

Design and Development of a Hydrostatic Support Device for Hot Incremental Sheet Forming of PMMA

Conte Romina^{1,a*}, Trimarchi Stefano^{1,b}, Gagliardi Francesco^{1,c},
De Napoli Luigi^{1,d}, Ambrogio Giuseppina^{1,e}

¹University of Calabria, via P. Bucci, 87036 Rende (CS), Italy

^{a*}romina.conte@unical.it, ^bstefano.trimarchi@unical.it, ^cfrancesco.gagliardi@unical.it,
^dluigi.denapoli@unical.it, ^egiuseppina.ambrogio@unical.it

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Abstract. Thermoplastic-based sheets (TBSs) are increasingly adopted in the automotive and aerospace sectors due to their potential for producing lightweight and durable structures. However, conventional manufacturing techniques, such as compression molding, offer limited process flexibility, as they rely on costly, dedicated molds. Single Point Incremental Forming (SPIF) represents a promising die-less alternative. Nevertheless, its application to thermoplastics requires strict control of the process conditions to avoid material failure. This study focuses on the validation of a novel experimental apparatus for pressure-assisted hot SPIF. The developed equipment enables precise, real-time control and regulation of both the working temperature and the hydrostatic support pressure, which are critical parameters for enhancing polymer formability. A key aspect of the experimental procedure is the use of an aluminum sacrificial sheet placed between the forming tool and the polymeric blank. This intermediate layer fulfills a dual role by ensuring a hermetic hydraulic seal to prevent fluid leakage and by promoting uniform pressure distribution during the forming process. The experimental results demonstrate the effectiveness of the proposed setup, achieving successful deformation of TBSs with high geometric accuracy. Overall, this research confirms the feasibility and robustness of the designed equipment for processing unconventional materials, offering a flexible and efficient alternative to traditional rigid tooling technologies.

Introduction

The manufacturing industry is increasingly driven by the demand for highly customized, lightweight, and high-performance components. In this context, Single Point Incremental Forming (SPIF) has emerged as a promising technology due to its extreme flexibility and the absence of dedicated dies, which significantly reduces lead times and costs for small-batch production. While SPIF has been extensively characterized for metallic sheets, the necessity to extend this dieless forming capability to thermoplastic based sheets (TBSs) is becoming crucial. These materials offer superior strength-to-weight ratios and chemical resistance, yet their shaping via traditional methods often lacks the versatility required for rapid prototyping and customized applications.

However, the transition from metals to polymers introduces significant challenges. Unlike metals, polymeric materials exhibit complex viscoelastic and viscoplastic behaviors that are heavily dependent on process parameters, particularly temperature. Early research by Martins et al. [1] demonstrated the feasibility of SPIF for commercial polymers at room temperature, identifying key failure modes and the critical role of tool-sheet interaction. More recently, the focus has shifted towards assisted forming strategies to overcome the limitations of cold forming, such as significant springback and limited formability. For instance, Almadani et al. [2] investigated a novel contactless hot air SPIF approach, highlighting how thermal management can reduce tool wear and improve geometric accuracy in polycarbonate sheets. These studies underscore the growing scientific interest in deforming polymers through non-conventional, incremental strategies to unlock new design possibilities.

Building on this background, the authors of the present work have conducted extensive research to define the process window for TBSs. Previous studies by Conte et al. [3] focused on the formability

of fiberglass-reinforced Polyamide 6 (PA6), developing specific setups to control the working temperature above the glass transition point. Further investigations [4, 5] explored the influence of process parameters on material failure and the potential for re-manufacturing thermoplastic composite structures, proving that SPIF can effectively process short-fiber reinforced matrices when thermal conditions are optimized. Indeed, SPIF could address the challenges of manufacturing TBSs preserving, at the same time their structural integrity and avoiding weak points due to uneven strain distribution [4, 5].

Despite these advances, the processing of long-fiber reinforced plastics remains a critical frontier due to the risk of fiber breakage and the higher forces involved. In a very recent preliminary study [6], the authors proposed a customized process solution specifically designed to handle the complexities of long-fiber composites. The current study aims to validate and commission the specifically designed equipment, by experimental tests. Indeed, while the previous work introduced the concept, this paper focuses on the testing phase, providing experimental evidence of the process feasibility and the reliability of the new setup. For this preliminary experimental phase, polymeric sheets were used. The following sections will describe the equipment in detail, the employed material, and discuss the results of the validation trials, demonstrating how this novel approach can successfully plastically deform polymer panels.

The Designed Equipment

The full experimental equipment is illustrated in Fig. 1.

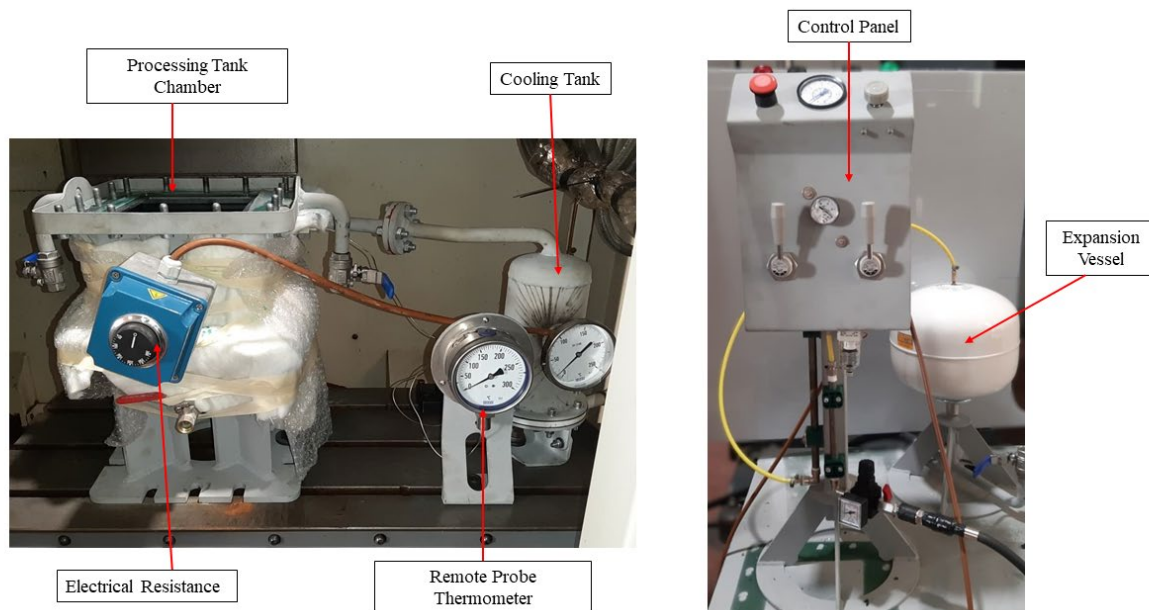


Fig. 1. Developed experimental equipment.

The equipment is designed to control temperature and pressure during the working phase [6]. A polymeric seal is located at the bottom of the processing tank, with glass wool positioned laterally. These materials act as thermal insulators to maintain a uniform temperature throughout the forming phase.

Specifically, the processing tank chamber is filled with a mixture of water and glycol. At the top, a seal, a polymer sheet, and a metallic sheet are stacked in that order, with the metallic sheet in contact with the rigid tool [4]. Once the upper edge of the metal sheet is clamped, the heating element is activated to reach the working fluid temperature. The fluid is then pressurized to generate a hydrostatic force, ensuring contact between the polymer and metallic sheets until both the forming and cooling phases are complete.

During the forming phase, the sheets deform into the processing tank chamber, causing volumetric displacement of the fluid. To maintain constant hydrostatic pressure, the system employs an

expansion vessel coupled with a pneumatic regulator. This regulator modulates the inlet air pressure to align with the required working pressure, ensuring stable system operation in conjunction with a vent valve.

Consequently, the pressure within the working zone is regulated via a control panel, which establishes the specific pressure profile required within the expansion vessel. A stratified thermal separator (cooling tank) is positioned at the exit of the processing tank to reduce the fluid temperature before its entry into the expansion vessel. A remote probe thermometer monitors the temperature within the processing tank. For safety reasons, a secondary thermometer measures the temperature in the cooling tank to preclude the return of high temperature and pressurized fluid into the expansion vessel.

The Process Feasibility

Materials.

SPIF was performed using 1 mm thick Al 2024 sheets and 2 mm thick Poly(methyl methacrylate) (PMMA) sheets [7]. The choice of aluminum was driven by its thickness and mechanical properties, which act to maintain dimensional stability and restrict upward yielding during the deformation of the underlying polymer.

Differential Scanning Calorimetry (DSC) was conducted to characterize the thermal properties of the PMMA, according to the ISO 11357 standard [8]. Analyses were performed using a DSC25 (TA Instruments). Three samples weighing between 2 and 6 mg were prepared and subjected to one cycle of a heating ramp at a constant rate of 10 °C/min. The resulting heat flow curve is presented in Fig. 2, from which a glass transition temperature (T_g) of 108 °C was determined.

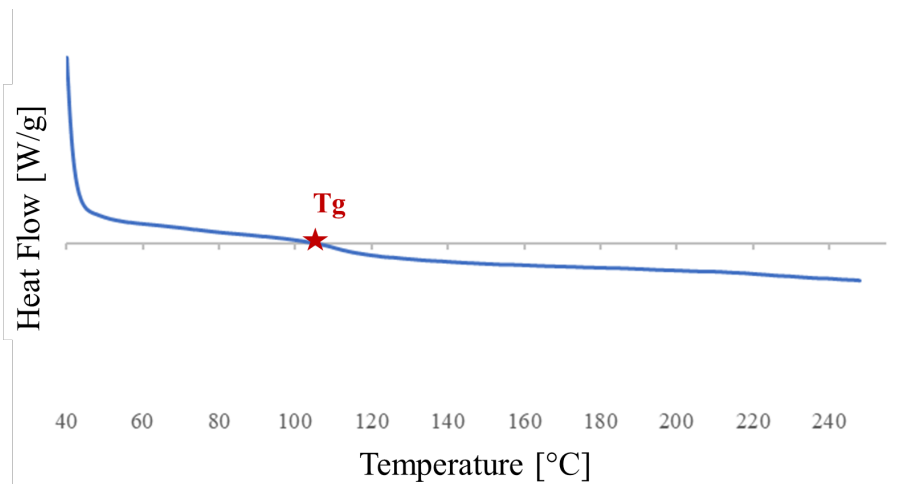


Fig. 2. PMMA heat flow curve.

Experimental phase.

During the process, a truncated cone specimen was fabricated, characterized by an upper diameter of 150 mm, a final height of 30 mm, and a wall angle of 30°. Three experimental tests were conducted by varying the hydrostatic pressure, which was set to 0.1, 0.2, and 0.4 bar, respectively.

For all tests, the working temperature was maintained at 115 °C. This temperature was selected based on the glass transition temperature of the polymeric material. The polymer was in contact with a water-glycol mixture, selected specifically to ensure controlled and safe boiling conditions throughout the experiments. To maintain a constant working temperature, the system was continuously monitored and heated using a thermocouple-regulated heating element. To ensure thermal equilibrium, the forming process was initiated only after a stabilization period of approximately 10 minutes; this duration was established by measuring the temperature on the upper face of the sheet during the start-up phase.

A rigid forming tool with a diameter of 10 mm was employed. The tool path followed a counterclockwise spiral trajectory with a vertical step-down of 1 mm per revolution, a spindle speed of 1000 rpm, and a feed rate of 400 mm/min. The upper and lower surfaces of the polymeric sheet, after completion of the forming process and subsequent unclamping, are shown in Fig. 3.

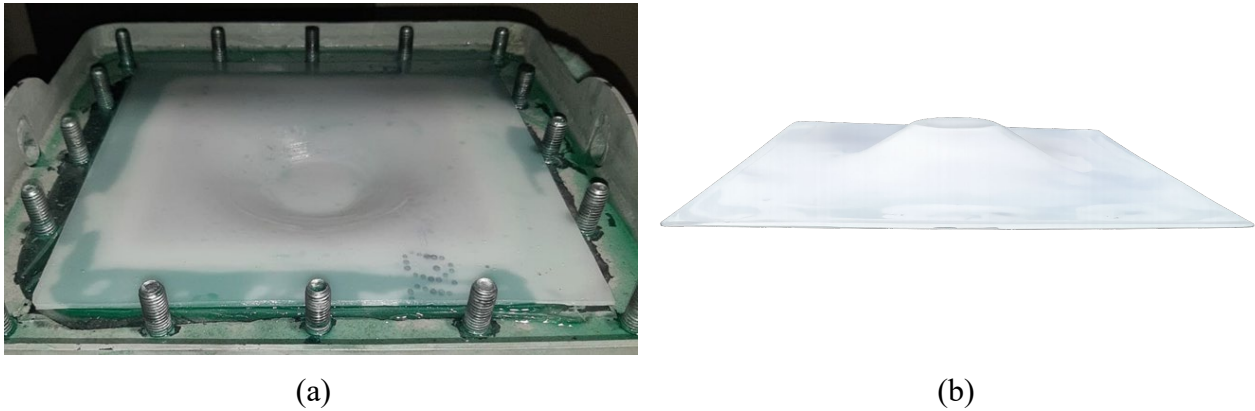


Fig. 3. a) Upper surface and b) lower surface of the PMMA SPIFed sheet.

After unclamping, the PMMA sheets were 3D-scanned using an Artec Eva system (accuracy: 0.1 mm, resolution up to 0.2 mm). The acquired scans were subsequently imported into GOM Inspect software, where the measured geometries were superimposed onto the nominal model. Geometric deviations were quantified by evaluating the distance between the scanned surfaces and the nominal geometry over the entire formed area. This analysis enabled the assessment of shape accuracy and the identification of localized deviations associated with different hydrostatic pressure conditions. The resulting deviation maps were used to investigate the influence of process parameters on the dimensional accuracy of the formed PMMA components.

Discussion of Results

The results shown in Fig. 4 demonstrate how pressure variation significantly affects the final geometry, with the three samples exhibiting seemingly contradictory trends. Specifically, the deviation maps on the left side of Fig. 4 illustrate the global 3D geometric deviations of the entire scanned specimens relative to the nominal geometry. To provide a more detailed local analysis, the graphs on the right side display the 2D deviation profiles extracted along a representative planar cross-section. These superimposed curves are included to explicitly highlight the point-by-point discrepancy between the manufactured shape and the target profile.

The specimen formed at 0.1 bar showed relatively low deviation metrics (Mean Absolute Deviation: 1.77 mm; SD: 2.42 mm), yet it presented visually consistent geometrical discrepancies, such as curved walls and a pronounced radius at the upper diameter. This behavior suggests that the pressure was insufficient to generate the necessary hydrostatic force, failing to ensure complete adhesion between the polymeric blank and the sacrificial Al sheet.

Conversely, the specimen formed at 0.2 bar appeared to replicate the target geometry more accurately at first glance. However, quantitative analysis revealed higher deviation metrics (Mean: 2.43 mm; Min: -7.44 mm) compared to the 0.1 bar case. This indicates that while the pressure increase effectively resolved the inter-sheet adhesion issue, the hydrostatic force may have been excessive relative to the structural stiffness of the Al sheet. Consequently, the Al layer likely yielded or deflected beyond the nominal tool path, introducing a discrepancy between the target shape and the final polymeric geometry.

Finally, the specimen formed at 0.4 bar experienced excessive deformation and thinning at the base diameter. Although it exhibits the lowest mean absolute deviation (1.59 mm), it also shows the largest deviation range (+5.29 mm to -10.99 mm), confirming that excessive pressure leads to process instability.

Overall, these findings clearly highlight that hydrostatic pressure plays a pivotal role in the process and must be carefully tailored according to the specific polymer type, the working temperature, and the structural resistance of the sacrificial metallic sheet.

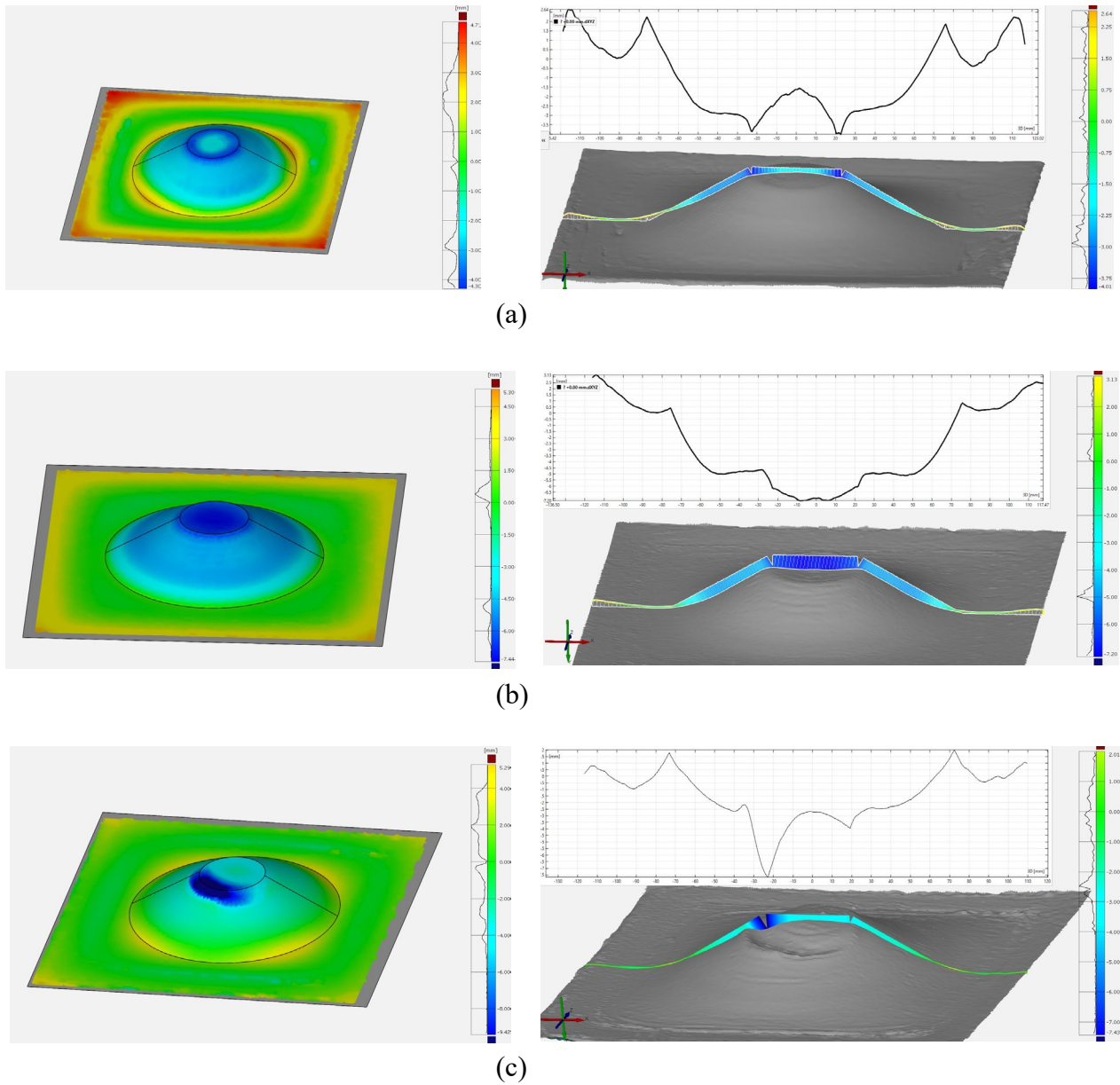


Fig. 4. Deviation maps showing differences between measured and nominal geometries for the three operating conditions: a) 0.1 bar, b) 0.2 bar, and c) 0.4 bar. For each condition, the global 3D deviation map is shown on the left, and the corresponding 2D deviation profile along a representative cross-section is displayed on the right.

Conclusion

The study successfully validated a novel experimental apparatus designed for the pressure-assisted hot SPIF of thermoplastic sheets. The proposed system demonstrated precise control of both the working temperature and the hydrostatic support pressure, effectively overcoming key limitations typically encountered in the forming of polymeric materials.

The experimental campaign conducted on PMMA sheets at a constant temperature of 115 °C highlighted the complex role of hydrostatic pressure in determining final part quality. Specifically, the results indicated that insufficient pressure (0.1 bar) fails to ensure complete adhesion between the polymer and the metallic sheet, leading to geometric defects such as curved walls. Conversely, while

increasing the pressure to 0.2 bar improved the visual replication of the shape by resolving the adhesion issue, it also revealed a critical trade-off: the hydrostatic force exceeded the structural stiffness of the sacrificial aluminum sheet, causing it to yield beyond the nominal tool path and introducing quantitative deviations. Excessive pressure (0.4 bar) proved detrimental, resulting in unstable and excessive deformation. Furthermore, the use of a sacrificial aluminum sheet proved effective in ensuring a hermetic hydraulic seal and promoting uniform pressure distribution throughout the forming process.

Overall, the findings confirm the reliability and versatility of the proposed equipment as a flexible solution for processing unconventional materials. Future work will focus on extending this approach to long-fiber-reinforced thermoplastics, exploring the controlled thermal and hydrostatic conditions to mitigate fiber damage and enhance material formability.

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