Investigation on the Bending Properties and Geometric Defects of Steel/Polymer/Steel Sheets—Three-Point and Hat-Shaped Bending

Payam Maleki 1, Mohammadmehdi Shahzamanian 2, Wan Jefferey Basirun 3, Peidong Wu 2,* and Abbas Akbarzadeh 1,*

1 Department of Materials Science and Engineering, Sharif University of Technology, Tehran P.O. Box 11365-8639, Iran; payam.maleki@sharif.edu
2 Department of Mechanical Engineering, McMaster University, Hamilton, ON L8S 4L7, Canada; shahzamm@mailbox.sc.edu
3 Department of Chemistry, University Malaya, Kuala Lumpur 50603, Malaysia; jeff@um.edu.my
* Correspondence: peidong@mcmaster.ca (P.W.); abbasa@sharif.ir (A.A.)

Abstract: Steel/polymer/steel laminates, also known as laminated steels, are composite materials consisting of bonding layers of steel and polymer. The polymer layer acts as a bonding agent between the steel layers, imparting additional properties such as low density, impact resistance, and thermal insulation, while the steel layers provide strength and formability. These laminated steels have found increasing applications in automotive, aerospace, and construction industries to reduce weight and improve fuel efficiency. The bending behavior of this laminates is more complex compared to that of a single layer of metallic sheets. This complexity arises from significant differences in mechanical properties, as well as the thickness ratio between the skin and the core. The flexural properties and behavior of different St14/TPU/St14 laminate sheets that were fabricated using the direct roll bonding (DRB) process were investigated through three-point and hat-shaped bending tests. The direct roll bonding process involves the bonding of steel and semi-melt polymer sheets under the pressure of rollers, ensuring a cohesive and durable composite material. The microscopic analysis of the cross-section of the SPS laminates after the bending processes shows the absence of delamination or slippage between the layers, which indicates the correct selection of materials and the bonding method. The results showed that the springback of three-layer laminates has an inverse relationship with the work-hardening exponent, yield strength, and yield point elongation value, while possessing a direct relationship with normal anisotropy and elastic modulus. Furthermore, the flexural strength and flexural modulus decrease with the increase in the volume fraction of the polymeric core, while the flexural rigidity increases. The findings indicate the DRB technique as a promising method for manufacturing a lightweight metal–polymer laminate with a high formability performance.

Keywords: roll bonding; steel/polymer/steel laminates; three-point bending; hat-shaped bending; springback; side-wall curl

1. Introduction

Monolithic metallic sheets, while providing strength, tend to be heavier, impacting the overall weight of the vehicle and potentially compromising fuel efficiency. The increasing demand for lightweight materials utilizing in-structure for fuel combustion vehicles to decrease air pollution and to control vibrations and noises in the household appliances has led to the emergence of three-layer metal/polymer-metal (MPM) composites [1,2]. Metal/polymer/metal denotes a composite material structure consisting of layers of metal and polymer arranged in a sandwich-like configuration, combining the properties of both materials to achieve specific characteristics and functionalities. MPM-sandwiched sheets exhibit appropriate mechanical properties, higher specific flexural stiffness, higher dent
Metals 2024, 14, 935

resistance, and special thermal and electrical behavior compared to monolithic metallic sheets [3]. Due to these advantages, MPM sheets are progressively being utilized in various sectors, including aeronautics, automotive, and the computer industries [4,5]. Monolithic metallic sheets may also exhibit limitations in design flexibility and formability, posing challenges in achieving complex shapes and intricate designs for automotive components. MPM sheets, with the added flexibility and formability imparted by the polymer layer, provide a greater versatility in design, allowing for innovative and streamlined automotive structures. Although three-layer composites have been examined through a variety of destructive and non-destructive testing methods [6,7], a deep understanding of the influence of the core thickness and adhesion strength on the bending behavior and post-bending geometrical defects under dynamic as well as quasi-static conditions is still missing and is described in the current paper. The significance of this work lies in its contribution to the existing body of knowledge in the field, fostering advancements and innovation in the metal/polymer composites. In this study, three-layered symmetrical sandwiched sheets were fabricated without the utilization of any adhesive through a laboratory-based direct roll bonding process that ensures a robust and defect-less bonding between the layers. The bendability and dimensional accuracy of the fabricated laminates were investigated through standard mechanical tests and precise measuring tools.

In a classification based on the thickness of the polymeric layer, Liu et al. [5] categorized SPS laminate sheets into two main types: lightweight laminated steel with a thick polymer core (40% to 60% of total volume) and laminated vibration damping steel (LVDS) with a thin polymer adhesive layer (less than 20% of the total volume). Joining the steel/polymer/steel (SMS) sandwich presents a significant processing challenge, primarily attributed to the polymeric core layer. This core layer, characterized by electrical insulation, softness, and a lack of thermal durability/stability, hinders welding processes, causes dimension distortion in mechanical joining, and degrades under elevated temperatures, such as during welding and certain coating processes. A significant portion of these issues is related to the quality and strength of the bond between metal and polymer. Various approaches have been devised to address these challenges, including cold and hot roll bonding (also known as Press Joining Rolling), adhesive bonding (manual layering), mechanical fastening, clinching, and hot and cold pressing methods for manufacturing MPM laminated sheets, depending on mechanical and thermal properties of the polymeric core material [5,8–11]. Adhesive bonded joints present challenges as they cannot be disassembled without causing damage and may release harmful environmental emissions. Furthermore, these joints are susceptible to deterioration from moisture, humidity, and temperature and exhibit limited resistance in chemically reactive conditions. The clinching method proves to be ineffective for joining metal/polymer/metal composite sheets due to significant defects such as its unsuitability for specific material combinations, crack formation in the interlocking areas, thickness limitations affecting joint quality, predominant failure modes like neck fracture and pull-out, and dependency on material combinations and orientations that complicate the joining process. Mechanical fastening presents constraints, including elevated component weight and stress concentration near fastener holes causing strength deterioration and corrosion. Additionally, the sensitivity of the layer’s configuration, coupled with the necessity of mechanical operations such as hole drilling and thread creation, further complicates the use of mechanical fastening. Recent studies indicate that additive manufacturing methods present a viable alternative to conventional joining techniques for metal–polymer structures [12,13]. However, several challenges persist, including surface impurities, oxidation, material incompatibility, porosity, and delamination at the interface. Among all these methods, roll bonding and hot-pressing techniques are highly recommended as the optimal methods for fabricating metal/polymer/metal composites, as they both result in well-bonded composites with excellent mechanical properties and structural integrity [8,11]. However, as with most fabrication processes, there may be limitations regarding material compatibility as well as pre- and post-processing requirements.
The most common composite forming methods include press brake bending, shot peening forming, incremental sheet forming, and die forming (which encompasses stamping, hydroforming, and electromagnetic forming), all of which are employed to deform flat pieces of composite sheets into desired shapes, such as V, U, or channel configurations [14]. These techniques are widely used in the automotive, aerospace, and construction industries, as well as in the production of household appliances and electronics [15,16]. Utilizing two stationary rollers and a downward moving mandrel, the three-point bending test simulates tensile and compression stresses on the specimen, demonstrating the flexural properties of the material. The hat-shaped bending process is a prevalent sheet metal-forming technique extensively used to fabricate automotive components, such as bumper beams, side frames, and center pillars and other channel-shape frames in various sizes. Several geometrical defects, which either do not occur or exhibit reduced intensity in the case of homogeneous materials, have been observed, during the bending of laminate sheets. Springback and delamination are two critical issues in bending laminated steels, leading to geometrical and dimensional inaccuracies and the loss of integrity through layer separation in formed components, respectively [16]. Delamination occurs especially during the deformation process of short flanges due to the large shear strains developed in the polymeric layer at the bending regions [17]. It has been shown that stronger interfacial properties lead to improved formability by reducing the risk of delamination [18]. One significant aspect to consider in addressing delamination issues is controlling bending parameters, such as blank holder force, forming speed, and frictional coefficient, as these factors play a crucial role in resolving delamination problems [19]. After removing the deformation load, elastic recovery occurs due to the release of the non-uniformly distributed stress in a drawn specimen, causing the final shape to deviate from the shape imposed by the forming tool. The side wall of the drawing sheet undergoes complicated bending and stretching deformation phenomena, with the stress distribution on the outer side (adjacent to the die) subjected to tensile stress, and the inner side (adjacent to the punch) subjected to compression stress, initiating a residual bending moment [20]. These residual stresses throughout the sheet thickness result in a geometrical inaccuracy called the side-wall curl. Furthermore, transverse stress generated during the forming process significantly contributes to phenomena like yielding, hardening, and thickness reduction in the stretch–bending regions of the bent specimens [21]. Moreover, uneven stretching loads exerted in the through-thickness direction play a crucial role in influencing both the springback angle and channel height.

There have been many investigations on the springback of MPM-sandwiched sheets due to the increased use of this material in sheet metal bending processes in recent years. Employing both analytical and finite element analysis (FEA) approaches to predict the springback in Al/PP/Al sheets, it was revealed that the change in thicknesses and the configuration of the layers could reduce springback [22]. Mosse et al. [23] highlighted the impact of temperature variation during lamination, die, and blank holder on significant shape deformation in channel-forming processes for fiber metal laminates. It was found that a pre-heating temperature of 160 °C for the laminate, followed by immediate transfer to press tooling heated to 80 °C, is essential. Holding the formed part between the die and punch until the polymer solidifies led to significant improvements in shape accuracy compared to monolithic aluminum sheet. In order to determine the effects of the thickness and properties of interlayer on the springback behavior of SPS laminates, Weiss et al. [24] conducted a draw-bending test to explore the influence of interlayer thickness and properties on the springback behavior of steel/polymer/steel (SPS) laminates, noting a decrease in springback with increased interlayer thickness and reduced interlayer material strength. Liu and Wang [17] introduced an analytical approach predicting springback and side-wall curl in MPM laminates after wiper die bending, highlighting that increased inner layer thickness and decreased die radius contribute to a higher springback factor (a decrease in the amount of springback). Regarding the Euler–Bernoulli straight and curved beam deflections loaded with axial force and bending moment, interfacial shear loads were introduced as contributing factors to the occurrence of side-wall curl. Numerous studies in
the literature focus on the investigation of springback phenomena. The bending behavior of various SPS sheets with different configurations and thicknesses was experimentally investigated using the three-point bending test and validated with analytical and numerical methods [25]. The results indicated that laminates with a thicker core possess reduced springback, but a greater crack probability due to the increased tensile stress on the outer layer. Additionally, the SPS symmetry effect minimally impacted springback values, while strain values and bending forces were notably influenced. After performing the V-die bending test, Engel and Buhl [26] suggested using symmetric SPS laminates to decrease the springback, emphasizing that reducing outer layer thickness significantly improves springback. Li et al. [27] demonstrated that enhancing bending speed, depth, and polymeric core thickness, along with decreasing yield stress, diminishes springback in the DC05/mixture of thermosetting resin and rubber/DC05 after a three-point bending test. Corona and Eisenhour [28] examined the effects of the yield stress and thickness of the steel sheet, and the stiffness of the polymer layer on the springback and side-wall curl of laminated steel sheets through wiping die bending. Their findings revealed a decrease in both curl and springback as the yield stress decreased and thickness increased. Moreover, due to the independent bending of the sheets, the curl diminishes to zero when the stiffness reaches zero but increases rapidly as the stiffness increases until it reaches the maximum. Xiao et al. [29] found that the extremely low elastic modulus of the polymer core was responsible for the abnormal bending behavior of the vibration-damping laminated steel sheets (with thin polymeric core). In a three-point bending investigation conducted by Link [30], focused on lightweight laminate sheets with a thin polymeric core (SPS), it was found that the elastic bending stiffness of SPS sheets closely resembled that of monolithic steel sheets with equivalent thickness. Moreover, the specific stiffness of SPS laminates was identified to surpass that of monolithic steel sheets. A study investigating the springback angles of Al/glass fiber-reinforced polyurethane/Al with various core thicknesses (0.4, 0.8, and 1.2 mm) through three-point bending test at different testing temperatures (25, 100, and 150 °C) indicated a reduction in springback with the increase in the temperature and thickness [31]. The results from an experimental and numerical investigation on the springback of Al3105/PP/Al3105 sandwiched sheets, conducted under V-die bending tests at various punch radii, revealed a minor reduction in springback angle with an increase in the total thickness of the APA sheets [32]. The bending and springback behaviors of Al/PE/AL sandwich sheets, featuring three distinct aluminum skins, were investigated through experimental and analytical methods, along with numerical simulations [33]. Analytical predictions of the springback angle closely aligned with experimental findings. Additionally, it was reported that the springback angle of the sandwiched sheet increases with the strength of the skin aluminum alloy sheets.

Although detailed studies were not performed on the side-wall curl defect in three-layer laminated sheets, there is a significant amount of published research focusing on this phenomenon in lightweight and formable monolithic metal sheets. In a comprehensive investigation focused on the influence of the material strength and thickness, and the die radius on the side-wall curl, Davies et al. proposed an experimental apparatus to examine the side-wall curl in the four different types of high-strength steels (HSSs) [34]. Also, they pointed out that the curl can be removed by the elimination of the nonuniform distribution of residual stresses on the specimen by the imposition of plastic deformation. The effect of restraining forces on the shape deviations, such as springback and side-wall curl, of a flanged channel made of SKDQ and high-strength steels was also studied [35]. It was found that the shape deviation decreases with the increase in the restraining force. Two new techniques alternative to the conventional draw bending called the ‘crash forming’ [36] and the ‘form forming’ [37] were proposed to eliminate the springback of HSS sheets in the U-bending process. However, the specimens still possess the side-wall curl defect due to the inclusion of the process of bending and the subsequent partial unbending. Lawanwong [38] suggested using a novel technology called the ‘double-action bending (DAB)’ to eliminate
the side-wall curl in the hat-shape forming of advanced high-strength steel sheets (AHSSs) as there is no cyclic bending–unbending involved in the process.

Sheet metal bending, a foundational forming technique extensively utilized across diverse applications, demonstrates distinctive forming potential, limitations, and forces in SPS (steel/polymer/steel) systems when compared to monolithic materials. These variations arise from the inhomogeneous properties present across the thicknesses of the layers and the strength of adhesion within the SPS systems. Although some theoretical and experimental analyses have been conducted to investigate the formability and geometrical defects in lightweight metal and MPM laminate sheets, no prior investigations have been reported regarding the bending behavior and geometrical defects of the St14/TPU/St14 laminate sheets after the bending operation. The reason is partly associated with the complexity of the material and challenges in processing. The present study holds considerable significance in the field of materials science and engineering, as well as the mechanical and aerospace engineering. The absence of adhesive agents in the fabrication process of S/P/S offers several benefits, such as the enhanced structural integrity, reduced manufacturing complexity, and improved cost-effectiveness. By studying the geometrical defects, such as springback and side-wall curl, it has become possible to understand the impact of the polymeric core volume fraction on the final sheet’s quality and performance. By investigating the effect of the mechanical properties of the S/P/S laminates on the springback behavior of these sheets and also comparing the results with the values of monolithic steel sheets, the findings of this study provide valuable insights into the bendability of the laminated steel sheets. Using unconstrained hat-shaped bending and three-point bending tests, the flexural properties and potential geometrical defects such as the springback and side-wall curl were comprehensively investigated. Furthermore, this study examines the influence of the mechanical properties of the composite and the steel sheets on the springback behavior. The current study carries substantial implications for the field of metal/polymer composites and strives to address the knowledge gap regarding the formability of these laminates. The main novel contribution of this paper is to demonstrate the feasibility of producing defect-free SPS laminates with varying thicknesses continuously through the roll bonding process, without using any adhesive agents, while maintaining excellent bendability properties comparable to monolithic metallic sheets.

2. Experimental Procedures

2.1. Laminate Fabrication

In order to fabricate the SPS laminate sheets, a cold-rolled low carbon steel (St14) with a thickness of 0.45 mm and a chemical composition described in Table 1 was used as the top and bottom sheets of the SPS three-layer sandwiched sheet. Also, a thermoplastic polyurethane (TPU) sheet with an initial thickness of 2 mm was used as the core layer of SPS sheets. The most important selection criteria of the low-carbon steel sheets for the laminated skin are its high compatibility with existing press-forming operations and subsequent welding and surface treatment processes while maintaining affordability. TPU was selected as the core of the SPS composite material for its relatively lower density, lower cost, excellent mechanical properties, and exceptional bonding properties.

| Table 1. The chemical composition of the low-carbon steel sheet (numbers are in %). |
|-----------------|------|-----|-----|-------|-----|-----|-----|-----|
| Fe              | C    | Si  | P   | S    | Cr  | Ni  | Mn  | Mo  | Al  |
| Base            | 0.09 | 0.02 | 0.01 | 0.005 | 0.012 | 0.03 | 0.3 | 0.03 | 0.04 |

After stacking the polymeric layer between the two metallic layers, the samples were placed in an oven with temperature of 200 °C for 5 min. Then, the samples (2.9 mm thickness) were passed through the rollers with the diameter of 15 cm and a constant rolling speed of 25 rpm undergoing different thickness reductions (Figure 1). In this research, four different thickness reductions (30, 40, 50, and 60%) were considered in order
to fabricate SPS laminates with different core thicknesses. Given the softer nature of the polymer in contrast to the steel skins, all thickness reductions were exclusively applied to the semi-melted polymer layer (the skin sheets were not deformed through the rolling process). To ensure the solidification of the semi-molten polymer, the samples were kept at room temperature for three days. The final thickness and coding of three-layer laminates are presented in Table 2. The fabrication process of SPS laminates through roll bonding is detailed in [39].

Table 2. Thicknesses corresponding to each laminate code.

<table>
<thead>
<tr>
<th>Laminate Code</th>
<th>Laminate Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-30</td>
<td>2.03</td>
</tr>
<tr>
<td>L-40</td>
<td>1.74</td>
</tr>
<tr>
<td>L-50</td>
<td>1.45</td>
</tr>
<tr>
<td>L-60</td>
<td>1.16</td>
</tr>
</tbody>
</table>

2.2. Mechanical Properties’ Characterization

To characterize the mechanical properties and anisotropic behavior of laminates and single steel sheet (0.45 mm), different specimens of steel and each SPS sheets were cut at different orientations to the rolling directions (0°, 45°, and 90°). The tensile specimens were used according to the ASTM E8/E8M [40] (Figure 2a,b) and with the tensile speed of 1 mm/min to determine the stress–strain curves and the sheet anisotropy parameter R-values [41].

The anisotropy was evaluated by interrupting tensile tests at an elongation value of 20% so that the plastic deformation was in the field of uniform deformation.

where $\varepsilon_w$ and $\varepsilon_t$ are the true width strain and true thickness strain, respectively, of a uniaxial tension specimen cut at an angle ($\theta$) to the rolling direction. The evaluation of $\varepsilon_w$ and $\varepsilon_t$ relies on establishing a specific grid pattern (such as dots or squares) on the surface of the tensile specimens (Figure 3a). Following a tensile test up to 20% elongation, the distortion of the pattern was assessed. If a non-deformed sheet with an initial thickness $t_0$ is marked with a grid of dots of initial diameter $d_{0w}$ during the tensile test, the grid will

![Figure 1. Schematic of the direct roll bonding process used to fabricate SPS laminates.](image-url)
be deformed into ellipses with major and minor axes $d_1$ and $d_2$, respectively (Figure 3b). By assuming volume constancy and utilizing Equation (2), the three principal strains longitudinal ($\varepsilon_l$), width ($\varepsilon_w$), and thickness strain ($\varepsilon_t$) can be calculated. It is important to note that $\varepsilon_l$ is determined based on $\varepsilon_t$ and $\varepsilon_w$ according to Equation (3). At a given angle ($\theta$) to the rolling direction, the anisotropy of the sheet is characterized by the plastic strain ratio, R-value, which is described in Equation (3) [42,43].

\[
\begin{align*}
\varepsilon_l &= \ln \frac{d_1}{d_0}; \\
\varepsilon_w &= \ln \frac{d_3}{d_0}; \\
\varepsilon_t &= \ln \frac{t_1}{t_0}
\end{align*}
\]

\[\varepsilon_l + \varepsilon_w + \varepsilon_t = 0 \quad (2)\]

\[R_\theta = \frac{\varepsilon_w}{\varepsilon_t} \quad (3)\]

Figure 2. Geometry of the tensile test specimens: (a) St14, (b) SPS laminate, and (c) TPU.

Figure 3. (a) Circular grid pattern imposed on the test specimen, and (b) measuring the major and minor diameters of the ellipsoid after straining.

The average R value ($\bar{R}$) was determined based on Equation (4) as follows [42]:

\[
\bar{R} = \frac{R_0 + 2R_{45} + R_{90}}{4}
\]

(4)

where the subscripts 0, 45, and 90 indicate the tensile specimen directions with respect to the rolling direction (RD).

Moreover, the mechanical properties of the TPU sheet were determined according to the ASTM D638 (Type IV) specifications [44] (see Figure 2c) with a tensile speed of 50 mm/min.
2.3. Hat-Shaped Bending

Unconstrained hat-shaped bending was conducted to reveal the mechanism of springback and side-wall curl and to measure their quantity. Figure 4a shows the schematic and dimension of hat-shaped bending upper and lower die. The size of the corner radius of the dies is 5 mm, and the gap between them (clearance) is $t + 0.1$ mm for all specimens. Rectangular specimens ($40 \times 220$ mm$^2$) were cut from all four SPS sheets (in the rolling direction) and were used in the hat-shaped bending experiments. Also, in order to compare the results, this test was performed on the monolithic steel sheets with a thickness of 0.45 mm. In this process, the upper die moves down with the speed of 0.3 mm/min and the pressing machine stops after the distance between the top of the upper die and the bottom of the lower die is equal to the thickness of the bending specimen. After 15 s, the two dies were separated and the bent sample was removed from the die to examine the amount of springback and side-wall curl and also to investigate the possible defects formed during the bending process. The amount of springback and the side-wall curl was measured immediately after the removal from the dies at five different times (time period between 0 and 1000 min), i.e., 3 h, 5 h, 10 h, and 16.5 h. All the tests were repeated three times, and the average of the calculated amounts was reported. It should be noted that, due to the effect of the test temperature on the results, this test was performed at the constant temperature of 25°C. Also, the contact surfaces were lubricated to reduce friction. In order to ensure the quality of the bonding between the polymeric core and two skin sheets, a scanning electron microscopy (SEM) analysis of the SPS deformed samples was performed before and after hat-shaping.

In order to measure the springback angles, high-quality pictures were taken before and after the unloading (at the mentioned times). Then, the springback angles were measured by the DigitizeIt 2.0.0 software on both the side walls and flanges, and the average angle in each case was reported. Figure 4 shows the target (b) and produced (c) specimens of the hat-shaped bending. As it can be seen, in addition to the side-wall springback phenomenon, side-wall curl also occurs in U-shaped parts. The side-wall springback, also known as section opening, is characterized by a deviation of the side wall from the precise punch shape by an angle denoted as $\theta$. Side-wall curl, on the other hand, manifests itself as a curvature in the side wall. Side-wall springback has long been recognized, especially for homogeneous steel sheets, and can be rectified by overbending. On the other hand, side-wall curls in laminated sheets are a more recent issue associated with both metallic and polymeric sheets and pose the most significant challenge in the assembly of components. In many cases, spot welds are necessary to connect the wall to a mated part. In instances where the gap resulting from the side-wall curl is excessive, welding becomes unfeasible.

Qualitatively, the occurrence of a wall curl arises from the polymer’s comparatively limited resistance to shear forces. Within the bend region, individual sheets undergo bending independently, resulting in disparate bending radii for each sheet and the consequent emergence of a relative displacement $\delta$ between them, as depicted in Figure 5a. For simplification, the relative displacement is assumed to be zero at the left extremity of the sheets in the figure. When the polymer stiffness is negligibly low, the offset $\delta$ is also observable at the upper end, as illustrated. Conversely, with a finite stiffness of the polymer, this displacement induces a shear stress $\tau$, which acts upon the steel sheets as depicted in Figure 5b. This shear stress leads to the generation of a distributed moment $m$ (of magnitude $\tau t^2/4$ for unit width) in the same direction on both sheets, resulting in their bending, as demonstrated in Figure 5c. Consequently, the laminate displays a curl, and the offset between the two sheets diminishes to $\varepsilon$ at the upper edge, as depicted in Figure 5d. At the extremities, a highly compliant polymer permits the sheets to slide past each other with minimal resistance, resulting in a negligible induced moment and minimal curl, where $\varepsilon$ equals $\delta$. Conversely, in the case of a highly stiff polymer, the tendency for the two steel sheets to bend as one diminishes the extent of the curl.
components. In many cases, spot welds are necessary to connect the wall to a mated part. In instances where the gap resulting from the side-wall curl is excessive, welding becomes unfeasible.

Figure 4. Schematic of (a) unconstrained hat-shaped bending, (b) target shape, and (c) shape deviation of the bent sample.

The measurement of the side-wall curl was performed according to Chen et al.’s method [43]. After measuring the side-wall maximum deviation $c$ from the corresponding chord $b$ in an assigned arc length, an equivalent circular arc in accordance with this parameter was constructed, as illustrated in Figure 6. Then, the curvature of the equivalent circular arc was considered as a measure of the side-wall curl, as denoted by $\rho$. According to Figure 6, the calculation of the radius of the curvature of the equivalent circular arc was performed following Equation (5) [43].

$$\rho = \frac{c^2 + \frac{b^2}{4}}{2c}$$  \hspace{1cm} (5)

Also, the side-wall curl factor was measured using Equation (6):

$$f_c = \frac{b}{2\rho} \times 100$$  \hspace{1cm} (6)

To prevent the effects of the end of the side wall $b$ was measured from a distance of $a$ from the bottom of the bent sheet, as it can be seen from Figure 6.
value to ensure the accuracy of the results. The schematic of the three-point bending test was performed according to the ASTM D-790M standard test method [45] at a crosshead speed of 1 mm/min. A minimum of five tests were performed for each reported value to ensure the accuracy of the results. The schematic of the three-point bending test and the exact quantity of the support span (L) are illustrated in Figure 7 and Table 3, respectively. The bending conditions change depending on the thicknesses of the three sheets. Rectangular specimens (25 × 120 mm²) cut from the SPS sheets (in rolling direction) were used in the three-point bending test. This test was carried out on a monolithic steel sheet with a thickness of 0.45 mm. Conversely, in the case of a highly stiff polymer, the tendency for the end of the side wall b was measured from a distance of a from the bottom of the bent sheet, as it can be seen from Figure 6.

**Figure 5.** Sketches that illustrate what causes the curl. (a) Each sheet bends independently, causing a relative displacement between them. (b) The shear stress in the polymer layer acts on the surfaces of the sheets. (c) The shear stress induces a distributed moment that results in each sheet bending. (d) The final shape with curling.

**Figure 6.** Side-wall curl measurement, based on an equivalent circular arc.

### 2.4. Three-Point Bending

In order to investigate the flexural response of the SPS and steel sheets, the three-point bending test was performed according to the ASTM D-790M standard test method [45] at 23 °C using a computer-controlled mechanical tester. These tests were conducted at a crosshead speed of 1 mm/min. A minimum of five tests were performed for each reported value to ensure the accuracy of the results. The schematic of the three-point bending test and the exact quantity of the support span (L) are illustrated in Figure 7 and Table 3, respectively. The bending conditions change depending on the thicknesses of the three sheets. Rectangular specimens (25 × 120 mm²) cut from the SPS sheets (in rolling direction)
were used in the three-point bending test. This test was carried out on a monolithic steel sheet with a thickness of 0.45 mm and in the same dimension to achieve comparable results.

![Figure 7. Schematic of the three-point bending test to investigate the bendingproperties of the composite material.](image)

**Table 3.** The exact values of the support span (L) for all specimens.

<table>
<thead>
<tr>
<th>Sample</th>
<th>L-30</th>
<th>L-40</th>
<th>L-50</th>
<th>L-60</th>
<th>Steel Sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support span (mm)</td>
<td>25.09</td>
<td>24.35</td>
<td>23.63</td>
<td>22.9</td>
<td>21.13</td>
</tr>
</tbody>
</table>

The tests were performed up to a bending angle of 60°, and there were no delaminations or any other defects, such as cracking of the outer skin and edge slippage, in the SPSs structure. The bending force versus extension data were automatically acquired by the computer during the bending tests. The maximum flexural stress sustained by the test specimen during the three-point bending test was calculated following Equation (7) (according to ASTM D-790M).

\[
\sigma_f = \frac{3F_{\text{max}}L}{2bd^2} \tag{7}
\]

where \(F_{\text{max}}\) is the maximum load on the load–deflection curve in N, \(L\) is the support span in mm, \(b\) is the width of the specimens (25 mm), and \(d\) is the depth (thickness) of the specimen in mm.

The elastic bending modulus was calculated using Equation (8) [25] for all the tested materials.

\[
E_b = \frac{L^3m}{4bd^3} \tag{8}
\]

where \(L\) is the support span in mm, \(b\) is the width of the specimens (= 25 mm), \(d\) is the depth (thickness) of the specimen in mm, and \(m\) is the slope of the tangent to the initial straight-line portion of the load–deflection curve in N/mm.

The flexural rigidity per unit width of the SPS sheets was calculated using Equation (9) [46] to provide information about their resistance against bending. A comparison of the flexural rigidity of SPS sheets with the monolithic steel sheet was conducted by computing the flexural rigidity per unit width of the steel sheet based on Equation (10) [46].

\[
\frac{EI}{b} = E_{\text{TL}} \left[ \frac{S_{\text{all}}^3 - (S_{\text{all}} - 2S_{\text{TL}})^3}{12} \right] + E_C \left[ \frac{(S_{\text{all}} - 2S_{\text{TL}})^3}{12} \right] \tag{9}
\]

\[
\frac{EI}{b} = \frac{E_{\text{TL}} S_{\text{all}}^3}{12} \tag{10}
\]
The overall thickness of the sandwiched $S_{all}$ and the thickness of the single top layers $S_{TL}$ were calculated from the Young’s modulus of the top layer material $E_{TL}$ and the core material $E_{C}$.

Because of the possibility of changes in the angle of the bent samples over time due to the viscoelastic properties of the polymer layer, the bending angle was measured five different times after performing the test (similar to measuring the springback in hat-shaped bending). The springback angle $\Delta \theta$ of each specimen was calculated by subtracting $\theta_f$ (interior angle after unloading) from $\theta_i$ (interior angle before unloading), $\Delta \theta = \theta_f - \theta_i$. The 2D schematic view of the bent sample before and after springback is depicted in Figure 8.

![Figure 8](image_url)

**Figure 8.** Two-dimensional illustration of the springback measurement in the three-point bending test.

### 3. Results and Discussion

#### 3.1. Mechanical Properties of Monolithic Sheets

Figures 9 and 10 show the stress–strain curve of the steel skin and polymeric core obtained from the tensile test, respectively. In Figure 9, after the occurrence of the maximum yield stress of the material, the stress does not increase with the increase in the strain. Strain aging refers to low-carbon steel, which ages during the heat treatment or naturally at room temperature. The presence of solute interstitials like carbon and nitrogen in low-carbon steels and similar metals leads to discontinuous yielding, characterized by a distinct yield point followed by a plateau in the stress–strain curve known as yield point elongation (YPE). The yield point phenomenon is explained in detail in [47].

![Figure 9](image_url)

**Figure 9.** Stress–strain curve of the ST14 steel sheet in the rolling direction.
Figure 8. Two-dimensional illustration of the springback measurement in the three-point bending test.

3. Results and Discussion

3.1. Mechanical Properties of Monolithic Sheets

Figures 9 and 10 show the stress–strain curve of the steel skin and polymeric core obtained from the tensile test, respectively. In Figure 9, after the occurrence of the maximum yield stress of the material, the stress does not increase with the increase in the strain. Strain aging refers to low-carbon steel, which ages during the heat treatment or naturally at room temperature. The presence of solute interstitials like carbon and nitrogen in low-carbon steels and similar metals leads to discontinuous yielding, characterized by a distinct yield point followed by a plateau in the stress–strain curve known as yield point elongation (YPE).

The yield point phenomenon is explained in detail in [47].

Figure 9. Stress–strain curve of the ST14 steel sheet in the rolling direction.

Figure 10. Stress–strain curve of the thermoplastic polyurethane sheet.

The stress–strain behavior of polyurethane sheet is divided into three stages (Figure 10). In small strains, the graph is almost linear and the polymer sample shows relatively stiff behavior. The softening of the material is the second phenomenon at the medium strains, and finally, at high strains, the strain hardening is gradually completed due to the crystallization phenomenon caused by the strain increase. The combination of these three phenomena leads to a high polymer strength with a very high elongation.

3.2. Flexural Properties and Bending Defects of Composite Sheets

3.2.1. Hat-Shaped Bending

Figure 11 illustrates the required force to bend the SPS sheets as well as the monolithic steel sheet. From the comparison of the curves, it is apparent that, as the thickness of the polymeric core increases, the maximum force required for the bending of the laminates also increases. Similarly, Liu and Xue observed this behavior during unconstrained cylindrical bending tests performed on three distinct composites (AA2024/PE/AA2024, AA1060/PE/AA1060, and AA5052/PE/AA5052), all of which were manufactured via hot-press bonding [33]. The force increment is a consequence of the laminated sheet undergoing permanent deformation and adjusting to the new shape demanded by the forming process. The progressive increase in the force reflects the material’s response to the applied stress, as it strives to accommodate the required shape change. This observation emphasizes the importance of carefully controlling the factors involved in the process to achieve the desired outcome and ensure the successful sheet forming through controlled plastic deformation process. An increase in the thickness of the polymeric core increases the overall stiffness and resistance to bending in the SPS laminates. Consequently, a higher maximum force is necessary to induce bending in these laminates compared to those with a thinner polymeric core. The increased resistance to bending is due to the enhanced structural integrity and load-bearing capacity provided by the appropriate bonding method. Furthermore, the required force for bending of the single steel sheet is more than half of the bending force of each SPS laminates. This highlights the positive impact of the polymeric layer on the bending properties of these symmetric laminates. Figure 11 also reveals that the maximum force required for permanent deformation occurs during the final third of the loading period. Therefore, the drawing force in this process is low, and immediately after the contact of the laminate flange area with the upper die, the process of plastic deformation begins, and the force increases.
As the laminate is bent, the polymer layer experiences compression forces, causing its phenomena may arise as a result of transverse flow, thereby causing variations in the volume fraction. In fiber metal laminates (FMLs), if the polymer is subjected to unevenly distributed pressure, leading to the heterogeneous distribution of the polymer layer between two metal layers. These defects commonly occur in fiber metal laminates when the forming tool does not fully travel, the appropriate forming force is not achieved, or there are inaccuracies in the dimensions of the forming tool. When a pressure gradient is introduced, both thinning and thickening phenomena may arise as a result of transverse flow, thereby causing variations in the volume fraction [48]. In fiber metal laminates (FMLs), if the polymer is subjected to unevenly distributed pressure, it will be squeezed outwards transversely towards adjacent regions, leading to polymer accumulation and thickening [49–51]. In SPS forming, limited thinning can be observed under stretching. In accordance with Figure 12, it is evident that a higher compaction force applied at the bottom radii region can lead to a decrease in thickness. Compaction involves the consolidation of the polymer layer due to plastic deformation. As the laminate is bent, the polymer layer experiences compression forces, causing its thickness to decrease. This reduction in thickness is the result of polymer molecules shifting and reorienting under stress. The degree of consolidation depends on the bending radius, the polymer’s mechanical properties, and the applied load. Moreover, within the polymer matrix, intermolecular forces play a crucial role in the compaction process. Van der Waals forces, hydrogen bonding, and other intermolecular interactions between polymer chains influence their ability to reconfigure and compact under stress [51–53]. These forces contribute to the material’s viscoelastic behavior and its response to bending forces. On the contrary, polymer accumulation during the SPS forming process predominantly occurs in the stretching zones, where the material experiences tensile stress. This accumulation is a direct consequence of the polymer layer being subjected to stretching forces during bending. As the material stretches, polymer molecules within the layer tend to aggregate, forming localized thickening regions [50,54]. This non-uniformity in thickness distribution can sig-

**Figure 11.** Bending force–time diagram of SPS laminates and steel sheet.

Generally, during the hat-shaped forming process due to the presence of polymeric core, the interior and exterior skin sheets experience different deformation mode in the bent area (the bottom corner of the SPS sheet), and thereby, the strain state of the exterior and interior skin sheets tends to reach tension and compression, respectively. This phenomenon produces various surface and interface defects in the three-layer composites. Figure 12 depicts the hat-shaped bending process, both before and after unloading, along with the resulting deformed SPS specimen. There is no evidence of typical mechanical defects such as delamination and wrinkling in the anticipated areas, which suggests the high bond strength of the laminates. However, the occurrence of non-destructive defects such as compaction and accumulation of the polymeric core cannot be prevented. Compaction and accumulation are defects that arise due to unevenly distributed pressure, leading to the heterogeneous distribution of the polymer layer between two metal layers. These defects commonly occur in fiber metal laminates when the forming tool does not fully travel, the appropriate forming force is not achieved, or there are inaccuracies in the dimensions of the forming tool. When a pressure gradient is introduced, both thinning and thickening phenomena may arise as a result of transverse flow, thereby causing variations in the volume fraction [48]. In fiber metal laminates (FMLs), if the polymer is subjected to unevenly distributed pressure, it will be squeezed outwards transversely towards adjacent regions, leading to polymer accumulation and thickening [49–51]. In SPS forming, limited thinning can be observed under stretching. In accordance with Figure 12, it is evident that a higher compaction force applied at the bottom radii region can lead to a decrease in thickness. Compaction involves the consolidation of the polymer layer due to plastic deformation. As the laminate is bent, the polymer layer experiences compression forces, causing its thickness to decrease. This reduction in thickness is the result of polymer molecules shifting and reorienting under stress. The degree of consolidation depends on the bending radius, the polymer’s mechanical properties, and the applied load. Moreover, within the polymer matrix, intermolecular forces play a crucial role in the compaction process. Van der Waals forces, hydrogen bonding, and other intermolecular interactions between polymer chains influence their ability to reconfigure and compact under stress [51–53]. These forces contribute to the material’s viscoelastic behavior and its response to bending forces. On the contrary, polymer accumulation during the SPS forming process predominantly occurs in the stretching zones, where the material experiences tensile stress. This accumulation is a direct consequence of the polymer layer being subjected to stretching forces during bending. As the material stretches, polymer molecules within the layer tend to aggregate, forming localized thickening regions [50,54]. This non-uniformity in thickness distribution can sig-
nificantly impact the mechanical and structural properties of the final product. Specifically, regions with accumulated polymer may exhibit heightened flexibility and resilience due to the thicker polymeric layer, while adjacent areas with thinner polymer layers may be more susceptible to deformation or failure. Nonetheless, in the case of SPS laminates, it is noteworthy that the extent of thinning and thickening observed remains within tolerable limits, and it does not reach a magnitude that would induce defects or fracture.

Figure 12. Hat-shaped bending process: (a) before unloading, (b) after unloading, and (c) deformed SPS specimen.

The predominant factor that prevents debonding in the steel/polymer interface is the mechanical interlocking (or hooking), as illustrated in Van der Leeden and Frens [55], who introduced the surface irregularities of the metallic sheets as the main factor leading to the emergence of mechanical interlocking, as illustrated in Figure 13. These irregularities contribute to an increased interfacial area, thereby enhancing the bond strength. While only type “b” may function as the primary source of mechanical interlocking, other irregularities (types “a” and “c”) could also induce mechanical interlocking, depending on the loading direction. The effectiveness of mechanical interlocking is significantly influenced by the roughness, porosity, and irregularities of the surface, but this is only observed under the adequate wetting of the substrate by the adhesive or polymeric layer. Figure 14 shows the cross-section of the SPS specimens in the bent area with the absence of delamination, wrinkling, and debonding. Therefore, it can be concluded that the strain distribution at the
bottom corner of the formed SPS sheets is lower than the forming, wrinkling, and fracture limit curves of the materials.

Figure 13. Three types of surface irregularities (Adapted from Ref. [55]).

Figure 14. Cross-section of the bent area of the SPS laminates: (a) L-30, (b) L-40, (c) L-50, and (d) L-60.
Considering that the bending of the SPS sheets leads to the creation of two neutral surfaces across the thickness of the laminate sheets (due to the lower flow stress of the polymeric core compared to those of the steel skins), by applying the bending force on the SPS sheet, the opposite shear stresses are formed in the interior and exterior layers of the laminate sheet in the wall area [22]. However, in this case, there is no core layer slipping and debonding. This defect-free interface can be the result of the high shear strength of the polymeric core (higher shear modulus) and the optimal bonding technique. Figure 15 illustrates the cross-section of the wall area of the SPS sheets. It can be seen that, due to the presence of the mechanical interlocks in the contact area of the polymeric core and steel skins, the generated shear stress cannot exceed the bond strength of the laminates.

![SEM images of SPS laminates](image1.png)

Figure 15. Cross-section of wall area of the SPS laminates: (a) L-30, (b) L-40, (c) L-50, and (d) L-60.

The side-wall springback results for the SPS laminates and single steel sheet are shown in Figure 16a. According to the diagrams, it is apparent that, in three-layer laminates, the initial springback of the side wall (at \( t = 0 \) min) decreases with the increase in the volume fraction of the polymer. The inverse relationship between the springback and the interlayer thickness for both steel/PP/steel and steel/PVC/steel is also reported by Weiss et al. [24]. However, Kella and Mallick [56] observed a different relationship between the core thickness and wall springback angle in the U-channel bending of AA5182-O/polypropylene/AA5182-O laminates. They revealed that, by increasing the core thickness while keeping the skin thickness constant, the wall springback angle initially decreases (up to a certain threshold) and then increases. The reason for this observation was attributed to the introduction of significantly high effective plastic strain (EPS) values in both upper and lower aluminum skins of the thicker sandwich laminates, resulting in an excessive thinning of the U-channel walls. As there is a similar behavior (inverse correlation between the extent of springback and the thickness of the material) exhibited by the monolithic steel sheet, it can be concluded that the bonding between the steel and the...
and the interlayer thickness for both steel/PP/steel and steel/PVC/steel is also reported by Weiss et al. [24]. However, Kella and Mallick [56] observed a different relationship between the core thickness and wall springback angle in the U-channel bending of AA5182-O/polypropylene/AA5182-O laminates. They revealed that, by increasing the core thickness while keeping the skin thickness constant, the wall springback angle initially decreases (up to a certain threshold) and then increases. The reason for this observation was attributed to the introduction of significantly high effective plastic strain (EPS) values in both upper and lower aluminum skins of the thicker sandwich laminates, resulting in an excessive thinning of the U-channel walls. As there is a similar behavior (inverse correlation between the extent of springback and the thickness of the material) exhibited by the monolithic steel sheet, it can be concluded that the bonding between the steel and the polymer is sufficiently robust, thereby enabling the three-layered laminates to function like a homogenous metallic sheet. Also, the wall springback angle of the single steel sheet is almost equal to that of the L-60 laminate. At prolonged times, the delayed springback of the side wall first increases and then stabilizes. Therefore, it appears that the delayed springback of steel/polyurethane/steel laminates is completed in the range from 0 to 800 min. The adjustment and restructuring of the molecular chains in the polymeric material leads to a reduction in the introduced shear reaction force (stress relaxation) in the range of \( t < 800 \text{ min} \). Figure 16a also reveals that the increase in the amount of delayed springback has a direct relationship with the volume fraction of the polymeric core. Therefore, it can be concluded that this characteristic is more dependent on the mechanical and physical properties of the polymeric layer. The analysis of property error correlations indicated that strain relaxation was the primary factor influencing springback in laminates [57]. Conversely, in polymers, both stress and strain relaxation were identified as key controlling properties of springback. Kleiner et al. [58] showed that placing the SPS deformed samples in heated tools accelerates the stress relaxation of the polymer and reduces the delayed springback time period.

Figure 16. The measured (a) side-wall springback angle and (b) flange springback angle of the SPS laminates and monolithic steel sheet.

Figure 16b compares the flange springback of the SPS laminates and the single steel sheet. It can be seen that the increase in the volume fraction of the polymer decreases the initial springback of the flange area. The measured springback angle of the monolithic sheet is lower than that of the L-60 sheet and almost equal to the measured amount of L-60. The comparison of the springback angles of the flange area and side wall of the SPS specimens shows that the measured amounts of initial and delayed springback for the flange area is lower than that of the side wall. It has been asserted that the flange springback angle exhibits a strong correlation with the side-wall curl in U-channel bending [56]. Moreover, the delayed springback of the flange area occurs in a shorter time period compared to
the side wall. Similar to the side walls, a more delayed springback is observed with the increase in the volume fraction of the interlayer. The noticeable point is that no delayed springback was observed in L-60, similar to the monolithic steel sheet. This means that the thin polymeric layer with a thickness of 0.26 mm has no significant effect on the delayed springback of this sheet.

The ultimate springback value of the SPS sheets is directly proportional to the normal anisotropy (R-value). In general, a higher R-value (≥1) minimizes the thinning of sheet during the forming processes. Furthermore, a decrease in the R-value with the increase in the polymer to steel volume fraction ratio shows a negative effect of the presence of the polymeric core on the thinning process. Although this may affect the specimen quality in processes such as deep drawing, there is no considerable change in the thickness of the sheets in fillet areas in this type of bending.

The Hollomon strain-hardening exponent represents the ability of the material to uniformize the strain distribution over the plastic deformed area prior to the diffuse necking. The reason for this inverse relationship of the n-value and the ultimate springback of the SPS laminate sheets is that the increase in the overall thickness of the SPS sheet increases the work-hardening effect, and the follow-up deformation of the deformed material will be difficult. This behavior can be related to the presence of the thicker polymeric core. By comparing the normal anisotropy and work-hardening exponent values of the skin steel and composite sheets, it can be concluded that the steel sheet has a dominant effect on these two properties with a more influential role.

Table 4 reveals that an increase in the yield strength of the SPS laminates corresponds to an increase in the ultimate springback observed in both of the side wall and flange. The relationship between the yield strength and the springback can be attributed to the mechanical response of the material during bending. As the yield strength of the SPS laminates increases, there is a corresponding increase in the ratio of the elastic to plastic strain. This signifies that a larger portion of the overall deformation during the bending is attributed to the elastic deformation, as opposed to the plastic deformation. Practically, this means that the laminated steel sheets with a higher yield strength exhibits a higher tendency to recover their original shape after undergoing bending, resulting in a larger springback.

Table 4. The effect of mechanical properties of composite and steel sheets on the ultimate springback of the flange and wall.

<table>
<thead>
<tr>
<th>Sample</th>
<th>R-Value</th>
<th>n-Value</th>
<th>$\sigma_y$ (MPa)</th>
<th>YPE (%)</th>
<th>Elastic Modulus (GPa)</th>
<th>Ultimate Side-Wall Springback (Deg)</th>
<th>Ultimate Flange Springback (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-30</td>
<td>1.63</td>
<td>0.268</td>
<td>97</td>
<td>4.8</td>
<td>86.3</td>
<td>10</td>
<td>6.2</td>
</tr>
<tr>
<td>L-40</td>
<td>1.65</td>
<td>0.252</td>
<td>123</td>
<td>4.2</td>
<td>117.8</td>
<td>11.4</td>
<td>8.1</td>
</tr>
<tr>
<td>L-50</td>
<td>1.71</td>
<td>0.248</td>
<td>137</td>
<td>3.9</td>
<td>158.4</td>
<td>14</td>
<td>9.1</td>
</tr>
<tr>
<td>L-60</td>
<td>1.73</td>
<td>0.24</td>
<td>163</td>
<td>3.7</td>
<td>174.3</td>
<td>15.7</td>
<td>10</td>
</tr>
<tr>
<td>Steel sheet</td>
<td>1.66</td>
<td>0.22</td>
<td>147</td>
<td>4</td>
<td>209.4</td>
<td>12</td>
<td>6</td>
</tr>
</tbody>
</table>

The yield point elongation is another material characteristic that contributes to the extent of the springback. As indicated in Table 4 and Figure 17, the SPS laminates with a higher YPE exhibit lower springback compared to those with low YPE. This reduction in the springback is due to the fact that, for the SPS laminates with a high YPE, a greater proportion of the stress tends to concentrate the thinning locally; as a result, a smaller proportion of the total strain is elastic (reversible), leading to a decrease in the springback.
Figure 17. Comparison between the stress–strain curves of SPS laminate sheets.

Typically, a higher slope in the unloading stress–strain curve, which corresponds to a higher elastic modulus (Young’s modulus), results in a shift towards less springback. This suggests that materials with a higher elastic modulus tend to exhibit reduced springback compared to materials with a lower elastic modulus. However, in this research, a direct relationship between the elastic modulus and the ultimate springback of the side wall and flange was observed. Therefore, it appears that the positive effects stemming from other material characteristics, such as the R-value (anisotropy coefficient), n-value (strain hardening exponent), yield strength, and yield point elongation, compensate the potentially negative influence of the elastic modulus on the springback.

Figure 18 depicts the side-wall curve factor of different specimens. It can be seen that the side-wall curl factor increases with the increase in volume fraction of the polymer. The lower the side-wall curl factor, the larger the radius of the curl (ρ), and therefore, the more obvious the wall curve defect. Typically, the St14/TPU/St14 laminates show a smaller side-wall curl due to the presence of the low-carbon steel in their structure, which has a high work-hardening exponent. Therefore, the difference in the side-wall radius of the different specimens is very small. Although the deformation of the thicker sheets is more severe than the thinner sheets, the larger moment of inertia of the thicker sheet reduces the side-wall curl severely. Studies have shown that the radius of the side-wall curl can be a complex function of the strain-hardening rate, the radius of the punch, friction and the blank holder force [36,46]. It has been demonstrated that, as the thickness of the AL/PP/AL laminate increases, the radius of curvature increases, causing a decrease in the side-wall curl; however, this trend is reversed after reaching a certain thickness where the laminate shows a decreased radius of curvature with the increase in the overall thickness [56]. This is attributed to the high plastic strains in the lower and upper skins of sandwich laminates with a core thickness exceeding a certain threshold.
Figure 18. The side-wall curve factor of different specimens.

3.2.2. Three-Point Bending

Figure 19 displays the force–extension curve of the SPS sheets as well as the monolithic steel sheet. As expected, due to the elastic behavior of sheets, the force required to bend the laminates increases linearly at the first stage of loading. In the plastic region, the specimen exhibits permanent deformation, and the force increases non-linearly until it reaches its maximum value before decreasing gradually. The phenomena of yielding and hardening occur between the end of the linear region, which represents the highest point in the elastic region, and the ultimate force, which represents the highest point in the plastic region [59]. According to Harhash et al. [25], the observed decrease in the bending force after reaching the maximum value could be attributed to three possible explanations: (a) the occurrence of cracking, (b) simultaneous changes in contact and geometrical conditions leading to alterations in friction, or (c) delamination at the metal/polymer interface. For these specimens, the gradual force reduction is correlated to geometrical changes. It can be concluded that no premature visible failure occurs in any of the samples until the operation is completed, as there is no sudden drop in the curves. The similarity between the trend of the curves of the three-layer laminates and the curve of homogenous steel sheet is also another sign of lacking failure in the SPS structure. The greater portion of the load-bearing capacity of the laminates relates to the presence of the polymeric layer and its ability to absorb and distribute the stress. Similar to the hat-shaped bending, the three-point bending of the three-layer sheets requires a greater force to bend as the core layer thickness increases. Harhash et al. [25] reported the same behavior for TS245/polyolefin (PP-PE)/TS245 composites with varying core thicknesses. Figure 19 also shows that the bending force required for the sheet decreases with the increase in the material strength.

Figure 20 shows the pre-unloading and post-unloading of three-point bending process of the SPS laminate. In comparison to the hat-shaped bending specimen, there is no evidence of the occurrence of springback immediately subsequent to the unloading process. Based on the optical microscopic image presented in Figure 20c, it is evident that the steel/polymer/steel laminate subjected to three-point bending tests does not exhibit symptoms of either debonding at the steel/polymer interface in the legs or wrinkling deformations in the bent region. Hook-like interlocks, acting as fasteners between two components, effectively prevent the sliding of two skin sheets relative to each other. Similar to hat-shaped bending samples, under bending load, the polymeric core can experience compaction, especially in the load application region. This is generally attributed to the relatively low elastic modulus of the polymer compared to the steel layers. The compaction of the polymer core leads to a redistribution of stresses within the composite, potentially
causing stress concentrations in the steel layers [54]. It also may lead to kinematic constraints, restricting the free movement of the adjoining steel layers and thereby altering the overall bending behavior [60]. The compaction can cause the polymer to reach or exceed its compressive yield strength, leading to micro-cracking or other modes of mechanical failure within the core [49]. On the contrary, accumulation, which generates particularly in leg areas, can increase the shear stresses at the steel–polymer interface, making debonding more likely. The accumulation phenomenon can introduce non-linearities in the stress–strain response, complicating the mechanical behavior and making it more challenging to mode. The asymmetry introduced by accumulation can lead to mechanical anisotropy, where the mechanical properties of the composite vary depending on the direction of load application [61]. Similar to hat-shaped bending specimens, it should be emphasized that the three-point bending tests on SPS laminates reveal that the defects, such as compaction or accumulation, remain within permissible bounds. These defects do not attain a critical scale that could potentially compromise the structural integrity of the composite.

The microscopic examination of the cross-section of three-point bent SPS specimens was meticulously carried out using a scanning electron microscope. This advanced imaging technique allows for a detailed exploration of the interface of the metal/polymer. Upon analyzing the comprehensive findings presented in Figure 21, a noteworthy observation emerged: the complete absence of any symptoms of debonding or sliding between the distinct layers at the interface of the fillet area of the SPS specimens. This signifies a robust bonding mechanism between these layers, which is crucial for the mechanical performance of the SPS specimens under the three-point bending conditions. These findings have significant implications for the overall understanding of the behavior of the material and its suitability for the intended applications. Since debonding, surface dimples, interface microvoids, while-forming wrinkling, and tensile and shear failure of the core have been reported for various metal/polymer/metal laminates with different bonding processes [61,62]; it is evident that the direct roll bonding method employed in this study demonstrates its superiority over other conventional techniques, making it a promising choice for future research.

Figure 19. Force–extension of the specimens in three-point bending test.
relatively low elastic modulus of the polymer compared to the steel layers. The compaction of the polymer core leads to a redistribution of stresses within the composite, potentially causing stress concentrations in the steel layers [54]. It also may lead to kinematic constraints, restricting the free movement of the adjoining steel layers and thereby altering the overall bending behavior [60]. The compaction can cause the polymer to reach or exceed its compressive yield strength, leading to micro-cracking or other modes of mechanical failure within the core [49]. On the contrary, accumulation, which generates particularly in leg areas, can increase the shear stresses at the steel–polymer interface, making debonding more likely. The accumulation phenomenon can introduce non-linearities in the stress–strain response, complicating the mechanical behavior and making it more challenging to model.

The asymmetry introduced by accumulation can lead to mechanical anisotropy, where the mechanical properties of the composite vary depending on the direction of load application [61]. Similar to hat-shaped bending specimens, it should be emphasized that the three-point bending tests on SPS laminates reveal that the defects, such as compaction or accumulation, remain within permissible bounds. These defects do not attain a critical scale that could potentially compromise the structural integrity of the composite.

Figure 20. Three-point bending process: (a) before unloading, (b) after unloading, and (c) deformed SPS specimen.

According to Table 5, since the flexural strength has an inverse relationship with the square of the overall thickness and also has a direct relationship with the required force (Figure 19) to bend the laminates, its decrease with the increase in the polymer volume fraction is reasonable. The specific flexural strength (which was calculated by dividing the flexural strength by the measured density) of the SPS sheet increases with the decrease in the core thickness. These results show that the values of the flexural strength and the specific flexural strength of the steel sheet are higher than all the three-layer laminates. The flexural modulus decreases with the increase in the polymer volume fraction, since this parameter has an inverse relationship with the cube of the overall thickness. Hua et al. [63] related the inverse relationship between core thickness and both flexural strength and modulus to the lower flexural strength and modulus of the polymeric sheet. The bending resistance (flexural rigidity) of the SPS sheet is directly proportional to the volume fraction of the polymeric core. By inserting the flexural rigidity values into Table 5 in Equation (10), the equivalent thickness of the three-layer sheets was calculated. These equivalent thicknesses represent the monolithic steel sheet with a thickness that has a flexural rigidity that equals that of the corresponding three-layer sheet. These results reveal that the
equivalent thickness is almost equal to the thickness of each of the three-layer sheets. Considering the lower density of three-layer sheets compared to the steel sheets, it can be concluded that a higher flexural stiffness along with a lighter weight makes the sheets advantageous in various industries. According to Kim and Yu [64], an optimum volume fraction of the polymeric core exists, leading to a proper combination of the lightweight effect and dent resistance in metal/polymer/metal composites.

The microscopic examination of the cross-section of three-point bent SPS specimens was meticulously carried out using a scanning electron microscope. This advanced imaging technique allows for a detailed exploration of the interface of the metal/polymer. Upon analyzing the comprehensive findings presented in Figure 21, a noteworthy observation emerged: the complete absence of any symptoms of debonding or sliding between the distinct layers at the interface of the fillet area of the SPS specimens. This signifies a robust bonding mechanism between these layers, which is crucial for the mechanical performance of the SPS specimens under the three-point bending conditions. These findings have significant implications for the overall understanding of the behavior of the material and its suitability for the intended applications. Since debonding, surface dimples, interface microvoids, while-forming wrinkling, and tensile and shear failure of the core have been reported for various metal/polymer/metal laminates with different bonding processes [61,62]; it is evident that the direct roll bonding method employed in this study demonstrates its superiority over other conventional techniques, making it a promising choice for future research.

![Figure 21](image.png)

Table 5. Calculated flexural properties and density of the monolithic steel and SPS sheets.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Flexural Strength (MPa)</th>
<th>Flexural Modulus (MPa)</th>
<th>Measured Density (gr/cm$^3$)</th>
<th>Specific Flexural Strength (MPa·cm$^3$/gr)</th>
<th>Flexural Rigidity (GPa·mm$^3$)</th>
<th>$S_{eq}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-30</td>
<td>41.5</td>
<td>1151.7</td>
<td>4.2</td>
<td>9.82</td>
<td>145.76</td>
<td>2.02</td>
</tr>
<tr>
<td>L-40</td>
<td>54.04</td>
<td>1617</td>
<td>4.57</td>
<td>11.82</td>
<td>91.93</td>
<td>1.73</td>
</tr>
<tr>
<td>L-50</td>
<td>71.88</td>
<td>2510.24</td>
<td>5.47</td>
<td>13.14</td>
<td>53.94</td>
<td>1.45</td>
</tr>
<tr>
<td>L-60</td>
<td>103.13</td>
<td>4154.57</td>
<td>6.3</td>
<td>16.36</td>
<td>31.81</td>
<td>1.22</td>
</tr>
<tr>
<td>Steel sheet</td>
<td>283</td>
<td>72098</td>
<td>7.8</td>
<td>36.28</td>
<td>1.59</td>
<td>---</td>
</tr>
</tbody>
</table>
The results of the measured springback of the three-layer laminates and the monolithic steel sheet show the absence of the springback in the three-point bending immediately after the unloading. As the time increases from 0 to 1000 min, the springback of all sheets increases initially before reaching a constant quantity. Since the springback behavior of the specimens in the three-point bending process is similar to the hat-shaped bending process, all the relationships between the mechanical properties and the springback values are similar to the hat-shaped bending results. According to the results depicted in Figure 22, it can be inferred that an increase in the core volume fraction results in a decrease in the springback angle. This correlation demonstrates that the modification of the core volume fraction has a significant influence on the bending behavior. Ahmed and Chatti [59] stated that, in analytical, numerical, and experimental examinations of three-point bending, the springback of steel/polyurethane/steel laminates exhibited a decrease with the increase in the core thickness.

![Figure 22. The measured springback angle of the SPS laminates after performing the three-point bending test.](image)

### 4. Conclusions

Composite sheets with varying nature and thicknesses have been developed to meet specific requirements in the automotive, construction, and aerospace industries. This study focuses on laminated metal sheets, emphasizing formability and bending defects. Factors such as material properties, layer thickness ratios, bonding at interfaces, joining methods, and tool characteristics play crucial roles in determining formability, shape fixability, and fracture resistance during manufacturing and service. The bonding techniques and forming tools significantly influence the service life and functionality of engineered structures in specific environments.

The study fabricated steel/polymer/steel sandwiched composites using the direct roll bonding technique without adhesive agents. Direct roll bonding is a solid-state manufacturing process known for the continuous production of composite materials by creating bonds between sheets, with or without heat application. The research examined the flexural properties and geometric defects of the composites through unconstrained hat-shaped bending, three-point bending, and uniaxial tensile tests. Additionally, scanning electron microscopy (SEM) analysis was utilized to investigate the interface of the specimens.

The main conclusions from this work are presented below.

1. Due to the stress relaxation in the polymeric layer of the bent samples, there is a delay in the springback, which stabilizes in a time interval from 0 to 1000 min.
2. The higher the volume fraction of the polymer, the lower the ultimate springback in the bent specimens. The reason for this is an increase in the n-value and YPE, while there is a decrease in the yield strength, elastic modulus, and R-value with the increase in the thickness of the polymeric layer.

3. As the SPS sheets’ thickness increases, the maximum required bending moment increases, which consequently increases the bending force. The bending rigidity of the three-layer sheets is equal to the bending rigidity of the homogeneous steel sheet at the same thickness and lighter weight.

4. Although the required force to bend the three-layer sheets increases with the increase in the volume fraction of the polymeric layer, the flexural strength and the flexural modulus decrease due to the increase in the total thickness.

5. The SEM analysis of the cross-section of the metal/polymer layers in the structure of the three-layer laminates shows that the presence of the mechanical interlocks at the metal/polymer interface prevents the delamination or slippage between the layers after the bending processes. Therefore, it can be concluded that the materials and the bonding method have been correctly selected.

6. In both hat-shaped bent and three-point bent specimens, defects such as compaction or accumulation remain within permissible bounds and do not attain a critical scale that could potentially compromise the structural integrity of the composite.

Roll bonding offers a solution for joining non-homogeneous materials, with a specific focus on improving formability and reducing weight. The roll-bonded SMS has demonstrated significant potential in terms of bendability. Further research is required to modify the core and skin materials and layers thicknesses, as well as to investigate their performance under asymmetrical conditions. Moreover, conducting experimental and analytical analyses to further understand the formability, weldability, and impact resistance of this laminates is essential.

**Author Contributions:** Conceptualization, P.M., P.W. and A.A.; Methodology, P.M. and P.W.; Software, P.M.; Validation, P.M., M.S. and A.A.; Formal analysis, P.M., M.S., W.J.B., P.W. and A.A.; Investigation, P.M., M.S., W.J.B., P.W. and A.A.; Resources, P.W. and A.A.; Data curation, P.M. and A.A.; Writing—original draft, P.M.; Writing—review & editing, P.M., M.S., W.J.B., P.W. and A.A.; Visualization, M.S. and A.A.; Supervision, A.A.; Project administration, A.A.; Funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Lubimyi, N.S.; Polshin, A.A.; Gerasimov, M.D.; Tikhonov, A.A.; Antsiferov, S.I.; Chetverikov, B.S.; Ryazantsev, V.G.; Brazhnik, J.; Ridvanov, I. Justification of the use of composite metal-metal-polymer parts for functional structures. *Polymers* 2022, 14, 352. [CrossRef]


34. Davies, R.G. ‘Side-wall curl’ in high-strength steels. J. Appl. Metalwork. 1984, 3, 120–126. [CrossRef]


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.