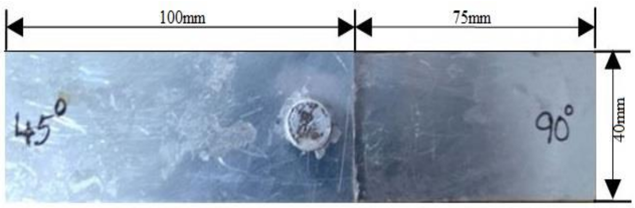
(a) 0°:P:0°



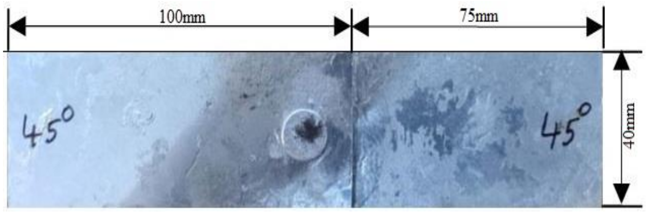
(b) 45°:P:0°



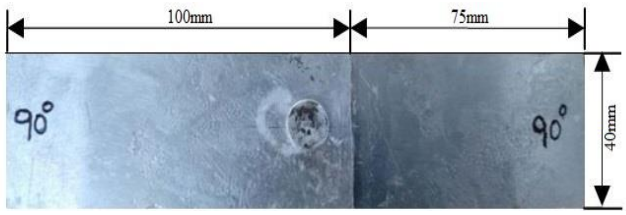
(c) 0°:P:90°



(d) 45°:P:90°



(e) 45°:P:45°

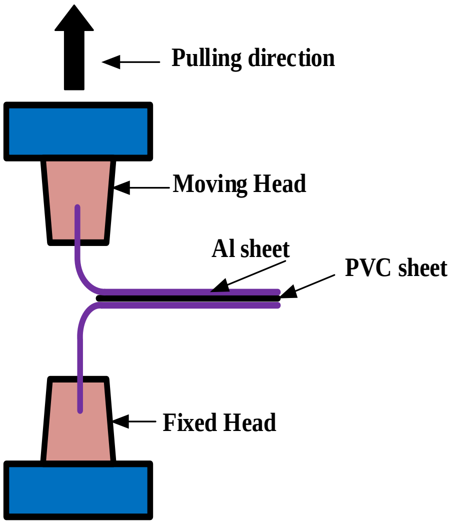


(f) 90°:P:90°

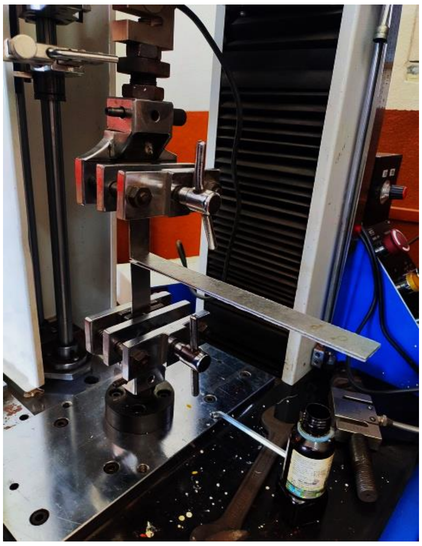
Figure 5. Lap shear testing sandwich sheet specimens with 1mm thickness PVC

2.2 T-Peel tests

A universal testing machine (UTM) was utilized to perform the T-peel test. Its grips were used to hold two flexible substrates that were bonded together. One substrate was positioned to stick up, while the other was oriented downwards, forming a "T" shape horizontally along the bonded region. Figure 6(a) illustrates the schematic representation of the T-peel test setup on a UTM. For the test, base material (Al5052) skins and PVC core sandwich sheets were cut into dimensions of $60mm \times 10mm \times 0.5mm$, while the PVC sheets were cut into dimensions of $60mm \times 10mm \times 0.5mm$. These dimensions ensured consistency and accuracy in the testing process.



(a)



(b)

Figure 6. (a) The specimen position for the T-peel test is shown schematically and (b) Clamped laminated sheet onto the UTM for T-peel test

Figure 6(b) illustrates the laminate position securely gripped onto the tensile machine along with its conceptual representation. It is important to carefully capture the correct load using the tensile machine and its crosshead position during the test, and those are the most crucial parameters used to determine the peel resistance of the laminate. As the tensile machine applies force, the laminate undergoes peeling at the bonded interface between the layers. The recorded load and the displacement of the crosshead provide valuable data that can be used to calculate the peel resistance, which is a measure of the bonding strength between the layers.

The sandwich sheets of Al5052-PVC-Al5052 samples were examined in this study and were tested with various combinations of rolling directions on Al5052, for example, (a) 0°-P-0°, (b) 0°-P-45°, (c) 45°-P-45°, (d) 45°-P-90°, (e) 0°-P-90° and (f) 90°-P-90° (shown in Figure 7 is 0°-P-0°). These combinations allowed for the evaluation of the peel resistance of the sandwich sheets. Six sandwich sheets were subjected to peel resistance testing following ASTM D1876 guidelines [31]. The result of the test, in addition to the load-displacement graphs, was the determination of the average peel strength. This parameter provided valuable insights into the bonding strength between the Al5052 skins and the PVC core in the sandwich sheets, allowing for comparisons between different rolling direction combinations.

Before Adhesive

After Adhesive

Figure 7. T-Peel test sandwich sheet sample of 0°-P-0°

3. RESULTS AND DISCUSSION

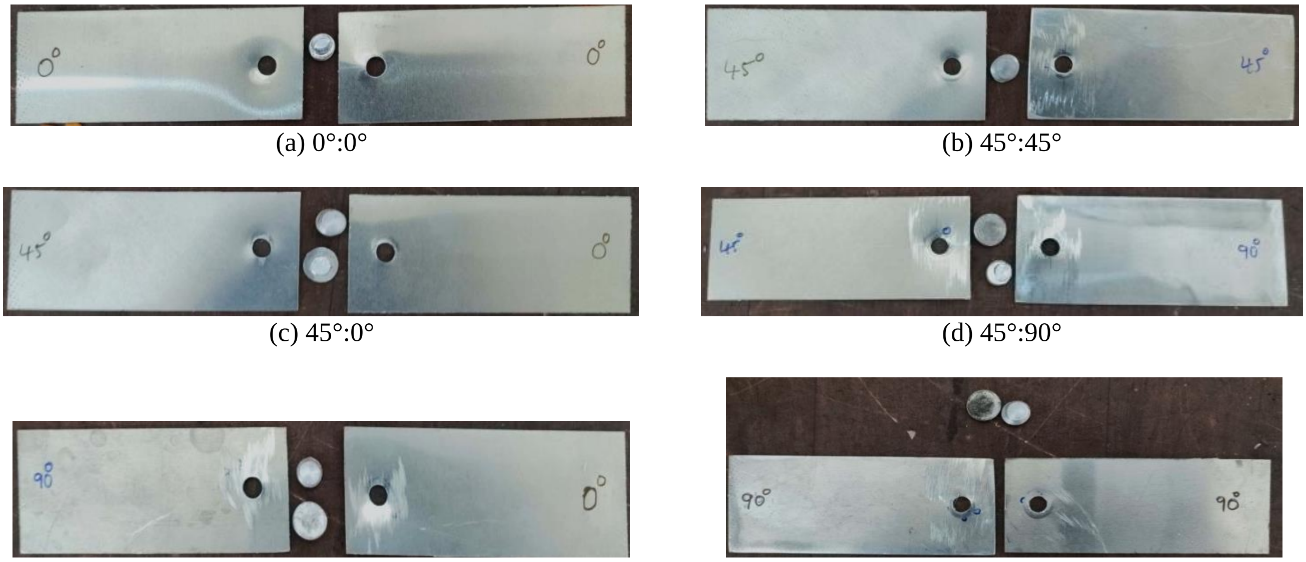
3.1 Lap Shear Test

As mentioned in Section 2, the lap shear tests were performed on the base materials (with the same and different rolling directions combinations) using a single rivet system. The bonding strength has been evaluated as per ASTM D3165 standards.

Lap shear test has been performed by categorizing in three cases such as,

- Case 1: Only Al5052 sheets of similar and different rolling combinations.
- Case 2: Al5052-PVC-Al5052 sandwich sheets of similar and different rolling combinations with 0.5mm thickness PVC.
- Case 3: Al5052-PVC-Al5052 sandwich sheets of similar and different rolling combinations with 1mm thickness PVC.

Case 1: Only Al5052 sheets of similar and different rolling combinations



(a) 0°:0° (b) 45°:45°

(c) 45°:0° (d) 45°:90°

(e) 0°:90° (f) 90°:90°

Figure 8. Al5052 sheets of similar and different rolling combinations without PVC with a single riveted system after test

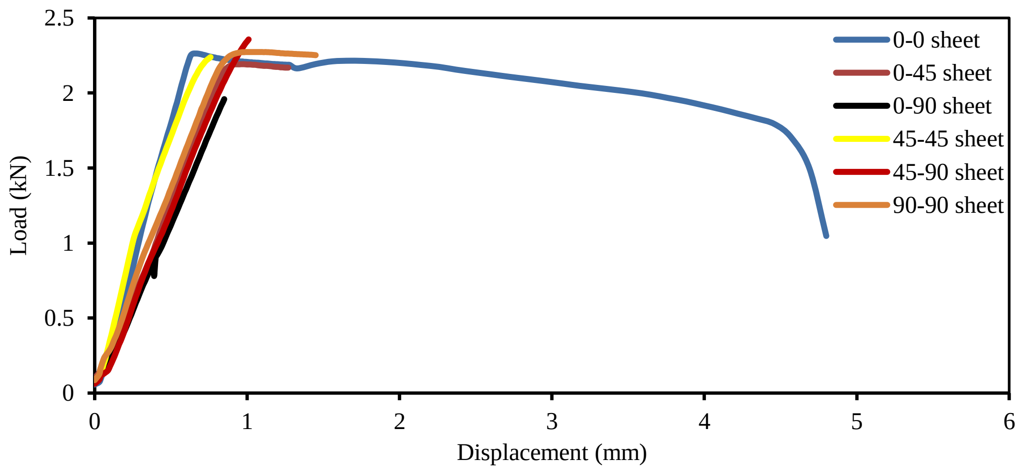


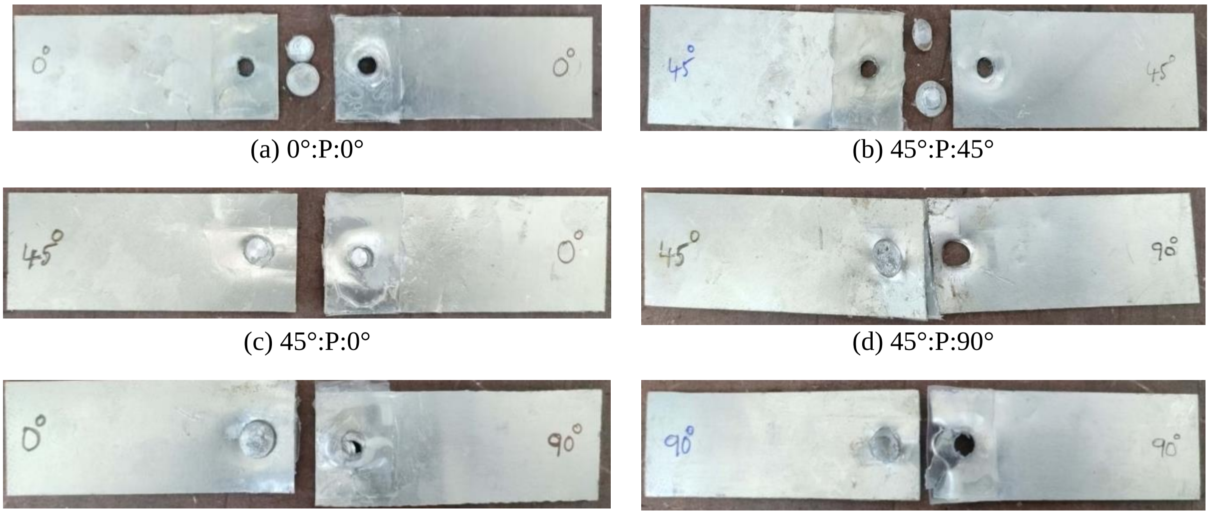
Figure 9. Load vs. Displacement of Al5052 sheets without PVC with a single riveted system after lap shear test

Table 3. Maximum lap shear strength of Al5052 sheet samples

Sample No. →	1	2	3	4	5	6
Rolling combination	0°- 0°	45°-45°	45°-0°	45°-90°	0°-90°	90°-90°
Maximum shear strength (kN)	2.250	2.186	2.160	2.344	2.105	2.249

Figure 8 illustrates the rivet failure phenomenon observed during testing. The failure pattern remained consistent across similar and different rolling direction combinations, although the load-bearing capacity varied. The load vs. displacement behavior for each sheet is plotted in Figure 9. Among the tested sheets, the 45°-90° sheet exhibited the most complete deformation, followed by 0°-0°, 90°-90°, 45°-45°, 45°-0° and 0°-90°. Notably, the 0°-90° sheet failed before reaching its maximum load capacity, indicating insufficient deformation. This behavior was consistently observed in multiple repetitions, suggesting the need for further testing to refine data accuracy. The maximum strength recorded for each sheet is summarized in Table 3. The highest strength was achieved by the 45°-90° sheet (2.344 kN), followed by 0°-0° (2.250 kN), 90°-90° (2.249 kN), 45°-45° (2.186 kN), 45°-0° (2.160 kN), and 0°-90° (2.105 kN).

Case 2: Al5052-PVC-Al5052 sandwich sheets of similar and different rolling combinations with 0.5mm thickness PVC



(a) 0°:P:0° (b) 45°:P:45°

(c) 45°:P:0° (d) 45°:P:90°

(e) 0°:P:90° (f) 90°:P:90°

Figure 10. Al5052-PVC-Al5052 sandwich sheets of similar and different rolling combinations with 0.5mm thickness PVC with a single riveted system after the test

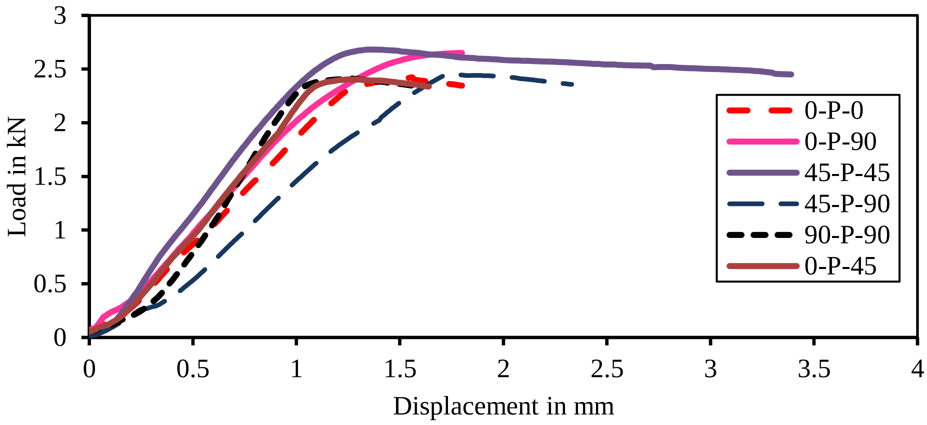


Figure 11. Load vs. Displacement of Al5052-PVC-Al5052 sheets with PVC 0.5mm thickness with a single riveted system after the lap shear test

Table 4. Maximum lap shear strength of Al5052-PVC-Al5052 sheet samples with PVC 0.5mm thickness

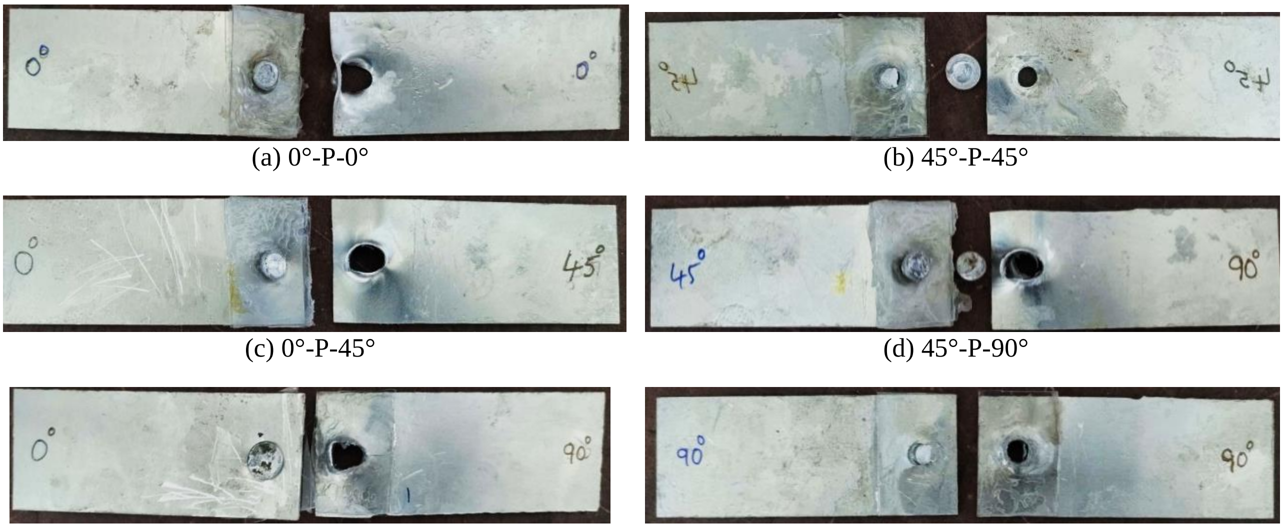
Sample No. →	1	2	3	4	5	6
Rolling combination	0°-PVC-0°	45°-PVC-45°	45°-PVC-0°	45°-PVC-90°	0°-PVC-90°	90°-PVC-90°
Maximum shear strength (kN)	2.372	2.674	2.357	2.446	2.647	2.386

In a similar manner, in case 2, for example, sandwich sheets with a 0.5mm thickness PVC core were taken for testing through lap shear tests. The failure observation was made within the riveting zone, load vs displacement behavior was plotted, and maximum shear strength was recorded for all combinations of sandwich sheets.

Figure 10 illustrates the rivet failure phenomenon observed during lap shear tests. Unlike Case 1, this case exhibited shearing at the rivet hole of the sheets, along with significant rivet deformation. The load vs. displacement behavior for each sandwich sheet is plotted in Figure 11. Among the tested sandwich sheets, the 45°-P-45° sheet exhibited the highest deformation, followed by 0°-P-90°, 45°-P-90°, 90°-P-90°, 0°-P-0°, and 45°-P-0°. All sheets underwent proper deformation before reaching their maximum load capacity, and similar trends were observed across multiple test repetitions. The maximum strength recorded for each sandwich sheet is summarized in Table 4. The highest strength was achieved by the 45°-P-45° sheet (2.674 kN), followed by 0°-P-90° (2.647 kN), 45°-P-90° (2.446 kN), 90°-P-90° (2.386 kN), 0°-P-0° (2.372 kN) and 45°-P-0° (2.357 kN).

The impact of PVC sheet participation during the lap shear tests with a single riveting in sandwich sheets has been clearly seen. For further observation, PVC thickness was increased from 0.5mm to 1mm in the next case.

Case 3: Al5052-PVC-Al5052 sandwich sheets of similar and different rolling combinations with 1mm thickness PVC



(a) 0°-P-0° (b) 45°-P-45°

(c) 0°-P-45° (d) 45°-P-90°

(e) 0°-P-90° (f) 90°-P-90°

Figure 12. Al5052-PVC-Al5052 sandwich sheets of similar and different rolling combinations with 1mm thickness PVC with a single riveted system after test

Building on cases 1 and 2, sandwich sheets with a 1 mm thick PVC layer were fabricated and tested through lap shear tests following standard procedures. The study followed a similar approach, analyzing the failure phenomenon in the riveting zone, load vs. displacement behavior and maximum shear strength in Al5052-PVC-Al5052 sandwich sheets with a total thickness of 3 mm.

Figure 12 illustrates the rivet failure phenomenon observed during lap shear tests. Similar to Case 2, shearing occurred at the rivet hole, with notable rivet deformation and hole expansion on the pulling side of the sheet in all sandwich specimens. The load vs. displacement behavior is presented in Figure 13. Among the tested sandwich sheets, the 45°-P-90° and 90°-P-90° configurations exhibited the highest deformation, followed by 0°-P-0°, 0°-P-45°, 0°-P-90° and 45°-P-45°. This trend was consistently observed in repeated tests. The maximum strength recorded for each sandwich sheet is summarized in Table 5. The highest strength was observed in the 45°-PVC-90° sheet (2.460 kN), followed closely by 90°-PVC-90° (2.457 kN), 0°-PVC-0° (2.372 kN), 0°-PVC-45° (2.372 kN), 0°-PVC-90° (2.370 kN) and 45°-PVC-45° (2.224 kN).

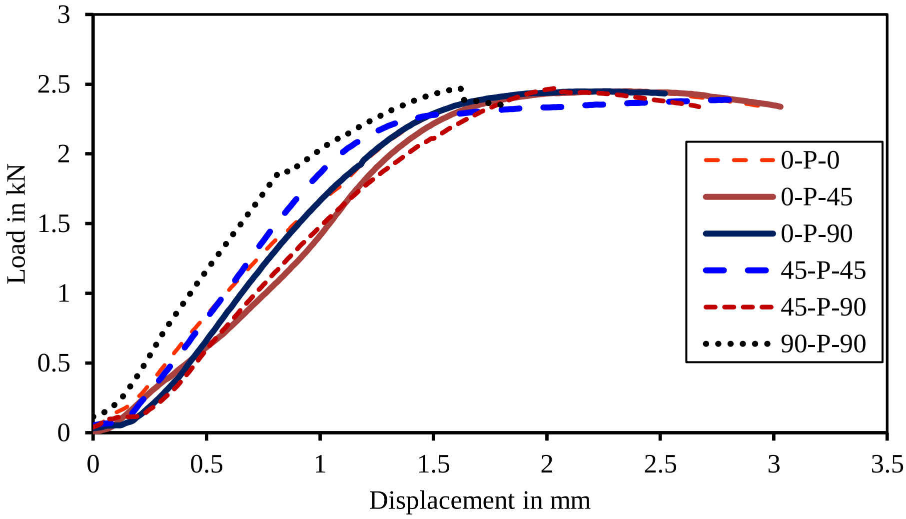


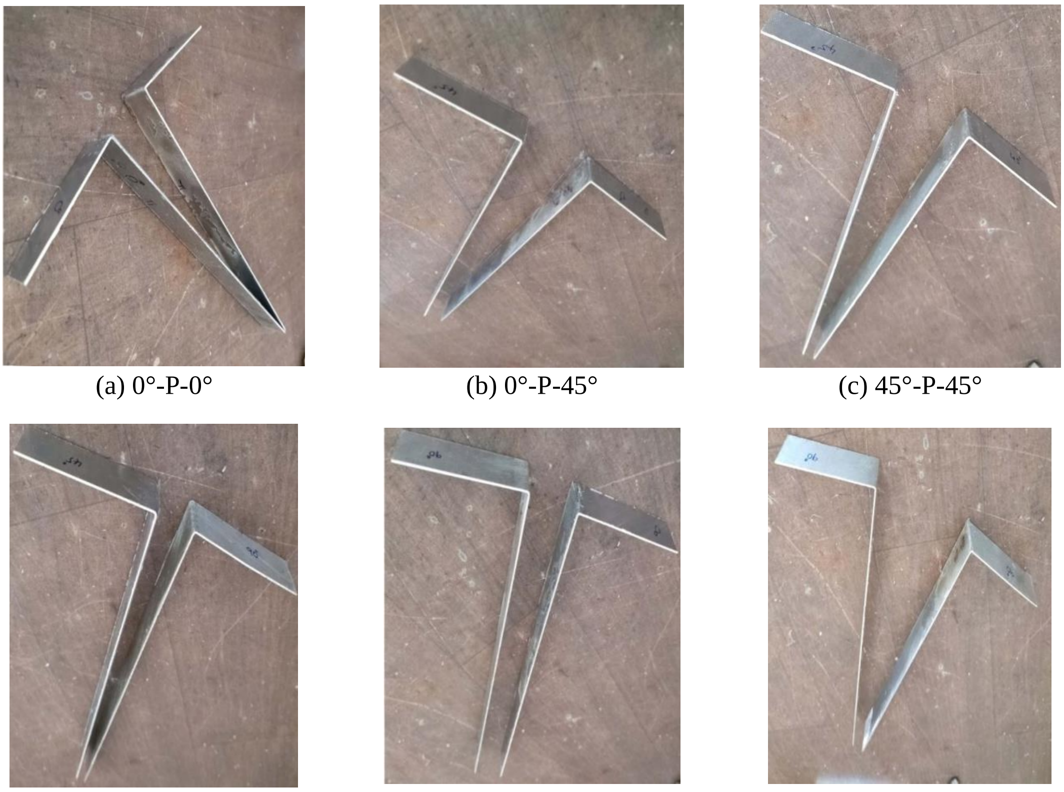
Figure 13. Load vs Displacement of Al5052-PVC-Al5052 sheet samples with 1mm thickness PVC

Table 5. Maximum lap shear strength of Al5052-PVC-Al5052 sheet samples with PVC 1mm thickness

Sample No. →	1	2	3	4	5	6
Rolling combination	0°-PVC-0°	45°-PVC-45°	0°-PVC-45°	45°-PVC-90°	0°-PVC-90°	90°-PVC-90°
Maximum shear strength (kN)	2.372	2.224	2.372	2.460	2.370	2.457

3.2 Peel Test

Like Lap shear tests on sandwich sheets with different rolling direction combinations, the T-Peel test was also performed on the UTM, as mentioned in section 2. The peeled sandwich sheets are shown in Figure 14, which shows different rolling direction combinations. All sandwich sheets were pulled with a constant pulling force to see the maximum peeling force that could be exerted by each sandwich sheet.



(a) 0°-P-0° (b) 0°-P-45° (c) 45°-P-45°

(d) 45°-P-90° (e) 0°-P-90° (f) 90°-P-90°

Figure 14. Peeled sandwich sheets of Al5052-PVC-Al5052 with 0.5mm thickness PVC

The peeling force was recorded by plotting peeling force vs. peeling distance. Figure 15 illustrates the peeling force vs. pulling distance behavior for sandwich sheets with configurations 0°-P-0°, 0°-P-45°, 0°-P-90°, 45°-P-45°, 45°-P-90° and 90°-P-90°. The recorded peeling forces are summarized in Table 6. Among the tested configurations, the 45°-P-45° and 0°-P-0° sandwich sheets exhibited the highest deformation, followed by 45°-P-90°, 0°-P-45°, 90°-P-90° and 0°-P-90°.

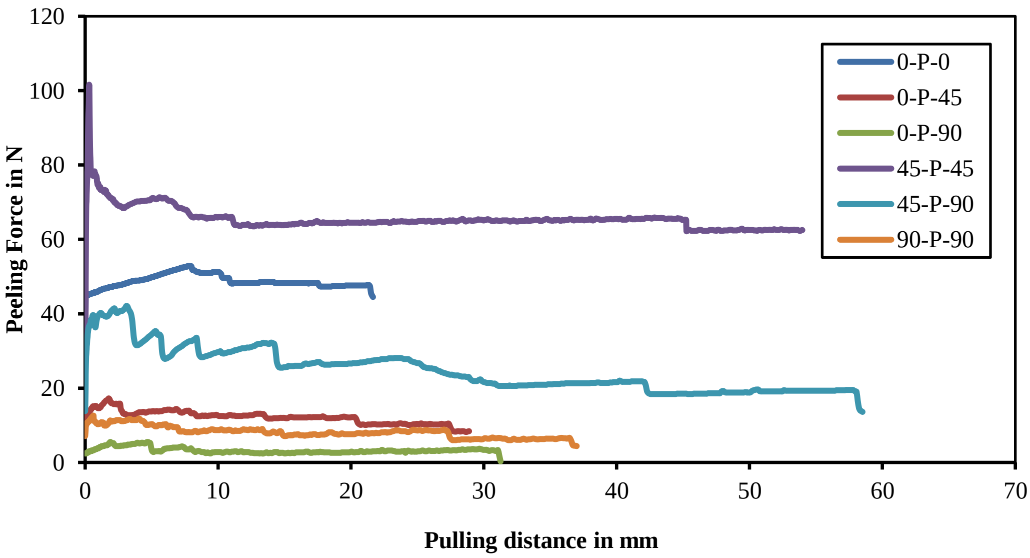


Figure 15. Peeling force vs. pulling distance in T-Peel test sandwich sheets of Al5052-PVC-Al5052 with 0.5 mm thickness PVC

Table 6. Maximum peeling force in T-Peel test sandwich sheet samples

Sample No. →	1	2	3	4	5	6
Rolling combination	0°-PVC-0°	0°-PVC-45°	45°-PVC-45°	45°-PVC-90°	0°-PVC-90°	90°-PVC-90°
Maximum Peeling Force (N)	52.8	17.2	71.1	39.8	4.8	12.5

As per the obtained peeling force data, among all the sandwich sheets, maximum peeling force has been noted for sandwich sheet of 45°-PVC-45° (71.1N) and followed by 0°-PVC-0° (52.8N), 45°-PVC-90° (39.8N), 0°-PVC-45° (17.2N), 90°-PVC-90° (12.5N) and 0°-PVC-90° (4.8N) respectively. The peeling force was measured after 24 hours. However, the 0°-PVC-90° sandwich sheet exhibits weak bonding, which requires improvement.

The inclusion of a PVC core in sandwich sheets plays a crucial role in determining their mechanical properties, performance and overall design. Factors such as core thickness, face sheets and core characteristics collectively influence the structural behavior of these sheets. Enhancing the mechanical properties, weight efficiency, and functionality of sandwich sheets relies heavily on optimizing the PVC core, whereas achieving the right balance between stiffness, load-bearing capacity, and weight is essential when adjusting core thickness.

In the lap shear test, maximum lap shear strength in the sandwich sheet with the rolling direction of 45°-PVC-45° is 2.674 kN with total thickness of 2.5mm (Al5052 is 1 mm (45°,45°), PVC 0.5mm in the lap area) and 45°-PVC-90° is 2.460 kN with total thickness of 3mm (Al5052 is 1 mm (45°,90°), PVC 0.5mm in the lap area). Because there is less material in the middle, the thin PVC 0.5mm core makes it easier for the bonding layers to grip and transfer pressures through the interface, improving adhesion to the outer layers. When put through lap shear testing, this may produce improved shear strength values. A thicker PVC 1mm core may create challenges for adhesion, as the bond between the outer layers and the core could become weaker with a thicker PVC layer. This could make the material more susceptible to delamination when subjected to shear forces, ultimately reducing the lap shear strength.

In the T-Peel test, the maximum peeling force in the sandwich sheet with the rolling direction of 45°-PVC-45° is 71.1N with a thickness of 2.5 mm (Al5052 is 1 mm (45°,45°), PVC 0.5 mm in the lap area) compared with other rolling directions of sandwich sheets. The high peel strength in the case is due to the shear and bonding forces being effectively distributed across the material interface. Flexibility and bonding strength are balanced by the 0.5mm PVC core. In general, a smaller PVC core would ensure that the core does not distort too easily under applied force and would allow for better adhesion with the aluminum outer layers, particularly at orientation angles like 45°. The peel test results at various angles are probably impacted by Al5052's anisotropic characteristics. For instance, at 0°, the aluminum might resist shear forces better due to its alignment with the material’s rolling direction. As the angle deviates (either to 0° or 90°), the peel strength typically decreases due to less effective shear stress distribution and the inherent properties of the materials at those orientations. However, at 45°- the interaction between the aluminum’s grain structure and the core layer may be optimized for shear transfer, leading to higher peel strength.

4. CONCLUSIONS

Based on the conducted research on Al5052 base sheet material and Al5052-PVC-Al5052 sandwich sheets in various rolling direction combinations (0°-PVC-0°, 45°-PVC-45°, 90°-PVC-90°, 0°-PVC-45°, 90°-PVC-45° and 0°-PVC-90°) primarily through lap shear and T-peel tests- notable findings were emerged. The significance of PVC in lap shear tests demonstrates a considerable impact compared to base sheets. The base Al5052 sheet's lower shear strength values when compared to the PVC 0.5mm lap configuration may be caused by the brittle nature of Al5052 under shear, improved PVC flexibility and stress distribution and optimal PVC-Al5052 bonding at specific orientations. When used as a lap material, PVC 0.5mm could help distribute shear forces more efficiently, resulting in higher shear strength than Al5052 on its own, which may fail suddenly under similar stress. Specifically, when a PVC thickness of 0.5mm is employed, better results are observed, likely due to improved adhesive bonding and rivet adjustments. When using PVC 0.5mm, the higher shear strength at the 45°-PVC-45° configuration can be due to the best possible distribution of shear stresses, material behavior under shear, improved surface interaction between PVC and Al5052 at this angle and the thinner PVC material's capacity to conform to the Al5052 surface more successfully. At this particular orientation, the combination produces a higher shear strength compared to other orientations. The greater flexibility and deformability of the thinner PVC, causing better stress distribution and more gradual failure, is the reason for the higher shear strength when using PVC 0.5mm as compared to PVC 1mm. The overall shear strength can be decreased by brittle failure under shear and local stress concentrations caused by the more rigid, thicker PVC (1mm). Thus, in lap shear testing using Al5052 skin sheets, the flexibility of PVC 0.5mm offers higher shear strength.

In the case of T-peel tests using PVC 0.5mm, the influence of rolling direction combinations becomes apparent. The optimal stress distribution, bonding efficiency and PVC's material properties lead to the high peeling force at 45°-PVC-45° (71.1 N), allowing the bond to withstand higher forces before separation. The 45° angle optimizes the force transfer, resulting in a higher maximum peeling force compared to other orientations. However, orientations such as 90°-PVC-90° and 0°-PVC-0° may fail faster or more brittle, lowering the maximum peeling forces. It is essential to make a note and acknowledge that while this research offers valuable insights, the results cannot be universally valid. Adhesive bonding mechanisms are intricate and dependent on various factors, such as the chemical composition of adherents and adhesives, surface irregularities, roughness, and topography, among others. Despite these complexities, the obtained results provide a valuable trend followed by the sheets within their tested range, offering valuable insights into the behavior of the materials under specific conditions.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

Chinmaya Prasad Padhy: Topic selection, Conceptualization, Compiling, Results, Validation, Supervision

P.Praveen Kumar Reddy: Literature execution, Methodology, Experimental work, Drafting

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