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Influence of Rolling Temperature on the Mechanical and Formability Properties of AA1050/AZ31/AA1050 Roll-Bonded Sheets

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Abstract. With the increasing demand for lightweight materials, the combination of aluminum and magnesium sheets enables the development of advanced laminates with a balanced combination of strength and ductility, making them suitable for forming applications. This work investigates the effect of rolling temperature on the mechanical behavior and formability of AA1050/AZ31/AA1050 sheets produced by roll bonding in the temperature range of 250–450°C. Tensile tests showed that the yield stress is weakly affected by rolling temperature, whereas the ultimate tensile strength increases up to 350°C and then stabilizes. The elongation at fracture increases monotonically with temperature, indicating improved ductility at higher rolling temperatures. Microhardness measurements revealed softening of the aluminum sheets with increasing temperature, while limited variations were observed in the AZ31 sheet. Formability was evaluated by Erichsen Cupping test. The maximum load and extension at break remained nearly constant over the investigated temperature range; however, higher rolling temperatures led to reduced delamination and improved interfacial bonding integrity during deformation. The results indicate that roll bonding at elevated temperatures promotes better strain distribution and enhanced bonding quality. Overall, roll bonding at 450°C provides the most favorable combination of mechanical performance, formability, and interfacial stability, making the produced sheets suitable for lightweight forming applications.

Introduction

The increasing demand for lightweight structural materials with enhanced mechanical performance has driven significant research efforts toward the development of metal–metal sheets composites; aluminum and magnesium are two key lightweight metals widely employed to achieve weight reduction [1].

In general, aluminum alloys combine low density with good corrosion resistance, high thermal and electrical conductivity, and excellent formability, making them highly versatile materials for structural and semi-structural applications. Their mechanical properties can be tailored over a wide range through alloying and thermomechanical treatments (including heat treatments and work hardening) [2,3], allowing a balance between strength, ductility, and manufacturability.

Magnesium alloys, on the other hand, are some of the lightest structural metallic materials currently in use and are valued for their high specific strength and stiffness [4]. These characteristics make them particularly attractive for aggressive lightweight design. However, their broader adoption is limited by intrinsic drawbacks, such as reduced ductility and formability at room temperature, pronounced anisotropy, and generally lower corrosion resistance compared to aluminum alloys due to its higher chemical reactivity [5,6]. As a result, significant research efforts are focused on overcoming these limitations through alloy design, processing innovations, and the development of hybrid or composite material solutions [7].

Roll Bonding (RB) is an effective solid-state joining process for the fabrication of layered metal composites [8], in which two or more metal sheets are stacked and plastically deformed together by rolling, promoting bonding through severe plastic deformation at the interface. Prior to rolling, the sheet surfaces are typically cleaned and mechanically roughened to remove oxide layers and enhance intimate contact [9,10]. When repeated through multiple cycles with a 50% reduction, Roll Bonding can be extended to Accumulative Roll Bonding (ARB), a Severe Plastic Deformation (SPD) technique capable of producing multilayer composites with refined or ultrafine-grained microstructures and enhanced mechanical properties, first introduced by Saito et al. [11].

Early studies have shown that severe plastic deformation induced by ARB can produce high-quality Al/Mg interfaces and refined microstructures, leading to improved mechanical properties with increasing ARB cycles. These improvements can generally be attributed to work hardening and grain refinement in both constituents [12,13]. Temperature and reduction percentage strongly affect interlayer bonding; an increase in either parameter, leads to improved bonding [14].

However, the evolution of the mechanical properties in Al/Mg composites is non-linear; for instance, it has been observed that while strength initially increases due to strain hardening and grain refinement, it may decrease in later cycles (typically after the 3rd or 4th pass) due to the loss of structural integrity in the magnesium layers and the presence of some intermetallic compounds (IMCs) [15].

More recent investigations have explored modified ARB routes, such as asymmetric accumulative roll bonding (A-ARB), which introduces additional shear strain through different roll speeds. This approach has been shown to improve strain distribution and further refine the grain structure, potentially enhancing the mechanical bonding at the interface [16]. Furthermore, post-processing heat treatments (annealing) have been studied to mitigate the high internal stresses induced by ARB. While annealing at moderate temperatures (around 200°C) can improve ductility through recovery and recrystallization of the Al and Mg layers, higher temperatures rapidly accelerate IMCs growth, which can negatively affect the composite's overall performance [17].

Despite the results shown in literature, most existing studies primarily address microstructural evolution and uniaxial tensile behavior. However, in industrial applications, sheet materials are rarely utilized in their flat, as-rolled state; they are almost always subjected to secondary forming processes involving complex stress states. Consequently, formability assessments such as the Erichsen cupping test are of paramount importance to evaluate the material's suitability for real-world manufacturing. Specifically, the role of rolling temperature in controlling the onset of interfacial damage and the eventual fracture of the protective cladding during forming remains a critical gap in current research. The present work aims to bridge this gap by investigating AA1050/AZ31/AA1050 composite sheets produced by roll bonding. By systematically correlating tensile behavior, fracture morphology, and interfacial stability, this study provides new insights into the processing–deformation–formability relationship using Erichsen cupping test.

Materials and Methods

The materials investigated in this study are a commercially pure aluminum alloy AA1050 (99.5 wt.% Al min.) and the AZ31 magnesium alloy, which contains approximately 3 wt.% Al and 1 wt.% Zn. AA1050 was selected for its excellent corrosion resistance, high ductility, and good workability, while AZ31 was chosen due to its low density and high specific mechanical strength. The combination of these two alloys enables the production of lightweight multilayer sheets with complementary physical and mechanical properties.

The AA1050 alloy was supplied in sheet form with a thickness of 1.2 mm, whereas the AZ31 alloy was supplied in sheet form with a thickness of 0.8 mm. Both materials were cut to identical dimensions of 100 mm in length and 50 mm in width prior to processing. The thickness ratio (1.2 mm Al / 0.8 mm Mg) was selected based on industrial requirements to ensure process stability during roll bonding, improved bonding quality, and protection of the Mg core from oxidation and cracking.

While a higher Mg fraction could increase specific strength, it would reduce formability and increase the risk of interfacial damage due to the lower ductility of AZ31. The chosen configuration therefore represents an industrially driven compromise between manufacturability, interfacial integrity, and mechanical performance. Future work will specifically address the optimization of the Al/Mg thickness ratio to further improve lightweight efficiency and strain partitioning.

Roll Bonding Procedure

Multilayer composite sheets were produced by Roll Bonding (RB). Prior to bonding, the surfaces of the AA1050 and AZ31 sheets were mechanically treated by paper grit 80 to remove surface oxides and contaminants and to increase surface roughness, thus enhancing interfacial bonding. The AZ31 magnesium sheets were ground on both surfaces, while the AA1050 aluminum sheets were ground only on the surface intended to be in contact with the magnesium sheet.

The sheets were stacked in an AA1050/AZ31/AA1050 configuration and secured with steel wire at both ends of the stack. Then, the assembled sheet stack was subjected to a preheating treatment in a furnace. Preheating temperatures ranged from 250 °C to 450°C, with increments of 50°C, and a holding time of 10 minutes was adopted for each temperature condition. Immediately after preheating, the sheet stack was extracted from the furnace and rapidly transferred (about 2 sec) to the rolling mill to minimize heat loss due to environmental exposure (Figure 1).

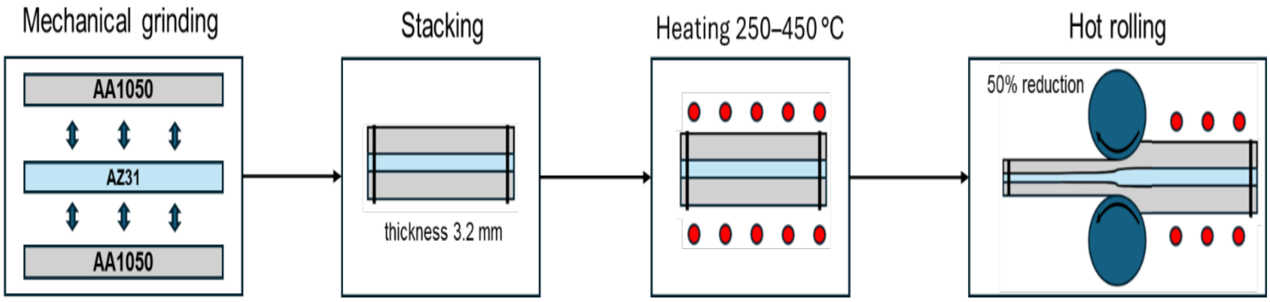


Fig. 1. Scheme of the Roll Bonding process for AA1050/AZ31 composite sheets.

Considering an initial total thickness of 3.2 mm, the rolling gap was set to 1.6 mm, corresponding to the theoretical final thickness after rolling (50% reduction).

Rolling was performed without the use of lubricants. After rolling, the composite sheets were air-cooled to room temperature.

Characterization Methods

Specimens for microstructural and mechanical characterization were extracted from the rolled composite sheets. Cross-sectional samples were mounted using cold-setting resin, followed by standard grinding and polishing procedures to obtain surfaces suitable for optical microscopy in order to study the thickness distribution of each layer at different rolling temperatures. Optical microscopy was employed to investigate the multilayer architecture of the composite sheets, focusing on layer thickness, interface continuity, and macroscopic bonding quality. The thickness of each layer was measured at 15 locations per layer to ensure statistical reliability (Figure 2.a).

Tensile specimens were machined from the composite sheets with the loading direction parallel to the rolling direction (RD). Figures 2.b-c show the tensile samples obtained from the composite sheets and the geometry of the tensile sample respectively.

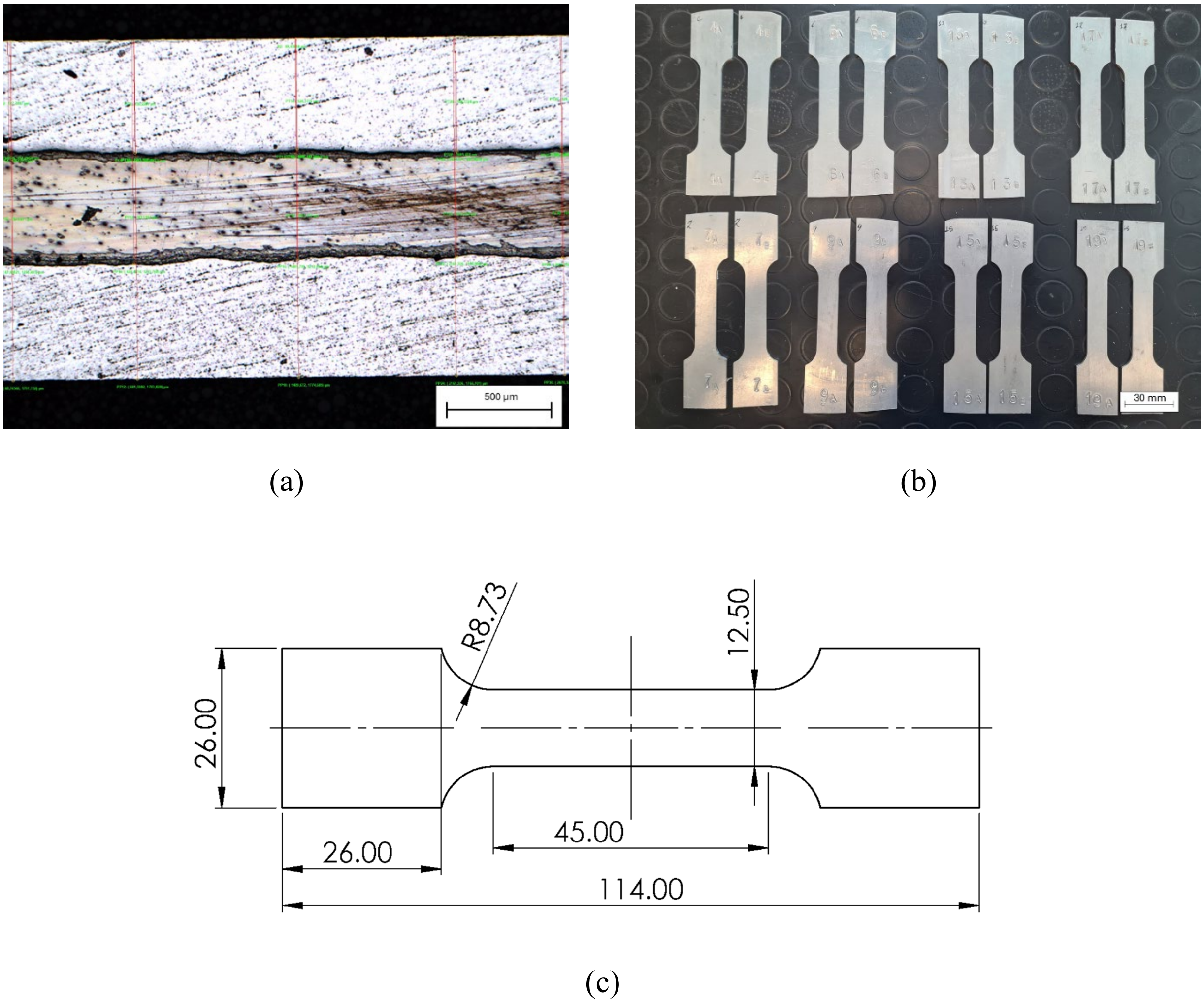
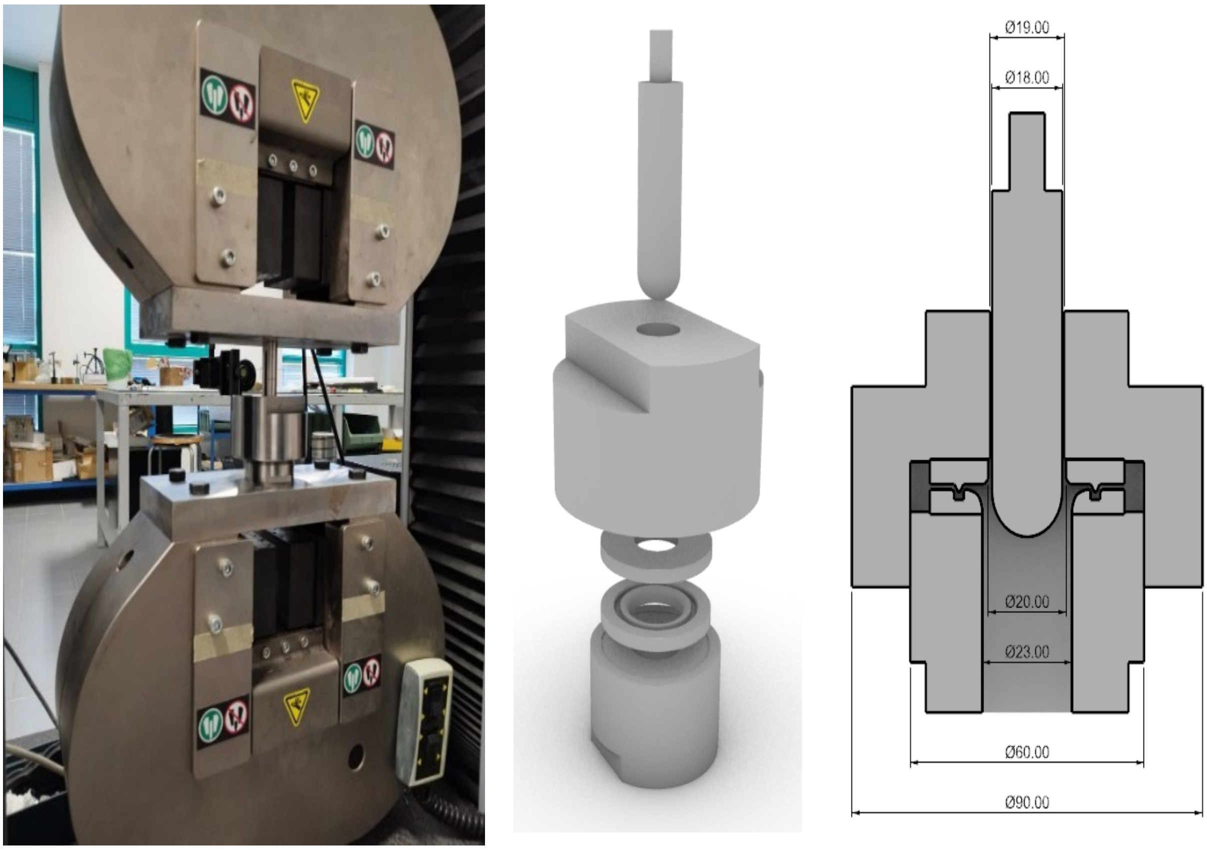


Fig. 2. (a) Cross-sectional image of a representative sample showing multiple thickness measurements of each layer, with the rolling direction aligned with the scale bar; (b) photograph of the specimens after machining, prior to mechanical testing; and (c) geometry and main dimensions of the dog-bone specimen.

Mechanical characterization was carried out by tensile testing to determine the yield strength ($\sigma_{0.2}$), ultimate tensile strength (UTS), Young's modulus (E), and elongation at fracture (A%). Tests were performed using an Instron 5585H universal testing machine equipped with an Instron 2620-601 extensometer, applying a constant displacement rate of 1 mm/min.

Formability tests were also conducted to evaluate the deformation behavior of the composite sheets under bending conditions. Erichsen Cupping tests were performed using the same universal testing machine employed for tensile testing and were carried out with the aid of the mechanical setup with the tools shown in Figure 3.a-c. The system consisted of two clamping rings, a tightening device, and a hemispherical punch (19 mm diameter), all supported by two plates required for mounting the setup on the testing machine. For each rolling condition, three circular specimens with a diameter of approximately 50 mm were prepared. The tests were carried out by placing a Teflon sheet between the punch and the specimen to reduce friction and applying a constant punch displacement rate of 2 mm/min. Load and displacement data were continuously recorded during all tests.

After testing, the specimens were cut along one diameter to examine the bonding between all layers and subsequently observed by optical microscopy.

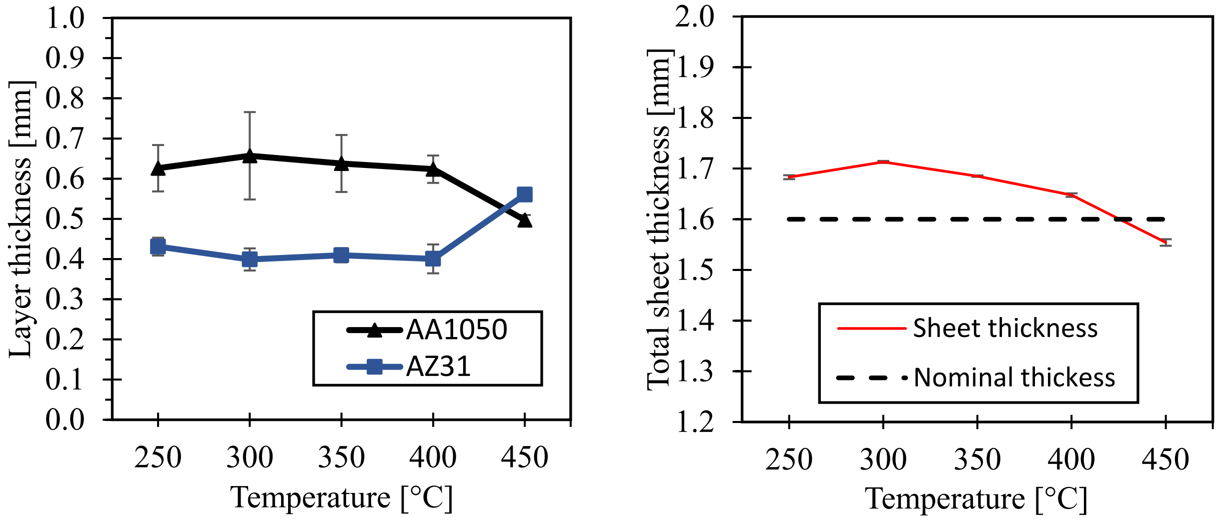


(a) (b) (c)

Fig. 3. Experimental setup for formability testing: (a) mechanical tooling installed on the universal testing machine, (b) three-dimensional view of the tooling assembly, and (c) dimensioned schematic cross-section of the system.

Results and Discussion

Figure 4 shows the effect of rolling temperature on the thickness distribution of the individual AA1050 and AZ31 sheets, as well as on the total composite sheet thickness. The total thickness remains close to the nominal value of 1.6 mm for all processing conditions, confirming good control of the rolling process. However, the thick partitioning between aluminum and magnesium sheets clearly depends on rolling temperature. At lower rolling temperatures, the AA1050 sheets accommodate a larger fraction of the imposed deformation, while the AZ31 sheet remains relatively thicker. With increasing rolling temperature, the thickness of the AA1050 sheets remains nearly constant up to 400°C and then decreases at 450°C, corresponding to a higher deformation level with respect to the initial thickness. Conversely, the thickness of the AZ31 sheet remains approximately constant up to 400°C, then increases at 450°C. This indicates a reduced contribution to plastic deformation at the highest temperature. This opposite trend reflects the different temperature dependence of the flow stress of the two materials [18,19]. At different temperatures, the flow stresses of AA1050 and AZ31 differ, leading to a redistribution of strain between the sheets and a modification of deformation partitioning during roll bonding.

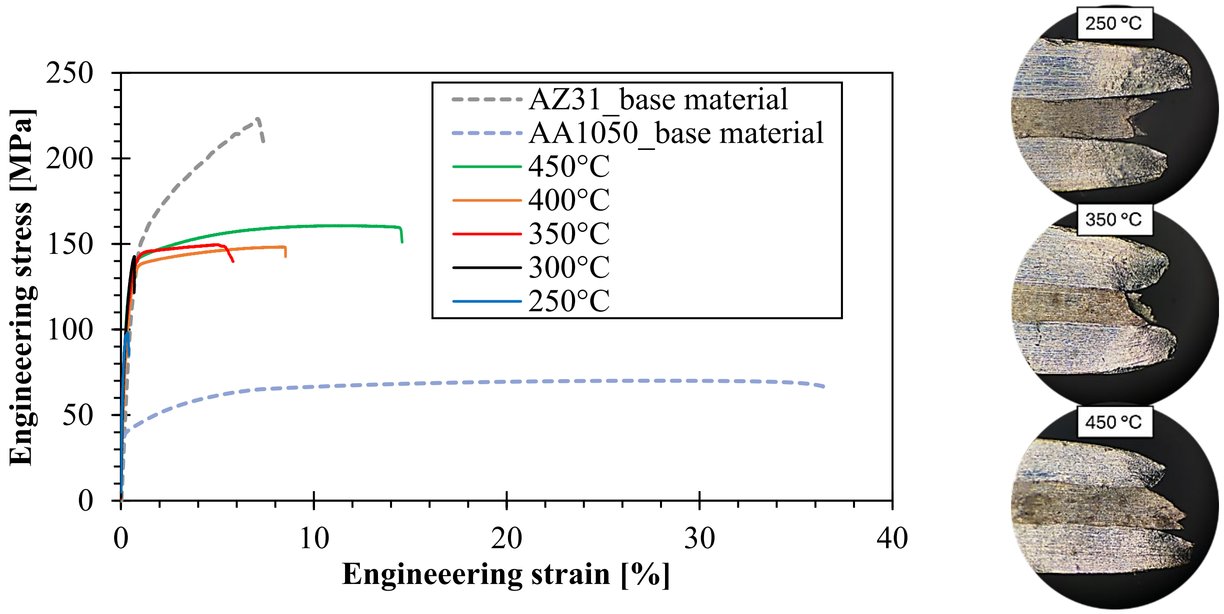


(a) (b)

Fig. 4. Effect of rolling temperature on sheet thickness after Roll Bonding: (a) thickness evolution of individual AA1050 and AZ31 sheets; (b) total composite sheet thickness compared with the nominal thickness.

Table 1. Mechanical properties of composite sheets.

Rolling temperature	UTS [MPa]	$\sigma_{0.2}$ [MPa]	$A_{\%}$ [%]	Young Module [GPa]
250°C	115 ± 21	114 ± 21	0.5 ± 0.1	50 ± 1
300°C	141 ± 5	121 ± 7	0.7 ± 0.0	64 ± 2
350°C	153 ± 5	116 ± 15	6.1 ± 0.1	80 ± 2
400°C	154 ± 1	118 ± 5	9 ± 0.5	62 ± 12
450°C	153 ± 2	117 ± 3	15.3 ± 0.7	58 ± 2
AA1050 - base material	70 ± 1	40 ± 2	36.4 ± 1.2	69 ± 1
AZ31 - base material	223 ± 2	130 ± 1	7.6 ± 2.0	43 ± 2



(a) (b)

Fig. 5. (a) Representative engineering stress–strain curves of AA1050/AZ31/AA1050 specimens processed at different rolling temperatures together with the base materials (AA1050 and AZ31); (b)lateral view of fracture surfaces of the tensile specimens tested at different rolling temperatures.

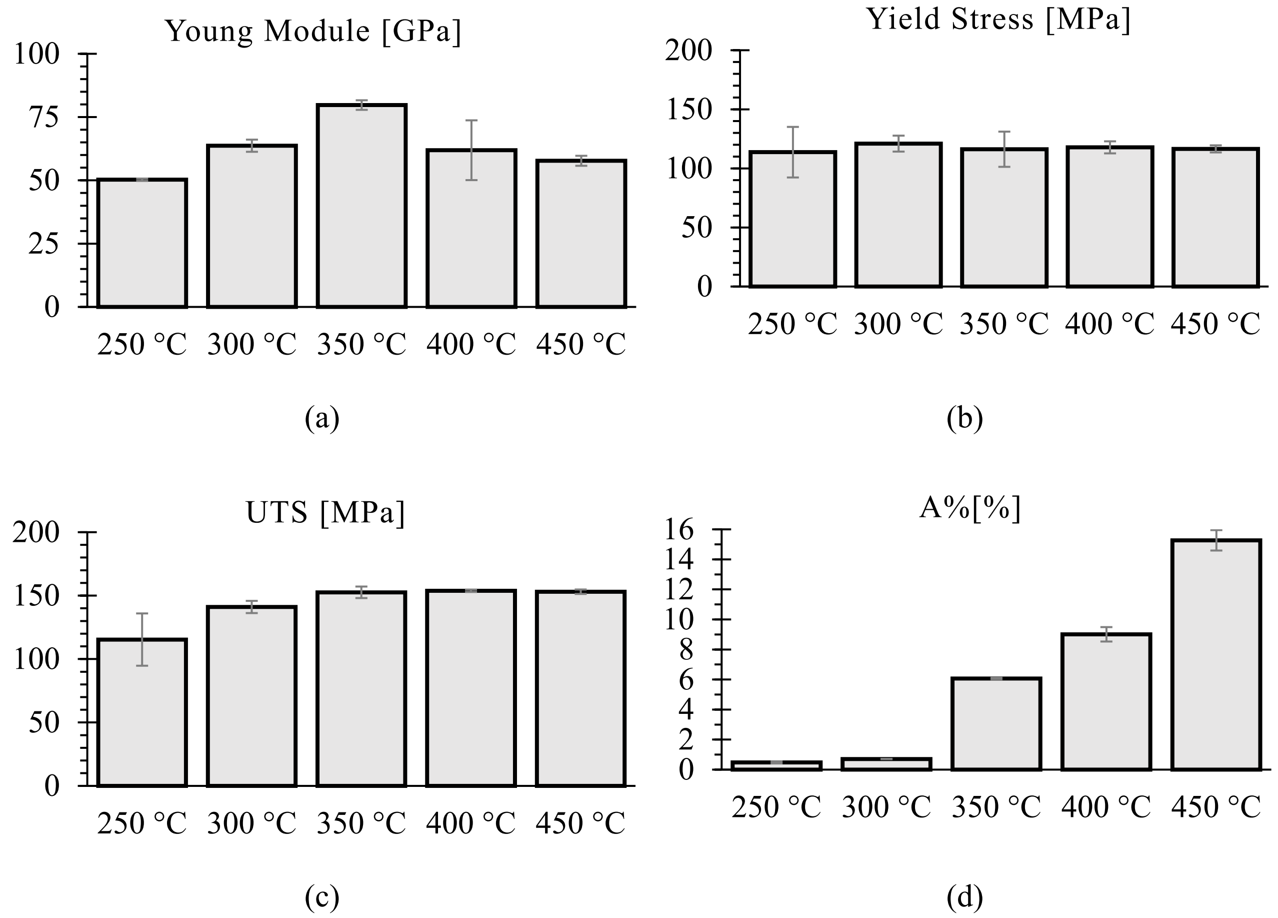
Figure 5.a shows the engineering stress–strain curves of the AA1050/AZ31/AA1050 composite sheets produced at different rolling temperatures while Table 1 and Figure 6 summarize the corresponding mechanical properties.

Rolling temperature has a limited influence on yield stress, which remain within the same range for all investigated conditions. In contrast, ultimate tensile strength (UTS) and elongation at fracture are strongly affected by rolling temperature. The UTS increases with temperature up to approximately 350°C, reaching values close to 153 MPa, and then remains nearly constant at higher temperatures. At the same time, the elongation at fracture increases markedly with rolling temperature, rising from values below 1% at 250–300°C to more than 15% at 450°C. This combination of stable strength and strongly enhanced ductility indicates a significant improvement in deformation compatibility at elevated rolling temperatures. While the tensile specimens used in this work have relatively small gauge dimensions (Figure 2), which can slightly overestimate the measured ductility, Nie et al. [13] reported similar mechanical properties for Al/Mg/Al composites after the first ARB cycle at 400°C. Temperatures higher than 450°C are not expected to further improve the mechanical response of the laminate. In this temperature range, the AZ31 layer experiences extensive dynamic recrystallization accompanied by significant grain growth and softening, which progressively lowers the flow stress and promotes slip-dominated deformation, thereby reducing its effective load-bearing capability and leading to unfavorable strain partitioning between the layers [20,21].

The relatively large deviations observed in the Young’s modulus values can be attributed to the intrinsic characteristics of multilayer composites and the experimental methodology. First, the AA1050/AZ31/AA1050 laminate is mechanically heterogeneous, and small variations in layer thickness, local bonding quality, and strain partitioning can significantly affect the initial elastic slope measured during tensile testing. Furthermore, the elastic response of the composite is governed by the rule of mixtures between aluminum and magnesium layers, whose elastic moduli differ substantially, amplifying the scatter when minor geometric or interfacial variations are present.

The fracture surfaces shown in Figure 5.b provide direct evidence of this transition. At the lowest rolling temperature (250°C), clear delamination between the AA1050 and AZ31 layers is observed, accompanied by limited necking and a relatively flat fracture profile. This indicates insufficient interfacial bonding and premature interfacial failure under tensile loading. As the rolling temperature increases, the extent of interfacial damage is progressively reduced. At 450°C, no evident delamination is observed, and the fracture surface is characterized by pronounced necking and a more ductile morphology even in AZ31 layer, confirming the formation of a stronger metallurgical bond between the layers.

In addition, a brief consideration of the interfacial shear strength is necessary to better interpret the mechanical response of the AA1050/AZ31/AA1050 laminates. In roll-bonded dissimilar composites, the overall load transfer between layers is strongly controlled by the interfacial shear strength, which depends on oxide layer disruption, plastic deformation at the interface, and metallurgical bonding quality. The results obtained in this study suggest that increasing the rolling temperature enhances the interfacial shear strength, as evidenced by the progressive reduction of delamination and the more cooperative deformation of the layers during tensile loading. From a processing perspective, further improvements in shear strength could be achieved through higher reduction ratio, the adoption of asymmetric rolling to introduce additional shear strain, or post-rolling heat treatments aimed at promoting diffusion bonding while limiting excessive intermetallic growth [22,14].



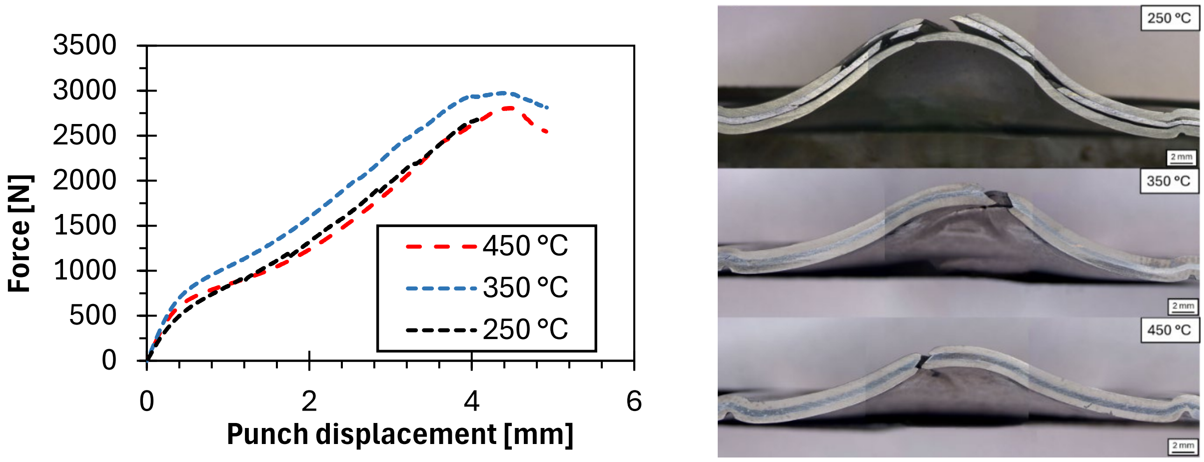
(a) (b)

(c) (d)

Fig. 6. Variation of the mechanical properties of sheets composites with processing temperature: (a) Young's modulus, (b) yield stress, (c) maximum strain at fracture, and (d) maximum stress.

The formability of the composite sheets was evaluated by Erichsen cupping tests, and representative results are shown in Figure 7 and Figure 8. Figure 7.a illustrates the typical load–extension curves obtained for specimens processed at 250°C, 350°C and 450°C, along with the final shapes of the deformed sheets after testing. It shows that the curves for different rolling temperatures exhibit a similar overall trend, characterized by a progressive increase in load up to a maximum value, followed by fracture.

Figure 7.b provides a clear correlation between the global mechanical response measured during the Erichsen cupping test and the damage mechanisms observed in the deformed composite sheets. The maximum load and extension values are comparable, confirming that the global formability response is only weakly affected by rolling temperature. However, the cross-sectional views reported in Figure 7.b reveal significant differences in deformation and damage evolution. At the lowest rolling temperature (250°C), the specimen exhibits pronounced interfacial separation and localized cracking, indicating insufficient bonding strength to sustain large plastic deformation. At the intermediate temperature (350°C), interfacial integrity is improved, although local damage is still visible near the apex. In contrast, the specimen processed at 450°C shows a more uniform deformation profile with limited delamination, demonstrating enhanced metallurgical bonding and improved strain compatibility between the aluminum and magnesium sheets. These observations highlight that similar load–extension responses may mask substantial differences in damage mechanisms. While global formability parameters remain nearly constant, the rolling temperature strongly influences interfacial integrity and failure mode. The improved performance observed at higher temperatures can therefore be attributed to enhanced bonding quality, which delays interfacial failure and allows more homogeneous deformation during the Erichsen cupping test.

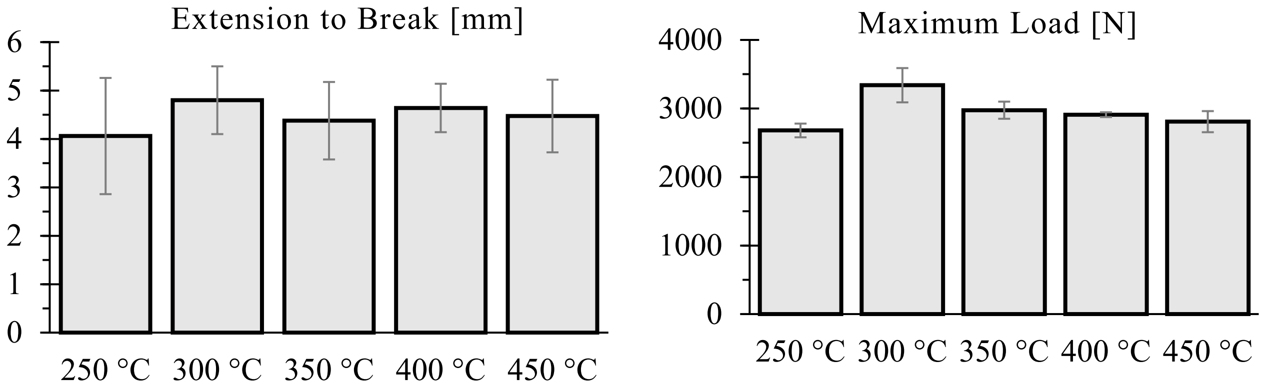


(a) (b)

Fig. 7. Results of the formability test at 450 °C: (a) load–extension curve recorded during the test, and (b) cross-section view of the deformed specimen after forming.

As reported in Figure 8 and Table 2, both the maximum load and the extension at break remain relatively stable over the entire investigated temperature range. The extension at break varies between approximately 4.1 and 4.8 mm, while the maximum load is around 3000 N. This indicates that the global response measured during the Erichsen cupping test is only weakly dependent on rolling temperature.

Despite the similar global response, macroscopic examination of the tested specimens reveals a clear influence of rolling temperature on damage evolution. Sheets produced at lower rolling temperatures exhibited early interfacial separation and localized cracking, whereas specimens rolled at higher temperatures showed reduced delamination and more uniform deformation. This observation indicates that improved metallurgical bonding at elevated rolling temperatures enhances formability by delaying interfacial failure and delamination.



(a) (b)

Fig. 8. Formability test results as a function of temperature: (a) extension at break and (b) maximum load.

The correlation between rolling temperature and interfacial integrity observed in our Erichsen cupping tests is further supported by the findings of Abbasi and Sajjadi [23], who investigated the three-point bending behavior of Al/AZ31/Al composites. In their study, low rolling temperatures (200°C) resulted in multiple "load drops" during bending, which were attributed to sequential delamination and the inability of the magnesium core to sustain tensile stresses at the outer radius. Similarly, our specimens processed at 250°C exhibited early interfacial separation and localized cracking during cupping (Fig. 6b), confirming that a low-temperature mechanical bond is insufficient for complex stress states. In summary, sheets processed at lower temperatures exhibit early interfacial separation during forming, whereas specimens rolled at higher temperatures show more uniform deformation and stable interfaces This demonstrates that effective formability is primarily governed by interfacial integrity rather than by global stiffness or strength.

Table 2. Formability test results of AA1050/AZ31 composite sheets produced at different preheating temperatures.

Temperature [°C]	**Maximum Load [N]**	**Extension to Break [mm]**
250	2679	4.1
300	3339	4.8
350	2975	4.4
400	2910	4.6
450	2808	4.5

Conclusion

AA1050/AZ31/AA1050 composite sheets were successfully produced by roll bonding in the temperature range of 250–450°C, demonstrating the feasibility of combining aluminum and magnesium into lightweight sandwich structures for forming applications. The main conclusions are as follows:

- rolling temperature was identified as a key processing parameter controlling interfacial quality and overall mechanical behavior.
- The ultimate tensile strength (UTS) increased with rolling temperature up to ~350°C before stabilizing, while elongation at fracture showed a continuous improvement.
- Erichsen cupping tests revealed that global formability parameters (maximum load and extension at break) were only weakly affected by rolling temperature; however, higher temperatures significantly reduced interfacial delamination and promoted more uniform deformation across the layers.
- Roll bonding at 450°C provided the best compromise between strength, ductility, formability, and interfacial integrity, making the resulting sheets suitable for lightweight forming applications.

Future work will focus on optimizing the initial thickness ratio between AA1050 and AZ31 sheets to tailor strain partitioning and improve the mechanical response. Further investigations will include determining forming limit diagrams (FLDs) through additional tests under different strain paths to better define the forming window of the composite. Process modeling will also be developed to support the optimization of roll-bonding parameters for targeted lightweight applications.

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