

Extending the Process Window of Sheet Injection in AW6082-T6 Aluminium via Localised Laser Heat Treatment

João P. G. Magrinho^{1,a*}, Angela Cusanno^{2,b}, Miguel Jesus^{1,c},
Antonio Piccininni^{2,d}, Gianfranco Palumbo^{2,e}, M. Beatriz Silva^{1,f}

¹IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

²Department of Mechanics, Mathematics and Management, Politecnico di Bari, Via Orabona, 4, Bari, 70125, Italy

^{a*}joao.magrinho@tecnico.ulisboa.pt, ^bangela.cusanno@poliba.it,
^cmiguel.lopes.jesus@tecnico.ulisboa.pt, ^dantonio.piccininni@poliba.it,
^egianfranco.palumbo@poliba.it, ^fbeatriz.silva@tecnico.ulisboa.pt

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Abstract. Integrating functional features into lightweight aluminium components remains a key challenge in advanced manufacturing, particularly when forming operations impose severe local deformation. This study focuses on the sheet injection process, a variant of Sheet-Bulk Forming (SBF), where thickening and lateral extrusion occur in previously bent aluminium sheets. The material investigated is AW6082-T6, a medium-strength Al-Mg-Si alloy widely used in transportation and structural applications due to its good strength-to-weight ratio and corrosion resistance. To improve formability and reduce the risk of defects such as fracture and folding, an approach based on Tailored Heat-Treated Blanks (THTB) was employed. Localised Laser Heat Treatment (LHT) was applied to selectively reduce strength and enhance ductility in critical deformation zones. Mechanical characterisation was performed via compression tests on both as-received (T6) and heat-treated (HT) materials. Experiments were conducted on a flexible SBF demonstrator using a two-stage process: bending followed by sheet injection. Numerical simulations were performed to guide LHT pattern design and predict material flow. Among the tested LHT strategies, one demonstrated superior performance, enabling higher injection volumes and reducing process forces while avoiding failure. The experimental results confirm that THTB are an effective method for extending the process window of sheet injection in AW6082-T6, offering a promising solution for the production of complex aluminium components with enhanced functionality.

Introduction

The increasing urgency of environmental challenges has intensified research into energy-efficient manufacturing solutions, particularly in the field of production engineering [1]. A lightweight design plays a crucial role in reducing energy consumption, CO₂ emissions, and operating costs, particularly in transportation and industrial applications. Achieving lightweight structures often requires reduced sheet thicknesses and the integration of multiple functional features into single components, leading to complex geometries and demanding manufacturing processes.

Sheet-Bulk Forming (SBF) has emerged as a promising hybrid forming technology that combines conventional sheet forming with bulk forming operations [2]. This approach enables the production of geometrically complex components with localised features such as ribs, bosses, and thickened regions directly from sheet blanks, reducing the need for secondary operations or assembly steps [3]. Previous studies have demonstrated the potential of SBF for manufacturing high-performance lightweight components. However, its industrial application remains limited by challenges such as local thinning or thickening, high forming forces, and process instability [4].

Among the various SBF variants, sheet injection (combining deep drawing with controlled lateral material flow into a cavity) offers significant potential for creating local reinforcements extending out of the sheet plane [5]. Despite its advantages, experimental investigations on sheet injection,

particularly for medium-strength aluminium alloys, remain scarce, limiting its wider adoption in lightweight structural applications [6].

A promising strategy to overcome formability limitations in sheet injection is the local tailoring of material properties using short-duration heat treatments. Laser Heat Treatment (LHT) allows precise, localised softening of selected regions, enabling the production of Tailored Heat-Treated Blanks (THTB) with spatially adapted mechanical properties. While this approach has proven effective in conventional sheet forming [7], its application to SBF has not yet been systematically investigated.

This study addresses this research gap by experimentally and numerically investigating the use of LHT to create THTB from AW6082-T6 aluminium sheets for sheet injection processes. The work evaluates the influence of local heat treatment on formability, process forces, and defect formation. The results aim to demonstrate the potential of LHT-enabled THTB to expand the process window of sheet injection and to advance SBF as an efficient manufacturing technology for lightweight, multifunctional components.

Material and Methods

Mechanical characterization. The work was carried out on AW6082-T6 aluminium alloy sheets with 3 mm thickness, selected for their favourable strength-to-weight ratio and suitability for lightweight structural applications. The as-received T6 condition is referred to as T6 material, while the locally heat-treated condition is denoted as HT material.

The study followed a four-step methodology: (i) mechanical characterisation of T6 and HT materials to provide input data for numerical simulations, (ii) finite element simulation of the sheet injection process to analyse force evolution and strain distribution, (iii) experimental laser heat treatment, and (iv) sheet injection experiments to validate the proposed approach.

Material behaviour was characterised using stack compression tests in accordance with ASTM E9-09 [8]. Specimens consisted of stacks of four circular discs (12 mm diameter) and were tested at room temperature on a 1200 kN hydraulic testing machine at a constant crosshead speed of 5 mm/min. The resulting true stress–strain curves (Fig. 1) show that LHT significantly reduces material strength while increasing ductility, confirming its effectiveness for improving formability in sheet injection.

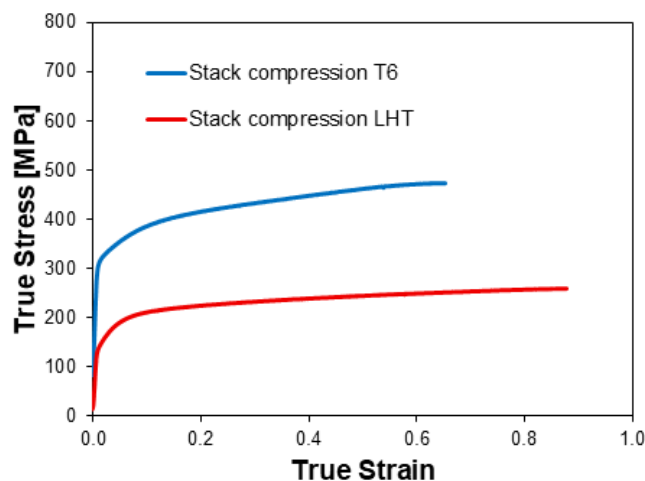


Fig. 1. True stress-true strain curves of aluminium AW6082-T6 and AW6082-HT obtained from stack compression (SC) tests.

Numerical modelling.

The bending and upsetting stages of the sheet injection process were numerically modelled using the in-house finite element software i-form [9]. The simulations were based on a finite element flow formulation with an updated Eulerian approach, in which velocities are treated as primary variables, and equilibrium is achieved through iterative minimisation of residual forces. Material behaviour was

defined using the true stress - strain data obtained from stack compression tests, and a von Mises yield criterion was adopted.

All numerical simulations were performed under two-dimensional plane strain conditions, justified by the constant specimen width (50 mm). The deformable blank was discretised with approximately 4000 quadrilateral elements, while tools were modelled as rigid bodies. Friction at the tool - workpiece interfaces was described using a constant friction law, with the friction factor calibrated to $m = 0.1$ based on experimental force measurements.

For the bending stage, the specimen was clamped between fixed die and blank holder and deformed by a wiping punch moving at 1 mm/s, allowing accurate prediction of the force - displacement and deformation evolutions (Fig. 2a). The subsequent upsetting stage simulated material flow into the die cavity using a two-piece blank holder (A and B) to control sidewall deformation and suppress folding (Fig. 2b). The simulations successfully reproduced the characteristic thickening and lateral material injection observed in SBF.

The numerical results identified a plastically deformed region of approximately 44 mm, which was used to define the laser heat-treated area in the experiments. In modelling THTB, a sharp transition between T6 and heat-treated zones was assumed to isolate the mechanical effects of local property modification on strain distribution and process forces.

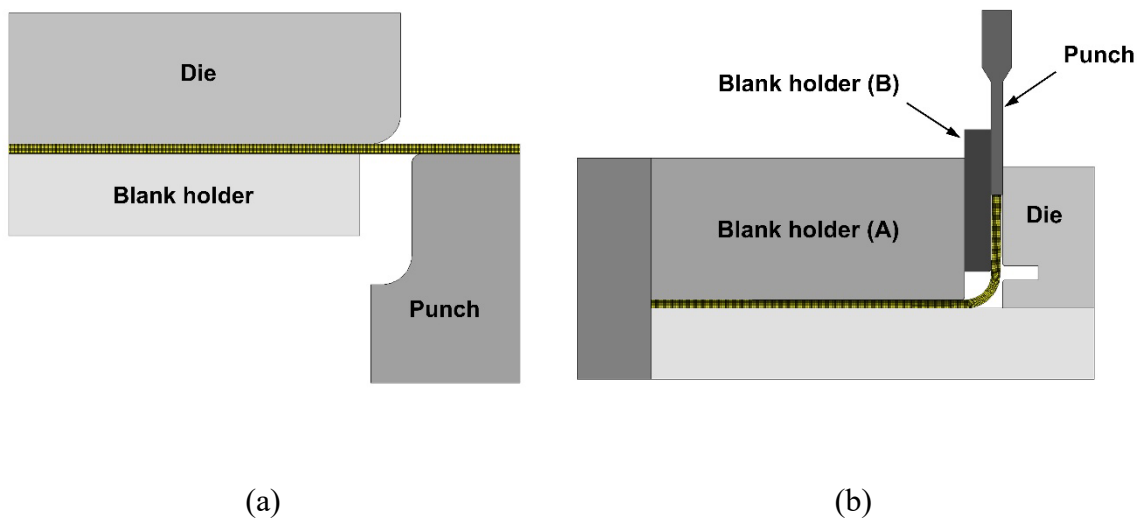


Fig. 2. Numerical model setup of the (a) sheet bending stage and (b) upsetting stage with identification of the main components.

Laser heat treatment.

To locally improve formability in regions subjected to severe deformation during sheet injection, LHT was applied to selectively tailor the mechanical properties of the blanks. Short, localised laser exposure transformed the initial AW6082-T6 condition into an overaged state within the high-strain region, producing a stable reduction in yield strength and increased ductility. This controlled transition from T6 to HT material enables a direct assessment of the influence of LHT on material flow, forming forces, and defect formation under identical process conditions.

LHT was performed using a CO₂ laser system with a top-hat energy distribution, allowing uniform heating over a square laser spot. A constant laser power and scanning speed were employed to achieve peak temperatures of approximately 450 °C, suitable for inducing local overaging. Based on numerical predictions, the heat-treated zone was designed to extend over a 44 mm region corresponding to the plastically deformed area during sheet injection.

Three LHT strategies were investigated in addition to the as-received T6 condition. These strategies differed in scan path orientation (longitudinal or transverse) and track overlap, enabling controlled variation of the heat-affected zone geometry (Table 1).

Table 1. Nomenclature for the LHT strategies.

Case	LHT orientation	Overlap
T6	-	
L_5mm	Longitudinal	5 mm
L_0mm	Longitudinal	0 mm
T_5mm	Transversal	5 mm

Sheet injection experiments.

Sheet injection experiments were performed using a flexible sheet-bulk forming (SBF) demonstrator [5] mounted on a 1200 kN hydraulic testing machine. The setup employs a unit cell concept, in which straight bent slices are used to replicate the deformation behaviour of circular deep-drawn cups. This simplified geometry remains representative for sheet injection studies, as deformation and material flow are dominated by the bent sidewall region, where strain paths and thickness reduction are comparable to those in circular geometries [5].

The sheet injection process was investigated through two sequential stages: bending to define the pre-geometry, followed by upsetting, during which lateral material injection into the die cavity occurs. Separate tooling setups were used for each stage, incorporating a punch, blank holder, and die (Fig. 3). This modular approach enables controlled investigation of the combined deep drawing and injection mechanisms.

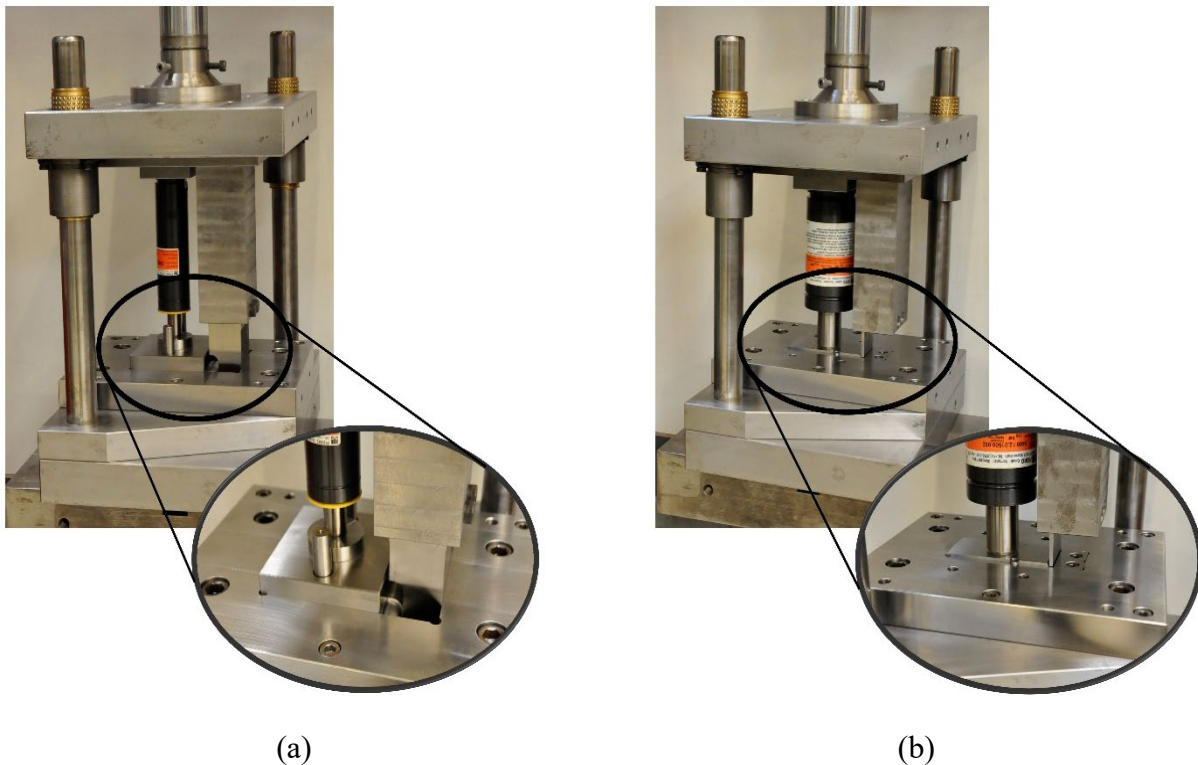
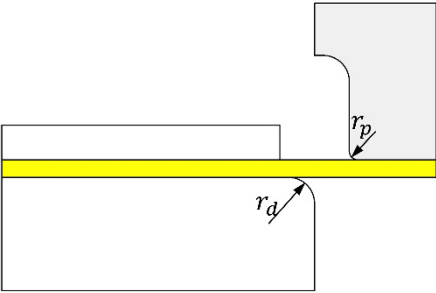
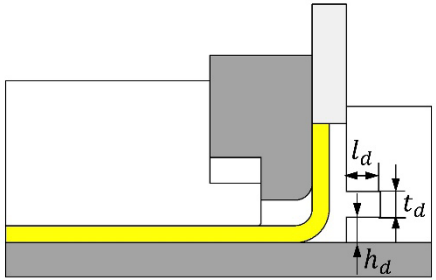


Fig. 3. Overview of the experimental sheet injection setup with identification of the main active components, (a) bending setup, and (b) upsetting setup.

Rectangular specimens (150x50x3 mm) were tested under four material conditions, including the T6 reference and three locally heat-treated variants. All experiments were conducted at room temperature under quasi-static conditions with a constant crosshead speed of 5 mm/min. Key process parameters for the bending and upsetting stages are schematically represented in Table 2.

Table 2. Overview of the experimental work plan, including die geometry for bending and upsetting stages.

	Geometry	Dimensions
Bending stage		$r_d = 9 \text{ mm}$ $r_p = 3 \text{ mm}$
Upsetting stage		$t_d = 5 \text{ mm}$ $l_d = 12 \text{ mm}$ $h_d = 10 \text{ mm}$

Results and Discussion

Bending stage.

The bending stage of the sheet injection process was carried out at room temperature under quasi-static conditions. For each material condition, three repeat tests confirmed good repeatability. Therefore, only representative force - displacement curves are shown. Experimental results were compared with finite element predictions, as illustrated in Fig. 4.

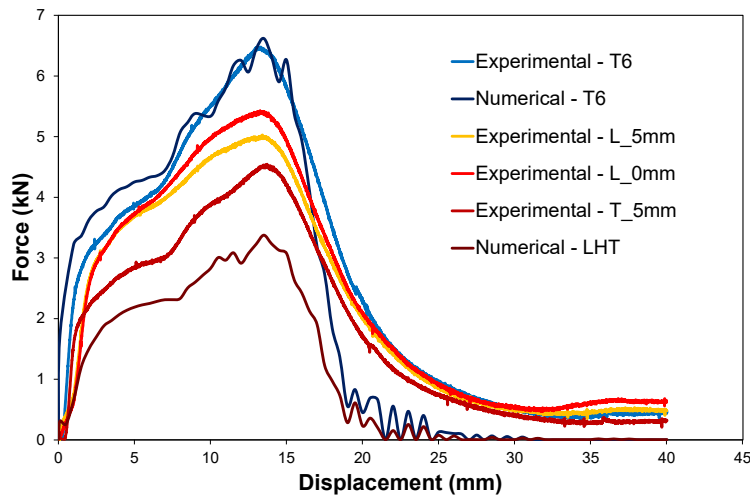


Fig. 4. Experimental and numerical force-displacement curves for the bending stage under all material conditions: T6 (reference), L_5mm (Longitudinal, 5 mm overlap), L_0mm (Longitudinal, 0 mm overlap), and T_5mm (Vertical, 5 mm overlap).

For the T6 reference condition, numerical and experimental curves showed good agreement, with a maximum bending force of approximately 6.5 kN. Minor discrepancies in the initial slope and residual force at the end of the stroke were attributed to progressive contact development and springback, respectively, which are not fully captured by the numerical model. The measured springback angle was approximately 6° .

For the LHT conditions, numerical simulations reproduced the general force trends but underestimated the experimental forces. This difference is attributed to the modelling assumption of a sharp transition between T6 and HT material, whereas the experimental blanks exhibited a gradual property gradient within the bent region. As a result, the effective material strength during bending was higher than predicted. Springback behaviour remained similar across all LHT strategies.

The L_0mm strategy showed the highest maximum force among the LHT cases (~5.7 kN), corresponding to a reduction of approximately 12% compared to the T6 reference condition (~6.5 kN). In contrast, the transversal T_5mm strategy exhibited the lowest maximum force (~4.6 kN), representing a reduction of about 29% relative to T6 and approximately 19% compared to L_0mm. The longitudinal overlapping condition (L_5mm) resulted in intermediate values, confirming a progressive decrease in force with increasing effective softening. These quantitative differences demonstrate that LHT significantly reduces bending forces, with overlapping strategies, particularly the transversal configuration, providing the most pronounced improvement while maintaining stable deformation behaviour.

Upsetting stage.

The upsetting stage, during which material injection into the die cavity occurs, was performed under the same quasi-static conditions as bending. Experimental force - displacement curves were compared with numerical predictions for all material conditions (Fig. 5).

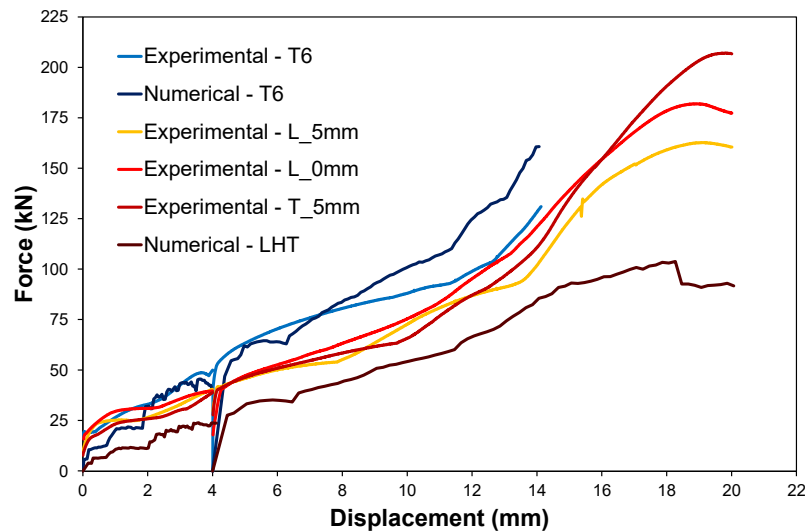


Fig. 5. Experimental and numerical force displacement curves for the upsetting stage under all material conditions: T6 (reference), L_5mm (Longitudinal, 5 mm overlap), L_0mm (Longitudinal, 0 mm overlap), and V_5mm (Vertical, 5 mm overlap).

For the T6 reference condition, numerical and experimental results agreed well in the early stage of deformation. Beyond a punch stroke of approximately 4 mm, differences emerged due to the activation of the two-piece blank holder, which promotes controlled material flow. At larger strokes, the experimental force remained lower than predicted as a result of sidewall folding, which reduced resistance and led to limited injection and premature fracture in the corner region.

For the LHT specimens, experimental and numerical curves followed similar trends up to the onset of injection. Slightly higher experimental forces were observed, attributed to gradual strength transitions within the heat-treated zone and friction effects not captured by the numerical model. During material injection, experimental forces increased more steeply due to burr formation along the sidewall, which locally increased friction but did not represent a critical defect.

Conditions with overlapping laser tracks (L_5mm and T_5mm) exhibited lower and more stable forces, consistent with their improved ductility, and resulted in defect-free geometries. In contrast, the non-overlapping condition (L_0mm) leads to increased forces and corner fracture during the final stages of injection (Fig. 6).

Overall, the results demonstrate that LHT significantly improves formability during sheet injection by reducing forming forces and suppressing fracture. Overlapping LHT strategies provided the most favourable balance between material softening and process stability, while numerical predictions successfully captured the main trends, with deviations highlighting the influence of friction and property gradients that warrant further investigation.

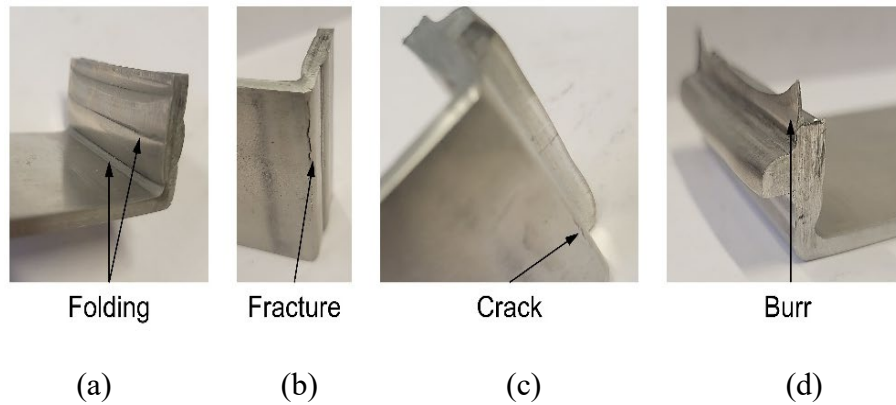


Fig. 6. Defects: (a) folding in T6 (reference); (b) fracture in T6; (c) fracture in L_0mm (Longitudinal, 0 mm overlap); and (d) burr in the LHT specimens.

Conclusion

This study demonstrated that LHT effectively tailors the mechanical properties of AW6082-T6 aluminium alloy for sheet injection processes. Mechanical characterisation showed a significant reduction in strength accompanied by enhanced formability, confirming the suitability of LHT for locally adapting material behaviour to high-strain forming operations.

Sheet injection experiments revealed that THTB substantially expand the process window compared to the T6 reference condition. While the untreated material exhibited early fracture, LHT strategies enabled increased material flow into the die cavity at reduced forming forces. Among the investigated approaches, the longitudinal strategy with overlapping tracks (L_5mm) provided the most stable behaviour, combining low forces, uniform softening, and defect-free geometries.

Overall, the results validate the feasibility of applying LHT to enable sheet injection of medium-strength aluminium alloys, enhancing the industrial potential of sheet-bulk forming for lightweight, functionally integrated components in transportation and structural applications.

References

- [1] A.E. Tekkaya, Energy saving by manufacturing technology, *Procedia Manuf.* 21 (2018) 392–396.
- [2] M. Merklein, J.M. Allwood, B.A. Behrens, A. Brosius, H. Hagenah, K. Kuzman, K. Mori, A.E. Tekkaya, A. Weckenmann, Bulk forming of sheet metal, *CIRP Ann. Manuf. Technol.* 61(2) (2012) 725–745.
- [3] K. Mori, T. Nakano, State-of-the-art of plate forging in Japan, *Prod. Eng.* 10 (2016) 81–91.
- [4] T. Schneider, M. Merklein, Manufacturing of geared sheet metal components by a single-stage sheet-bulk metal forming process. In: D. Dimitrov, C. Schutte. *Proceedings International Conference on Competitive Manufacturing, Stellenbosch* (2013) 177-182.
- [5] J.P.G. Magrinho, M.B. Silva, P.A.F. Martins, A flexible sheet-bulk forming demonstrator, *Int. J. Adv. Manuf. Tech.* 103 (2019) 1405-1417.
- [6] J.P.G. Magrinho, M.B. Silva, P.A.F. Martins, Injection by sheet-bulk forming, *Precis. Eng.* 59 (2019) 73-80.

- [7] A. Piccininni, G. Palumbo, Design and Optimization of the Local Laser Treatment to Improve the Formability of Age Hardenable Aluminium Alloys. *Materials* 13(7) 2020.
- [8] ASTM International. Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature. ASTM E9-09:2018.
- [9] C.V. Nielsen, P.A.F. Martins, Metal forming: formability, simulation and tool design. Amsterdam: Academic Press, 2021.