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Mechanical Characterization by Profilometry-Based Indentation Plastometry of Locally Heat-Treated Blanks for Sheet Injection Applications

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Abstract. The sheet injection process, a hybrid sheet-bulk forming technique that integrates bending and injection to create complex features such as ribs, offers significant potential for advanced manufacturing applications. However, its implementation with lightweight aluminium alloys is hindered by their limited room-temperature formability. To address this, locally softened, tailored heat-treated blanks produced via laser heat treatment (LHT) can enhance local ductility while maintaining global strength. This study investigates the mechanical property gradients induced by LHT in 3 mm thick AW6082-T6 aluminium alloy sheets using Profilometry-based Indentation Plastometry (PIP). The laser treatment, performed with a 2.5 kW CO_2 laser, produced localized heat treated regions, whose effectiveness was evaluated through microhardness testing. PIP enabled the direct extraction of local stress-strain curves without the need for specimen extraction and was validated against conventional tensile tests. Results showed that PIP accurately captured local variations in mechanical properties, with heat treated zones exhibiting increased ductility compared to the T6 condition.

Introduction

In recent years, increasing demand for lightweight and, at the same time, high-performance components have driven the development of advanced metal forming processes capable of combining high geometric complexity with optimal mechanical properties [1]. Within this framework, sheet-bulk forming processes have emerged as a promising solution, as they enable the integration of conventional sheet forming operations with localized bulk deformation, allowing the production of functional features such as ribs, bosses, and reinforcements directly from sheet materials [2]. Among these processes, sheet injection represents a hybrid forming approach that combines bending and upsetting, offering significant potential for applications in the automotive and transportation sectors [3]. Despite these advantages, the application of sheet injection to aluminium alloys remains challenging due to their limited formability at room temperature, particularly in precipitation-hardened conditions such as T6 [4]. Alloys of the 6xxx series, widely used for their favorable strength-to-weight ratio and corrosion resistance, exhibit reduced ductility and early strain localization under complex loading paths, which can lead to cracking during forming [5]. To overcome these limitations, the use of tailored blanks with spatially graded mechanical properties has been increasingly investigated as an effective strategy to enhance local formability while preserving global structural performance [6].

Local modification of material properties can be achieved through different approaches, including partial annealing, mechanical processing, and thermal treatments. Among these, laser heat treatment (LHT) has attracted considerable attention due to its high flexibility and ease of integration into industrial production lines [7]. By locally controlling the thermal cycles, LHT enables the induction of softening in selected regions, resulting in a controlled reduction of strength and a corresponding increase in ductility [8].

The presence of strong gradients in mechanical properties, however, poses significant challenges for material characterization, which is particularly crucial when the forming process is reproduced numerically, as accurate local constitutive laws are required to predict material flow, strain distribution, and failure [9]. Conventional or even miniaturized tensile testing is often unsuitable, as it requires specimen extraction and provides only average properties over the specimen [10]. As a result, localized characterization techniques are required to accurately capture the mechanical behaviour within treated and untreated zones. Hardness testing is widely used as a first and rapid approach to assess local variations in mechanical properties and to qualitatively evaluate the presence of strength gradients induced by localized treatments [11]. Nevertheless, hardness measurements alone are not sufficient to fully describe the mechanical response, particularly in terms of strain-hardening behaviour [12].

In this context, Profilometry-based Indentation Plastometry (PIP) has proven to be an effective semi-destructive method for determining local stress-strain curves from a single indentation test [13]. By combining residual indentation profile measurements with iterative finite element simulations, PIP enables the identification of yield stress, strain hardening behaviour, and ultimate tensile strength [14], making it particularly suitable for the assessment of tailored materials.

In the present work, the mechanical property gradients induced by different laser heat treatment strategies applied to 3 mm thick AW6082-T6 aluminium alloy sheets were investigated with specific reference to sheet injection applications. PIP was employed to extract local stress-strain curves in critical forming zones and was validated through comparison with conventional tensile testing on the base material. The effect of the LHT on the distribution of mechanical properties was analysed and correlated with microhardness measurements, providing insight into the potential of tailored heat-treated blanks for advanced sheet-bulk forming processes.

Material and Methodology

Material.

An aluminium alloy (AW6082-T6) with a thickness of 3 mm was investigated. The mechanical properties are summarized in Table 1, with yield stress and ultimate tensile strength determined from tensile tests performed according to ASTM E8/E8M (2024).

Table 1. Mechanical properties of the investigated alloy.

Vickers Hardness [HV]	Yield Stress [MPa]	Ultimate Tensile Strength [MPa]
120	298	344

Laser Heat Treatments.

To locally enhance the formability in regions that are critical during the sheet injection process, specifically during the bending and upsetting stages (see Fig. 1a), a Laser Heat Treatment (LHT) was applied to locally modify the material properties along the critical zones. The LHT was performed using a 2.5 kW CO_2 laser source (Rofin Slab DC 025). The system consisted of a heat-treatment head moving along the vertical (z) axis and equipped with a Diffractive Optical Element (DOE) to generate a top-hat energy distribution over a 20 mm square spot. Motion in the horizontal plane was provided by a working table moving along the x- and y-axes. Fig. 1b shows the LHTed zone (highlighted in red), where the points A-F denote the start-end positions of the three laser tracks used to fully cover the treated area with the 20 mm square spot. Two different laser scanning strategies were adopted, referred to as S2 and S2R. In the S2 strategy, the laser followed a set of linear, parallel tracks moving from left to right: the first track from point A to point B, the second from point C to point D, and the third from point E to point F. In contrast, the S2R strategy employed the same linear and parallel tracks but with a reversed scanning direction, moving from right to left. These two strategies were selected to generate different thermal histories and spatial temperature distributions, leading to different mechanical property distributions after the LHT. Before the laser heating, the side of the blank facing the laser beam was sprayed with a thin layer of black paint to reduce reflections. All tests were conducted with a constant laser power of 1350 W and a feed rate of 4 mm/s, with a 5 mm overlap between adjacent parallel tracks in both scanning strategies.

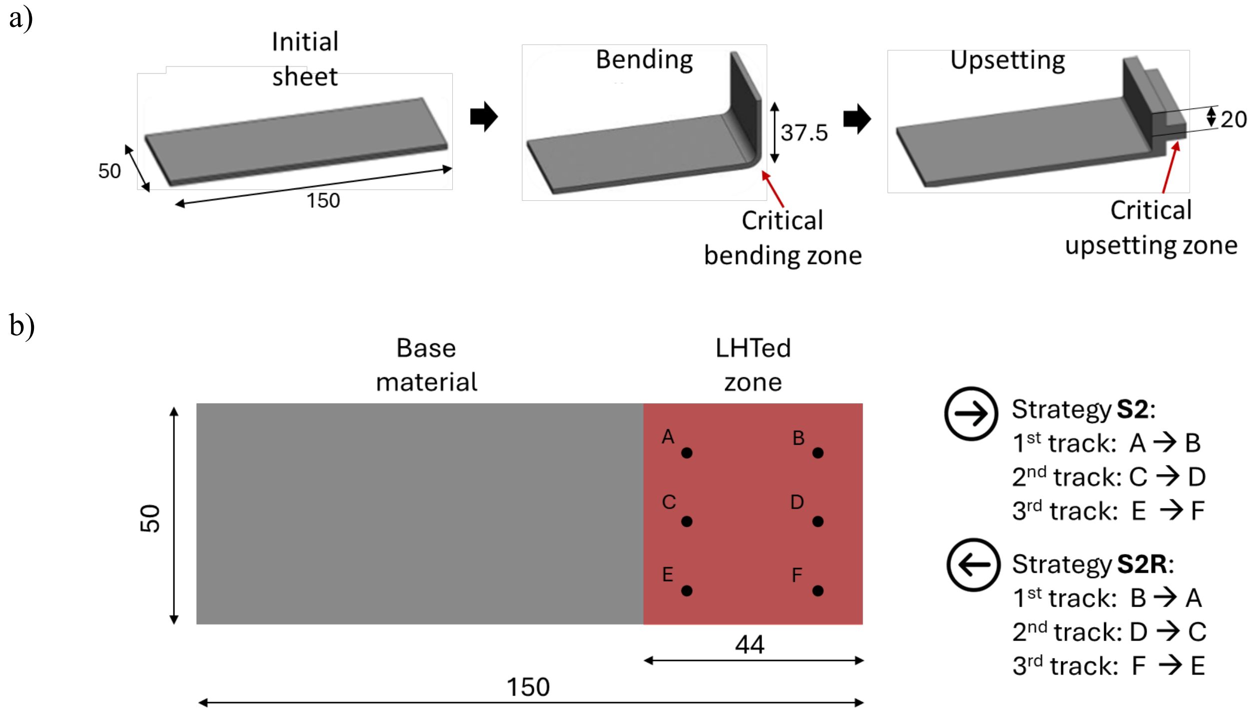

Fig. 1. a) Schematic representation of the sheet injection process (adapted from [15]); schematic representation of the investigated LHT strategies; dimensions: mm.

Mechanical characterization of the heat-treated samples.

Before each mechanical characterization test, the samples were cleaned to remove the black paint and subsequently polished. Vickers microhardness tests were conducted seven days after heat treatment to account for the hardness evolution due to natural ageing [16]. These tests were used to evaluate the effectiveness of the LHTs and to compare the two LHT strategies in terms of hardness distribution along the aluminium sheets. The tests were conducted in accordance with the EN ISO 6507–1:2018 standard using a fully automatic Qness Q10 A+ microhardness tester, with a load of 200 gf and a holding time of 15 s. Three key points were analyzed: (i) point P1, corresponding to the base material; (ii) point P2, corresponding to the critical zone during the bending stage and (iii) point P3, corresponding to the critical zone during the upsetting stage, according to the locations shown in Fig. 2a. Following the microhardness measurements, profilometry-based indentation plastometry (PIP) tests were conducted at the same three key points to obtain the stress-strain curves, yield stress, and ultimate tensile strength. PIP tests were carried out using the PLASTOMETREX PLX-Benchtop system shown in Fig. 2b. During the test, the sample was placed on the sample platform, and an indentation of approximately 100-200 µm deep was performed using a spherical Si_3N_4 indenter with a radius of 1 mm. After indentation, the residual indent profile was scanned using the contacting stylus profilometer in four directions (x, y, xy, and yx) through the central axis of the indent. The recorded maximum load and the residual indent profile were analyzed using the CORSICA software supplied with the PLX system. CORSICA performs an inverse analysis to identify the constitutive parameters that best reproduce the experimental response, providing the true stress–strain curve corresponding to the tested point. The Young's Modulus and Poisson's ratio were set to 69 GPa and

0.3, respectively. The material behavior in the FE simulation was described using the Voce constitutive model [17], expressed in Eq. 1:

$$\sigma = \sigma_s - (\sigma_s - \sigma_Y)exp\left(-^{\varepsilon}/_{\varepsilon_0}\right). \tag{1}$$

where σ is the true stress, ε the true strain, σ_Y the yield stress, σ_s a saturation stress, and ε_0 a characteristic strain.

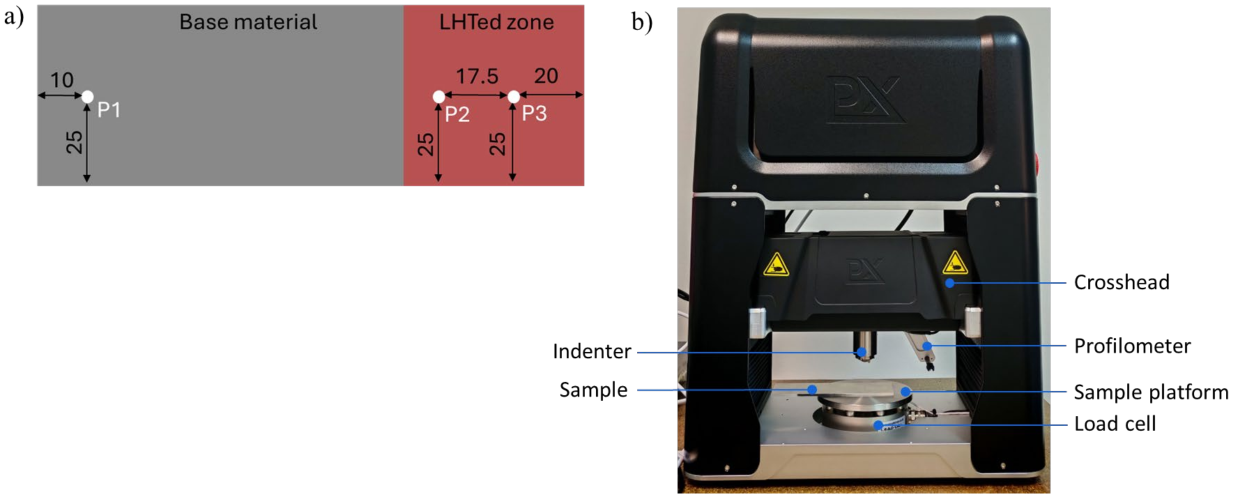

Fig. 2. a) Key points analyzed during microhardness and PIP test (dimensions: mm); b) Set-up for the PIP tests.

Results and Discussion

Profilometry-based indentation plastometry results.

The reliability of Profilometry-based Indentation Plastometry (PIP) in extracting local mechanical properties was first assessed by comparing the tensile parameters obtained from PIP with those measured by conventional uniaxial tensile tests on the base material, as shown in Fig. 3. The yield stress identified by PIP was found to be in the range of 312-340 MPa, which is in very close agreement (percentage difference: 9.3%) with the tensile test value of approximately 298 MPa reported in Table 1, as well as UTS values (percentage difference: 1.5%).

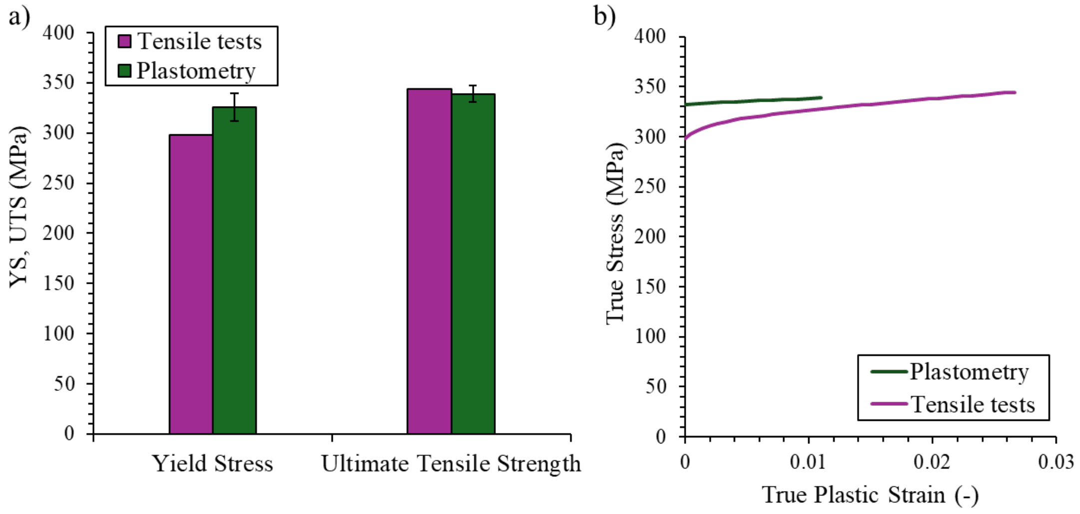

Fig. 3. Comparison between a) YS and UTS and b) flow stress curves obtained from PIP and from conventional uniaxial tensile tests on the base material.

The overall agreement demonstrates that PIP can accurately reproduce the tensile response of the material, validating its use for local mechanical characterization in regions where standard tensile specimens cannot be extracted.

The effect of the two LHT strategies (S2 and S2R) on the resulting mechanical properties on the aluminium blanks is illustrated in Fig. 4, which shows the stress-strain curves identified by PIP at the base material location (P1) and at the critical zones corresponding to bending (P2) and upsetting (P3) for both S2 and S2R strategies. For both strategies, the laser heat treatment resulted in a clear reduction in yield stress and ultimate tensile strength, accompanied by an increase in strain at necking, compared to the T6 base material condition. This behaviour confirms the occurrence of local softening within the LHTed zone.

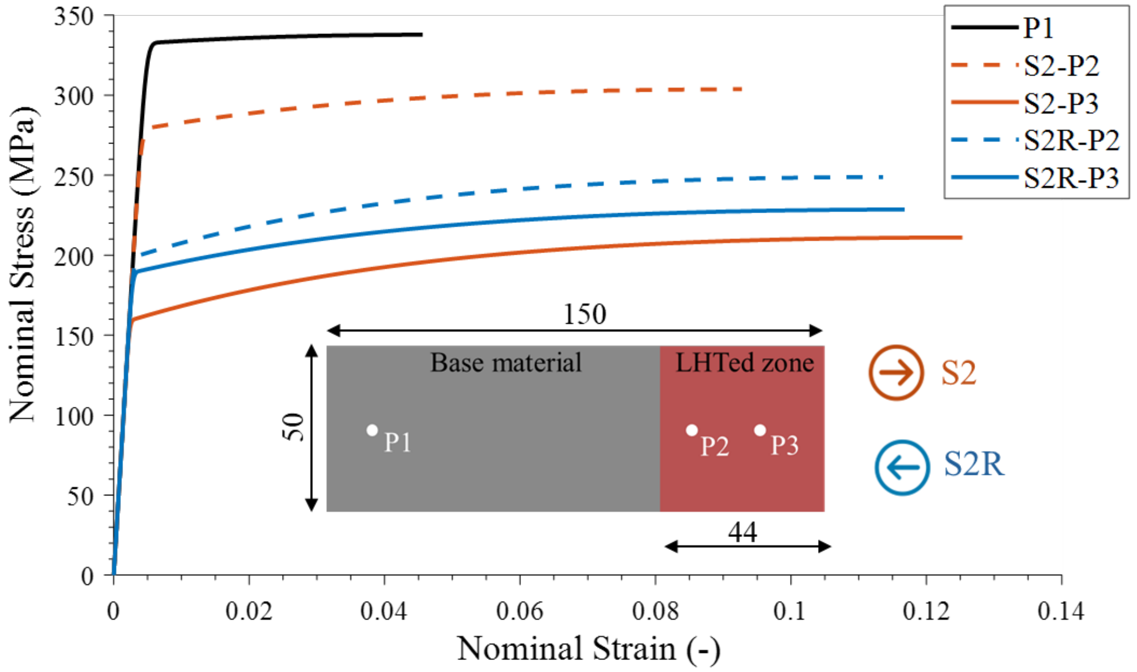

Fig. 4. Stress-strain curves obtained by PIP for the different strategies.

For the S2 strategy, a gradual transition between the treated zone and the untreated region is observed. In particular, the stress-strain curve associated with point P2 (labelled as *S2-P2* in Fig.4) remains close to that of the base material, whereas the curve corresponding to point P3 (*S2-P3* in Fig.4) is significantly lower. This trend is quantitatively confirmed by the mean absolute percentage difference, calculated by comparing the stress values of P2 and P3 with those of the reference curve P1 at each common strain level, determining the absolute percentage deviation, and then averaging these deviations over the entire shared strain range. The *S2-P2* curve exhibits a percentage difference of approximately 11% with respect to *P1*, while *S2-P3* shows a substantially larger deviation of about 40%. This behaviour can be attributed to the processing sequence of the S2 strategy, in which point P2 corresponds to the starting location of the laser track, whereas point P3 is located at the end of the track and is therefore exposed to higher temperatures. In contrast, in the S2R strategy, the stress-strain curve of point P2 (labelled as *S2R-P2* in Fig.4) exhibited a more pronounced reduction (about 30%) compared to the S2 strategy. Moreover, the curves corresponding to points P2 and P3 are close to each other, indicating a more homogeneous thermal history along the laser tracks. Conversely, the S2 strategy led to a larger scatter among the identified curves, which can be associated with a less uniform temperature distribution induced by the laser heat treatment.

Comparison between PIP and hardness tests results.

Vickers microhardness measurements performed after 7 days from the LHT at the same locations as the PIP tests are reported in Fig. 5 and show trends fully consistent with those observed for the tensile parameters identified by PIP. A clear reduction in hardness was measured in the laser-treated zones compared to the base material, consistent with the decrease in yield stress and ultimate tensile strength extracted from the PIP analysis. This correlation highlights the effectiveness of the laser heat treatment in inducing controlled softening and validates hardness as a quick indicator of local strength variations. However, hardness measurements are not sufficient to capture changes in strain hardening behaviour. In contrast, PIP enabled the full reconstruction of local stress-strain curves, offering a more comprehensive mechanical characterization. This demonstrates the added value of combining hardness testing with PIP for the assessment of tailored heat-treated blanks.

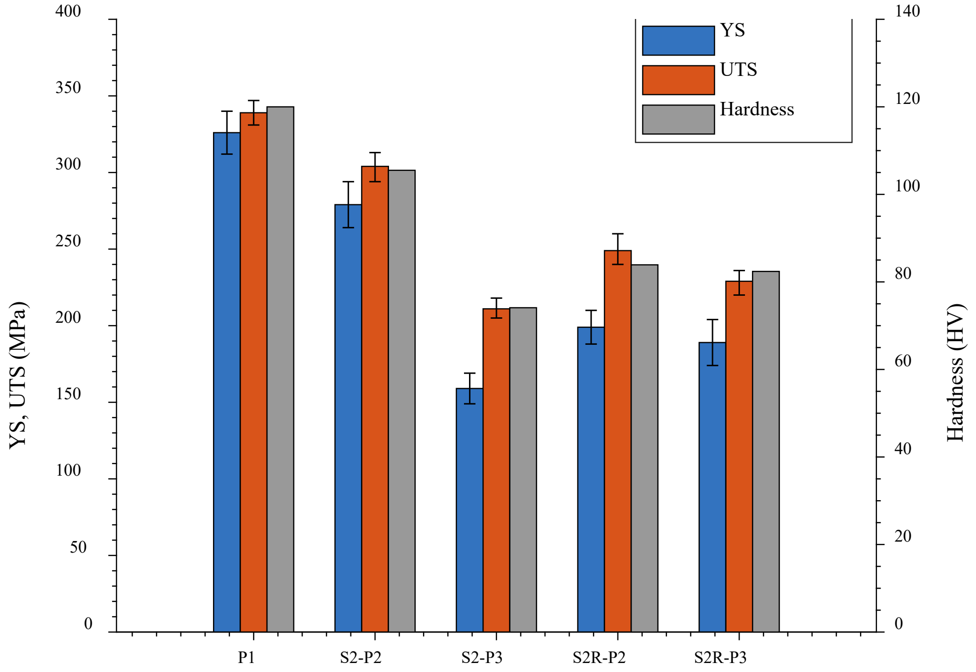

Fig. 5. Comparison between YS, UTS and hardness measured on the three key points.

Conclusion

This work investigated the mechanical property gradients induced by a laser heat treatment in 3 mm thick AW6082-T6 aluminium alloy sheets, with specific reference to applications in sheet injection processes. Profilometry-based Indentation Plastometry was employed as a local mechanical characterization technique and validated against conventional tensile testing.

The comparison between tensile tests and PIP demonstrated that the latter is capable of accurately identifying local stress-strain behaviour, confirming PIP as a reliable and semi-destructive tool for the characterization of tailored blanks, where standard tensile testing is not feasible due to spatial variations in material properties.

Both investigated laser scanning strategies successfully produced localized softened regions, resulting in a reduction in yield stress and an increase in local ductility compared to the T6 base material. Among the two strategies, the S2R approach provided a more uniform softening effect within the LHTed zone. This behaviour is particularly advantageous for sheet injection operations, as it promotes higher deformations corresponding to the critical zones of both bending and upsetting stages while preserving the overall strength of the component.

Hardness measurements confirmed the effectiveness of the laser heat treatment and showed a clear correlation with the strength reduction identified through PIP. However, hardness alone was insufficient to capture changes in ductility and strain hardening behaviour, highlighting the added value of PIP in providing full local mechanical characterization.

Thus, profilometry-based indentation plastometry represents an effective tool for the design and mechanical characterization of the laser heat treatment to produce tailored heat-treated aluminium sheets to be subjected to sheet injection process. This work establishes a robust basis for future developments, notably process optimisation and advanced numerical modelling of the sheet injection process using tailored laser heat-treated aluminium sheets. In fact, PIP-based investigation will enable node-specific material properties in the FE model thus improving predictive accuracy.

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