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Improving Material Formability and Tribological Conditions through Dual-Pressure Tube Hydroforming †

Gracious Ngaile * **and Mauricio Avila**

Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC 27695-7910, USA
* Correspondence: gngaile@ncsu.edu

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Abstract: Dual-pressure tube hydroforming (THF) is a tube-forming process that involves applying fluid pressure to a tube's inner and outer surfaces to achieve deformation. This study investigates the effect of dual-pressure loading paths on material formability and tribological conditions. Specifically, pear-shaped and triangular cross-sectional parts were formed using dual-pressure modes where fluid pressure on the inside of the tubular blank was alternated with pressure on the outside surface of the tubular blank, causing the tube to expand/stretch and contract. During expansion, the tube conformed to the die's cavity, while during contraction, the contact area between the die and the workpiece reduced, leading to decreased friction stress at the tube–die interface. Additionally, the reversal of pressure loadings caused the tubular blank to buckle, altering the stress state and potentially increasing local shear stress, improving material formability. Dual-pressure THF has demonstrated that the pressure loading paths chosen can substantially influence material formability. Comparing the geometries of parts formed by dual-pressure THF and conventional THF shows a significant increase in the protrusion height of both the pear-shaped and triangular specimens using dual-pressure THF.

Keywords: dual-pressure tube hydroforming; loading path; lubrication; formability

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1. Introduction

Tube hydroforming (THF) is a material-forming process that uses a pressurized fluid instead of a hard tool to plastically deform a given tubular material into a desired shape. The THF process is widely used for making parts for the automotive, aerospace, motorcycle, and bicycle industries. Tube hydroforming is also used for making components for sanitary use, such as faucets, and other parts for household appliances, such as refrigerator handles, etc. [1–3]. In recent years, significant research and development have focused on expanding the application of tube hydroforming technology to encompass the micro-, meso-, and macro-scales. This shift has been driven by the trend towards miniaturization in various industries, including medical engineering, electrical and electronic systems, optoelectronics, chemical systems, sensors, and thermal management [4]. The advancements in micro-tube hydroforming have allowed researchers to extend the benefits of this process to smaller-scale components. By utilizing fluid pressure, researchers can shape small-diameter tubes into intricate geometries with high precision. This capability is particularly valuable in industries that require the production of complex micro-components.

THF is still a relatively new manufacturing process but has demonstrated numerous benefits such as generating stronger yet lighter hollow parts and producing stiffer components with less spring back and accurate dimensioning. The limitations of THF include a longer cycle time than that of traditional stamping and a higher startup cost. In order to enhance the process window, extensive research has been conducted in the field of tube hydroforming (THF). Several focus areas include process design and optimization of the loading path, segmentation of the dies, and sequential movement to facilitate the forming of complex shapes with varying geometrical cross-sections. For example, producing irregular bellows with tight corner radii and sharp angles poses a significant challenge, necessitating inventive movable die designs and carefully planned loading paths [5,6]. Furthermore, computational modeling is crucial in THF research, requiring accurate material properties for input into numerical models. It allows for the simulation and analysis of the forming process, aiding in optimization and performance prediction. Materials such as aluminum alloys, commonly used in THF, exhibit relatively low ductility at room temperature, which hinders the advancement of products aiming for lighter weight and better performance. Consequently, research efforts have been directed towards accurately predicting the forming limits and formulating advanced yield criteria for these materials under complex loading conditions, emphasizing their importance [7,8].

Increasing the temperature is one strategy to enhance the formability of materials such as aluminum alloys. However, elevated temperatures can accelerate material failure due to excessive thinning or necking mechanisms. Additionally, precipitation processes accompanied by high-temperature treatments often reduce the strength values of certain aluminum alloys. In order to avoid microstructural changes, deformation can be carried out at subzero temperatures [9]. Tensile tests performed on AA5182-H111 and AA6016-T4 materials over a temperature range of 25 °C to −196 °C demonstrated increased strain hardening, and the onset of necking was delayed as the temperature decreased [9]. A novel method for fabricating specially shaped aluminum alloy tubular components, cryogenic medium pressure forming, was recently introduced. This process leverages the enhanced cryogenic plasticity and hardening ability of the material. During the process, the tube is subjected to simultaneous cooling and pressurization using a cryogenic medium. The desired-shape tubular component is then formed by applying flexible loading with the cryogenic medium [10,11]. These researchers also established cryogenic biaxial stress–strain relationships using a novel analytical model to characterize the hardening behavior. The resulting cryogenic biaxial flow stress significantly enhanced plasticity and hardening ability, with a strain hardening exponent of 0.43 observed at −196 °C.

The complex interaction of process variables at the tool–workpiece interface poses a challenge in determining precise friction values for use in numerical modeling. The evaluation of tribological performance and establishment of friction values in THF have predominantly relied on tribotests developed in the past two decades. These tests were specifically designed to replicate the process conditions in the guided zone, transition zone, and expansion zone [12–15]. However, there are ongoing efforts to develop friction models that specifically aim to accurately quantify the nonlinear friction observed at the tube–die interface. A variable friction law that takes into account the sliding velocity, contact pressure and viscosity was developed and implemented in the commercial software Abaqus [16]

Another critical design aspect of THF is preforming. Depending on the shape complexity of the tubular part and formability of the tubular material, the incoming straight tube might need to be bent or crushed before the final THF process is carried out. During the hydroforming of a long tubular part of a complex cross-section, the axial feeding provides limited material flow, and the pure expansion occurs at some middle part of the tube, due to geometric constraints or friction. In this case, crushing is used to deform the tubes in advance in order to accumulate material in the die cavity. THF die systems that involve the moving of dies to crush the pressurized tubular blank have been found to significantly lower the pressure requirement for THF [17].

In conventional tube hydroforming, the material is typically fed into the die cavity using an axial cylinder while simultaneously ramping up the pressure. This coordinated action is crucial for deforming the tube and ensuring that it conforms to the shape of the die cavity. However, if there is a lack of proper coordination between the feeding and pressure application, wrinkles may be induced in the formed tube. While tube wrinkling is often considered a defect in tube hydroforming (THF), it is important to recognize that under certain conditions, wrinkles can actually serve a beneficial purpose by facilitating the accumulation of material in the die cavity [18–20]. Additionally, researchers have observed an improvement in material formability during tube hydroforming when the fluid pressure is pulsated, a technique commonly known as pulsating hydroforming [21]. By applying pulsating pressure, wrinkles are intentionally induced and subsequently eliminated. In essence, this method offers a means of deliberately creating useful wrinkles in tube hydroforming processes.

Researchers [22] have developed a two-stage preforming process that leverages the formation of wrinkles to accumulate material in the forming zone. This innovative approach takes advantage of the inherent characteristics of wrinkles to redistribute material and enhance the forming capabilities of THF. The wrinkles are initiated with the aid of an analytical model based on bifurcation analysis and post-buckling analysis of the elastic-plastic circular cylinder under axial compression. The analytical results offer valuable guidance to the process design of two-stage preforming. This methodology was carried out for two bulged SS 304 parts, where the tube expansion rate was found to be significantly higher with two-stage preforming than with direct THF. Thin-walled parts that necessitate significant expansion are often impractical to produce in a single tube hydroforming (THF) step. However, through the utilization of numerical simulations, researchers [23] have successfully developed a four-stage tube hydroforming process for a T-shaped tubular part made of the nickel-based superalloy GH4169, achieving the desired expanded diameter. To restore ductility to the material, annealing was required after each stage of the hydroforming process.

Dual-pressure tubular hydroforming (THF), also known as double-sided tube hydroforming, builds upon the concept of traditional THF by applying pressure not only on the internal surface of the tubular workpiece but also on the external surface. This variant of the process offers three significant advantages. Firstly, dual-pressure THF creates a more favorable tri-axial stress state, enhancing the formability of the material. This means that the material can be shaped more easily and with less risk of deformation-related issues. Secondly, this technique has the potential to suppress fractures by facilitating void closure. By applying pressure on both the inside and outside of the tubular specimen, any voids or gaps in the material can be effectively closed, reducing the likelihood of fracture occurrence. Thirdly, lubricant can be utilized as a pressure medium in dual-pressure THF. This lubricant not only exerts the necessary pressure on the outside of the tubular specimen, but also acts as a lubricating agent, enhancing the tribological performance by reducing friction. This lubrication aids in the overall deformation process.

While metals such as aluminum alloys and magnesium alloys are sought after due to the increasing demand for lighter components, their low formability compared to steel and steel alloys presents several challenges when attempting to use them in tubular hydroforming [24]. In addition to the inherent material properties, the prevailing stress state also plays a crucial role in determining the formability of a metal when it undergoes plastic deformation [25].

A comprehensive plastic instability analysis of a dual-pressure THF process was conducted by [26] with a specific emphasis on the impact of counter pressure (external pressure) on plastic instability. Their research aimed to investigate the influence of external pressure on the onset of plastic instability and its subsequent effects. Through their study, they derived a mathematical relationship that clearly demonstrated how the application of external pressure delays the occurrence of plastic instability. As a result, this delay enhances the material's deformation capabilities, leading to a significantly larger critical strain and improved ductility of the tubular material. Researchers [27] conducted a thorough parametric study on the dual-pressure tube hydroforming (THF) process, specifically focusing on forming a part with a square cross-section. They systematically varied the internal and external pressures to investigate their effects. The researchers observed that subjecting the tube wall to hydrostatic pressure resulted in an improved forming limit of the tube. Moreover, the external pressure had notable implications on various factors, including the fraction of grain boundaries, the number and size of micro voids, and the microhardness. Consequently, the critical effective strain in the transition zone was increased. In another study, researchers [28] explored the influence of dual-THF on free bulging and corner filling experiments using 5A02 aluminum alloy and 2A12 aluminum alloy tubes. Their investigations revealed that the external pressure significantly influenced the fracture behavior of these tubes, leading to notable changes in the type, quantity, size, and proportion of dimples on the fractured surface. Furthermore, they discovered that increasing the external pressure transformed the fracture mode from a void accumulation fracture to a pure shear fracture. This transformation had a substantial impact on enhancing the fracture limit of the tubes.

This paper investigates the influence of different loading paths on the tribological conditions and material formability in dual-pressure tube hydroforming (THF). The loading paths in question involve the application of internal and external pressure within the dual-pressure THF process. The primary objective of this study was to investigate and differentiate the impact of lubrication on the formability of materials from the effects resulting from changes in the stress state induced by alterations in the deformation path.

2. Mechanisms to Improve Material Formability and Tribological Conditions through Dual-Pressure Tube Hydroforming (THF)

Figure 1 shows a cross-section of a tube placed on a conventional THF die to produce a triangular tubular product. To reduce friction at the interface between the die and the tube, solid or liquid lubricant is commonly used. Good lubrication results in large expansion and a more uniform wall thickness distribution along the profile. In contrast, bad lubrication can result in premature failure and non-uniform wall thickness distribution, due to high friction stress, τ, induced at the tube–die interface.

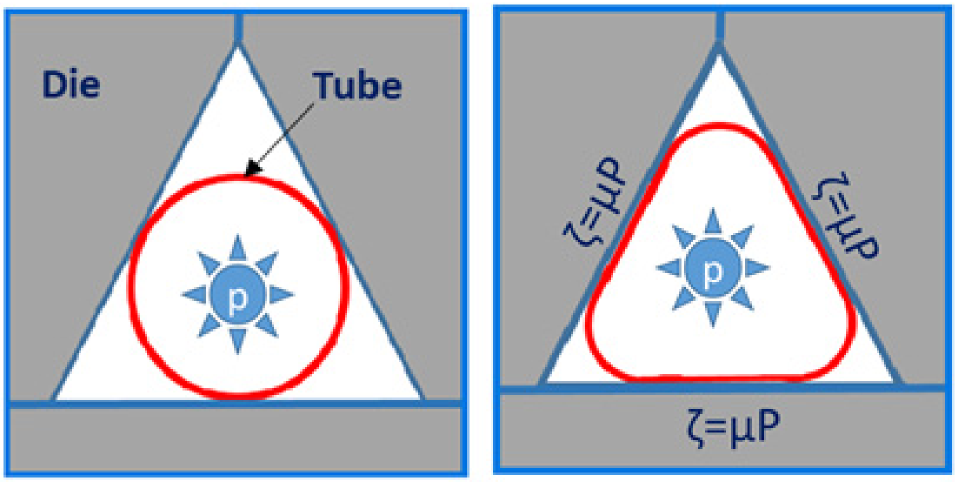

Figure 1. Conventional tube hydroforming.

In contrast, dual-pressure THF substantially reduces friction stress through two mechanisms: (1) increase in lubricant supplied to the interface, because the lubricant is used as a medium that exerts pressure on the outside of the tube; and (2) minimizing the metal-to-metal contact area between the die and the tubular specimen, through innovative design of the pressure loading paths so as to result in nearly hydrostatic lubrication conditions. Figure 2 shows a schematic of dual-pressure THF. Figure 2c shows an instant where the tubular specimen is pre-shaped via external fluid pressure such that metal-to-metal contact is substantially reduced. As deformation progresses from Figure 2a–d, the captured fluid on the outside dimpled regions tends to spread toward the metal-to-metal contact regions, further enhancing tribological conditions. Thus, a tubular shape produced by dual-pressure THF results in large expansion and fairly uniform wall thinning.

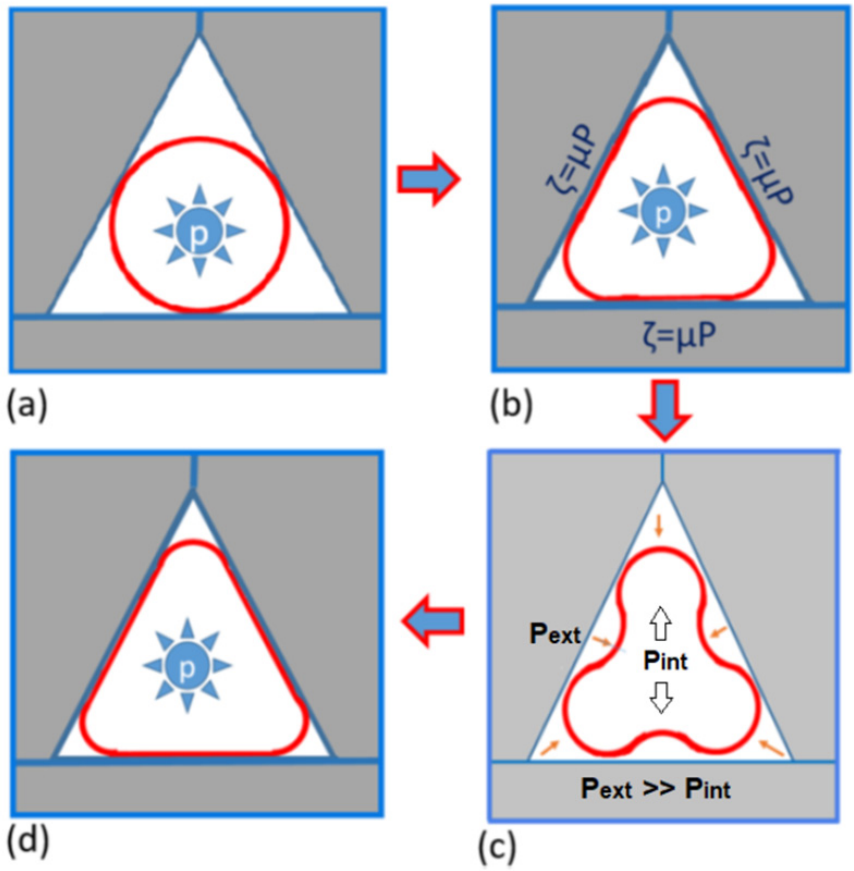

Figure 2. Dual-pressure tube hydroforming cycle: (**a**) Initial tube-die configuration before hydroforming, (**b**) deformed shape after 1st internal pressurization of the tube, (**c**) collapsed tube after external pressurization, and (**d**) 2nd level of internal pressurization to produce a part.

A graph of the proposed dual-pressure THF loading paths, showing hypothetical internal and external pressure profiles, is given in Figure 3. The internal pressure loading path is responsible for expanding the tube to fill the die cavity. The figure shows three intervals where the internal pressure is ramped to expand the tube. In the first interval, internal pressure is ramped up to P_1 and subsequently released to a lower pressure at time t_1. At this juncture, the tube is partially formed. The induced friction stress at the tube–die interface is bound to decrease due to replenishment of lubricant from the external pressure loading path. As seen in Figure 3, at the start of the process, t_o, the external pressure loading path supplies lubricant to the tube outer surface and maintains a low pressure up to time $t_{1.}$ Between time t_1 and t_2, the fluid pressure acting on the outside of the tube is increased, causing the tube to buckle inward (also see Figure 2c). This action allows lubricant to be supplied to starved regions, substantially reducing the metal-to-metal contact. From time t_2 to t_3, the internal pressure is again ramped up to P_2 and subsequently released to a low pressure. This is followed by raising the external pressure in between time t_3 and $t_{4,}$ again causing the tube sample to buckle and enabling lubricant to be supplied to starved regions. Finally, the internal pressure is ramped to calibration pressure P_3 at time $t_{f,}$ completing the dual-pressure THF process cycle. In practice, an optimal set of loading paths could be established through numerical modeling by quantifying the pressure oscillating frequency and amplitudes for both internal and external pressure loading paths.

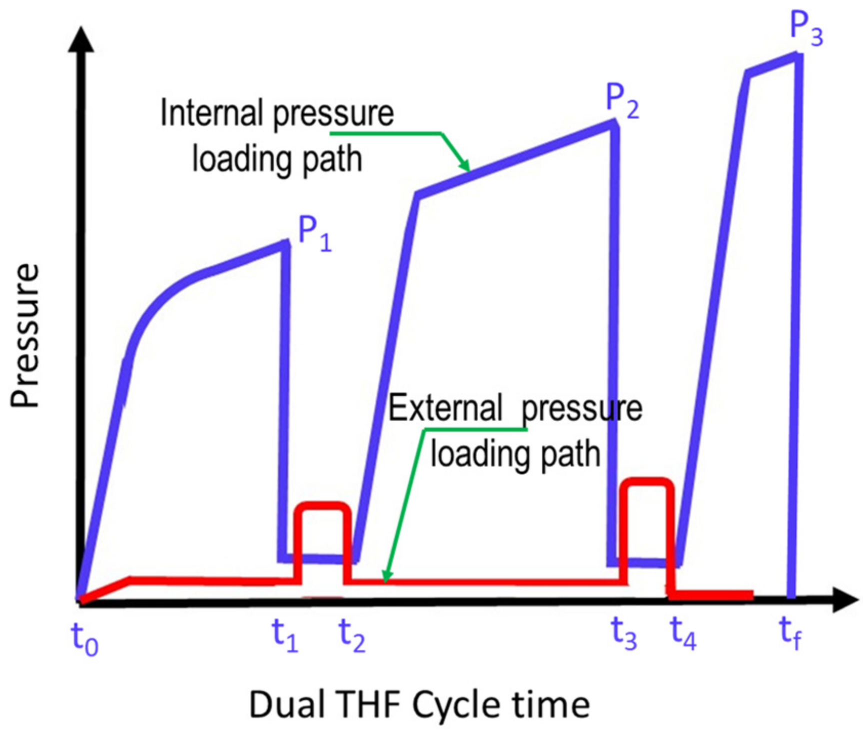

Figure 3. Hypothetical dual-pressure THF loading paths. "P1, P2, and P3 represent the maximum fluid pressure values reached during pressurization levels 1, 2, and 3, respectively".

Figure 4 illustrates the mechanisms through which external fluid pressure can enhance both formability and tribological conditions by inducing the collapse and subsequent expansion of a tube. This process alters the stress state on the deforming tube wall, with potential to improve its formability.

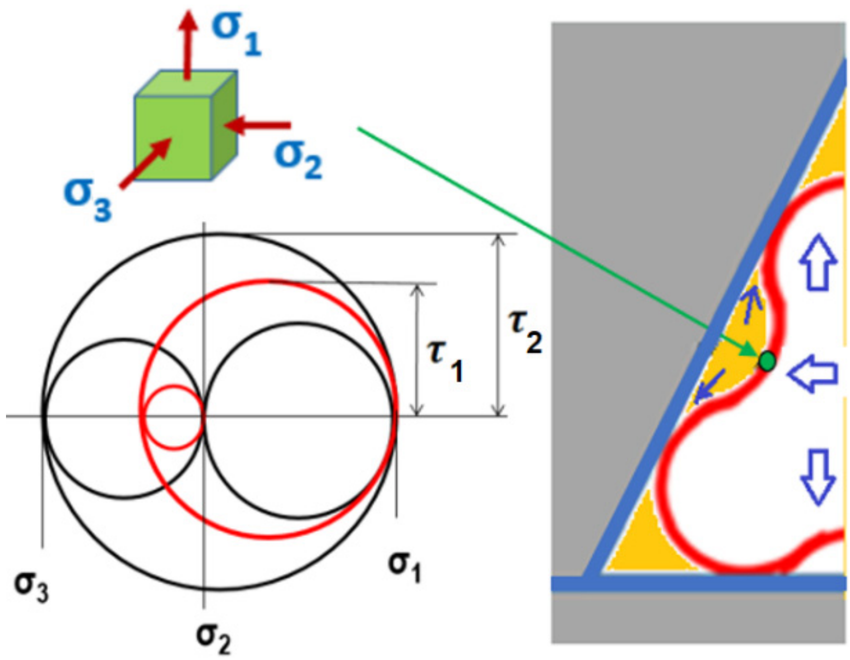

Figure 4. Mechanisms for enhancing formability and tribological performance.

The Mohr circle diagram demonstrates that certain regions of the tube wall experience a stress state that promotes ductility. Specifically, as the magnitude of the compressive stress σ_3 increases, the corresponding shear stress shifts from τ_1 to τ_2 (Figure 4), leading to enhanced ductility. Therefore, the loading path for dual-pressure THF is a critical parameter for improving formability. However, it is important to note that the enhancement of material formability under this mechanism requires the presence of both internal and external pressure loads acting on the internal and external surfaces of the tube, respectively. Furthermore, if the loading path only leads to a minor increase in the magnitude of compressive stress in the Mohr circle, the resulting improvement in ductility is negligible.

As briefly outlined in the introduction section, previous research studies examining the induction of wrinkles to facilitate increased material supply into the die cavity have primarily concentrated on the total mass of material transferred from the guiding zone to the die cavity. However, it is important to acknowledge that the pathway through which this material is supplied to the die cavity, via wrinkling, leads to a change in the stress state. This change has the potential to induce the reorientation of dislocations within the deforming material. Such behavior is likely to impact the ductility of the material.

3. Dual-Pressure THF Tooling Design and Experimental Procedures

To test the proposed procedure, an experimental setup for dual-pressure THF was designed. The CAD models for major parts of the tooling setup are shown in Figure 5. This setup can be used only for tube expansion because it has no mechanism for tube material to be fed to the die cavity. Two sets of die inserts were designed for hydroforming a triangular cross-section and a pear-shaped cross-section. Figure 5 shows internal and external pressurized fluid ports, oval grooves for sealing, and conical punches for flaring and sealing the tubular specimen.

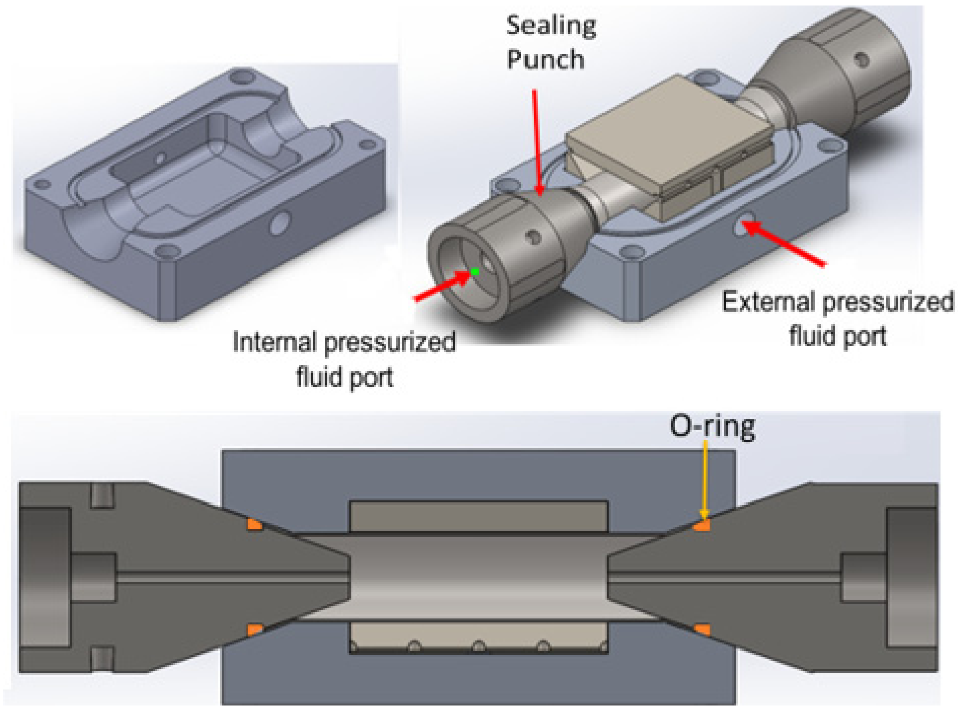

Figure 5. Tooling architecture for dual-pressure THF.

The test setup was designed to endure pressures of up to 210 MPa, and the dies were securely clamped using a 1500 kN hydraulic press, as illustrated in Figure 6a. The setup was equipped with two pressure intensifiers, enabling internal and external pressurization. To operate the tube hydroforming equipment, the pressure load paths were initially inputted into a data acquisition system and programmed using the DO Live software package. The communication between the data acquisition system and the equipment occurred through the PLC controllers, ensuring seamless coordination and control during the hydroforming process. Figure 6b shows the dual-pressure THF tooling and a collapsed tubular blank after applying external pressure. Dual-pressure THF experiments were carried out using annealed stainless-steel SS 304 tubing with an outer diameter of 34.9 mm and wall thickness of 1.65 mm. The tube samples were cut to 180 mm long.

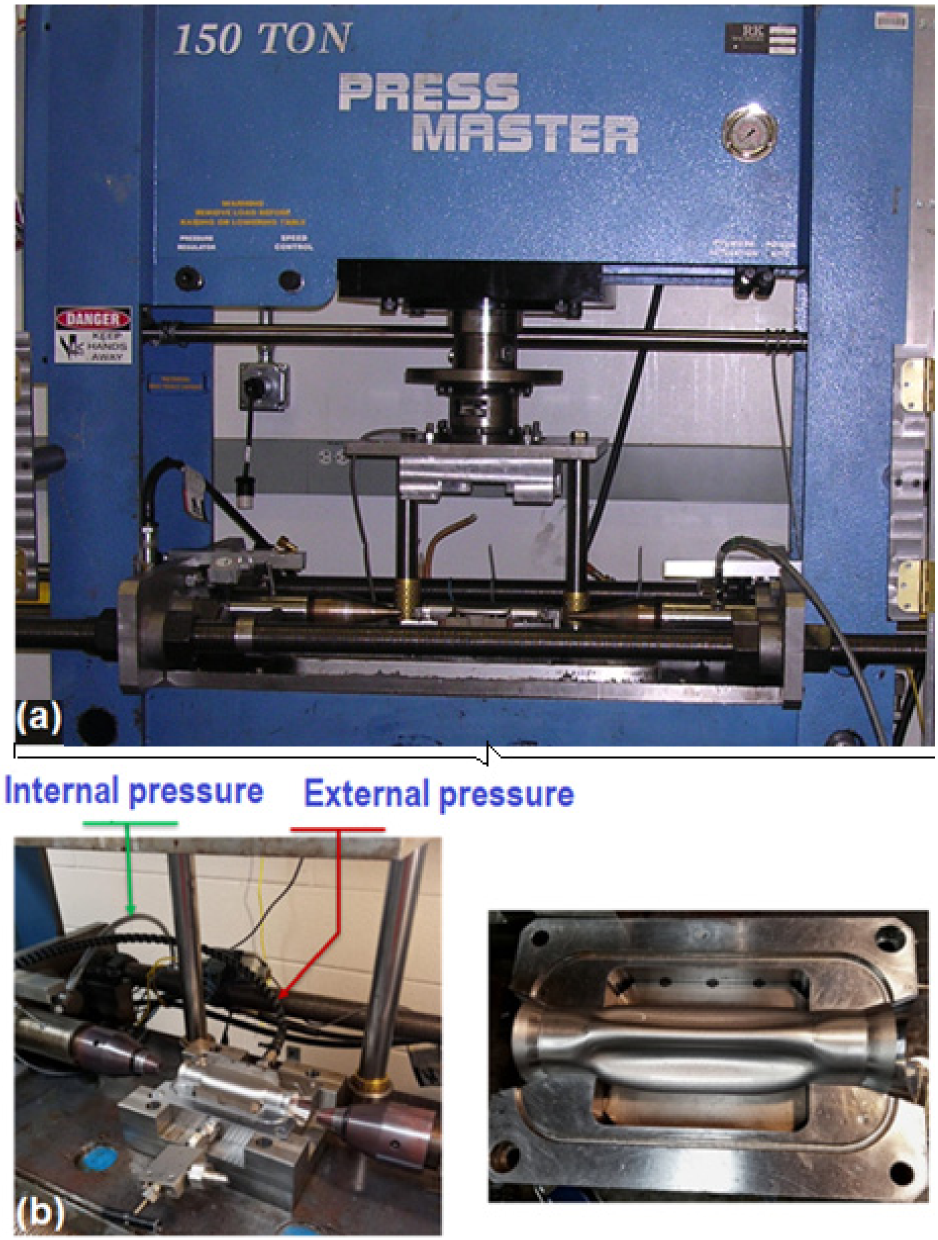

Figure 6. (**a**) A 150-ton hydraulic press, (**b**) dual-pressure THF tooling and a collapsed tubular blank.

Table 1 provides the experimental matrix employed in this study. Multiple loading paths were utilized, including (a) incrementally increasing the internal pressure to a specific level, releasing it to zero, and then applying external pressure to collapse the preformed tubular blank, afterwards finally reapplying the internal pressure to its maximum value, and (b) raising the internal pressure to the maximum forming pressure, releasing it to zero, applying external pressure to collapse the tube, and finally reapplying the internal pressure to its maximum value. The pressurization was conducted using SAE 30 hydraulic oil, which also served as a lubricant for both internal and external pressurization. To simulate excellent lubrication conditions, several experiments were conducted using a Teflon sheet as a lubricant.

Table 1. Experimental matrix.

Hydroformed Part	Loading Paths	Lubricants
Triangular shape	C-LP, DP-LP# 1, DP-LP#2, DP-LP#3	SAE 30 Oil
	C-LP, DP-LP#3	Teflon sheet
Pear-shaped geometry	C-LP, DP-LP#4, DP-LP# 5	SAE 30 Oil
	C-LP, DP-LP#5	Teflon sheet

C-LP: conventional THF loading path; DP-LP: dual-pressure THF loading path.

The triangular geometry was chosen to replicate the characteristics of hydroformed parts, while the inclusion of the pear-shaped geometry in the test matrix served as an additional geometry primarily because it is commonly employed for evaluating lubricants in tube hydroforming. As the material flow modes for these two geometries exhibit similarities, fewer loading paths were utilized for the pear-shaped geometry.

Figure 7 illustrates three loading paths (DP-PL#1, DP-PL#2, and DP-PL#3) utilized to hydroform triangular tubular parts. For DP-PL#1, the internal pressure is initially ramped up to 70 MPa to partially hydroform the tubular blank before being released to zero. Subsequently, a maximum external pressure of 11 MPa is applied, which, despite being significantly lower than the internal pressure, was found to be sufficient to collapse the tube. After the tube is collapsed, a second internal pressurization is conducted at a maximum pressure of 81 MPa, followed by a second external pressurization at 11 MPa. In the final stage of the loading path, the internal pressure is ramped up to 91 MPa.

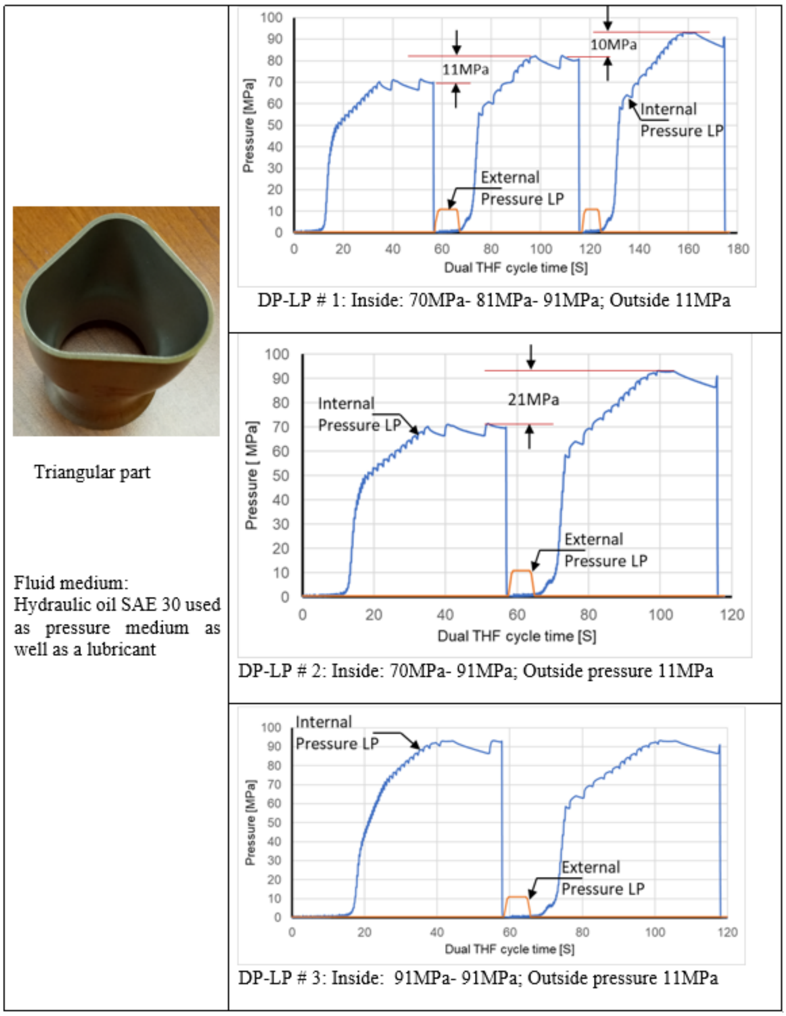

Figure 7. Loading paths used in dual-pressure THF for triangular parts.

DP-PL#2 employs similar procedures to DP-PL#1, but with two levels of internal pressurization carried out at maximum pressures of 70 MPa and 91 MPa. The external pressure required to collapse the tubular blank is applied only once at 11 MPa. In DP-PL#3, there are two internal pressurization levels, both performed at a maximum pressure of 91 MPa, while the collapse pressure is set at 11 MPa.

Figure 8 displays loading paths #4 and #5 utilized for the dual-pressure tube hydroforming of pear-shaped components. DP-LP#4 comprises two levels of internal pressurization, with the first level set to 70 MPa to produce a preform blank, followed by a second level at the maximum pressure of 91 MPa. During the intermediate stage, a collapse pressure of 11 MPa is applied. In DP-LP#5, there are two internal pressurization levels, both performed at a maximum pressure of 91 MPa, while the collapse pressure is set at 11 MPa.

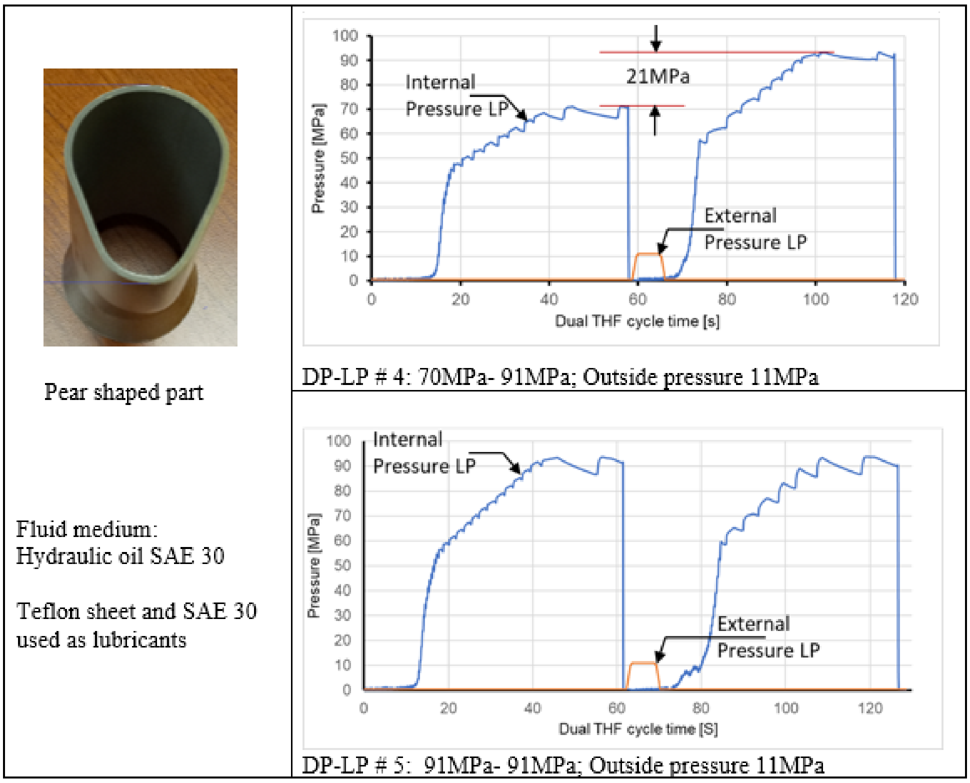

Figure 8. Loading paths used in dual-pressure THF for pear-shaped geometry.

4. Results and Discussion

Figure 9 illustrates the progression of deformation in tubular samples for the production of a triangular part using dual-pressure loading path #1. This loading path involved three levels of internal pressurization. At level one, the tubular sample was partially formed at a pressure of 70 MPa (Figure 9a). The wider side of the resulting triangle extended 42 mm from the original tube diameter of 34.9 mm. Figure 9b shows collapsed tube samples after external pressurization. External pressurization was carried out at a pressure of 11 MPa, which was sufficient to significantly collapse the tube. Various pressure levels were tested to determine when the tube would begin to buckle. It was observed that the tube started to buckle at around 10 MPa, and at a pressure of 15 MPa, the tube exhibited severe buckling such that subsequent internal pressurization could not fully eliminate wrinkles.

Figure 9. Dual-pressure LP #1 for triangular-shaped parts: (**a**)The tube deformation shape during the first level pressurization loading path at 70 MPa, (**b**) the tube deformation shape for the first level of external pressurization at 11 MPa, (**c**) the tube deformation shape for the second level pressurization at 81 MPa, (**d**) the tube deformation shape for the second level of external pressurization at 11 MPa, and (**e**) the tube deformation shape for the third level of internal pressurization at 91 MPa.

At level two, the tubular sample was pressurized to 81 MPa, and at level three the tube was pressurized at 91 MPa. The wider sides of the resulting triangles for these two pressure levels were 44 mm and 46 mm, respectively (Figure 9c,e). The external pressurization pressure was kept the same at 11 MPa. It is noteworthy that the collapse pattern remained uniform and consistent across all tubular samples. Specifically, the collapse geometry displayed dimple formation within the three flat sides of the triangular shape that was formed (Figure 9b,d).

This observation suggests that the internal pressurization levels for all the tests were significant enough to generate distinct flat regions. Had the flat regions been too small, it would have increased the likelihood of non-uniform or asymmetric wrinkle formation. It is worth noting that the pressure required to buckle the tube is a very small percentage of the pressure used for pressurization. In this case, it amounts to 12% (11.0 MPa/91.0 MPa). From an economic standpoint, a small percentage is preferred because the dual-THF process requires additional energy for external pressurization compared to the conventional THF process, which only requires internal pressurization.

The majority of tube samples shown in Figure 9 display a few markings. While these markings may appear large in the figure, they are actually quite small. Some of these marks result from the tube coming into contact with sharp edges on the mating dies during both the preforming and final THF operations. Additionally, during the collapse of the tubular sample, the end cylindrical collars experience a slight collapse as well. When pressurized, these collapsed cylindrical regions exhibit some markings, indicating that a perfect cylindrical collar could not be achieved.

One of the primary objectives of this study was to examine how loading path affects material formability. Formability was evaluated based on the extent to which the base triangle width (Hx) and height (Hy) were stretched. Surprisingly, loading paths #1 (Figure 7: D-PL #1) and #2 (Figure 7: D-PL #2) did not enhance formability for the triangular geometry, despite conducting four samples for each loading path. The conventional LP for THF yielded a base width (Hx) measurement of approximately 46.4, and there was no significant difference observed with the above-mentioned dual-pressure loading paths. Conversely, a considerable change was noted when loading path #3 was used, as seen in Figure 10. The base width (Hx) increased from 46.4 mm to 47.5 mm, a difference of 1.1 mm.

	Hx	**Hy**
Conventional LP	46.4mm	38.2mm
Dual-PLP	47.5mm	38.3mm

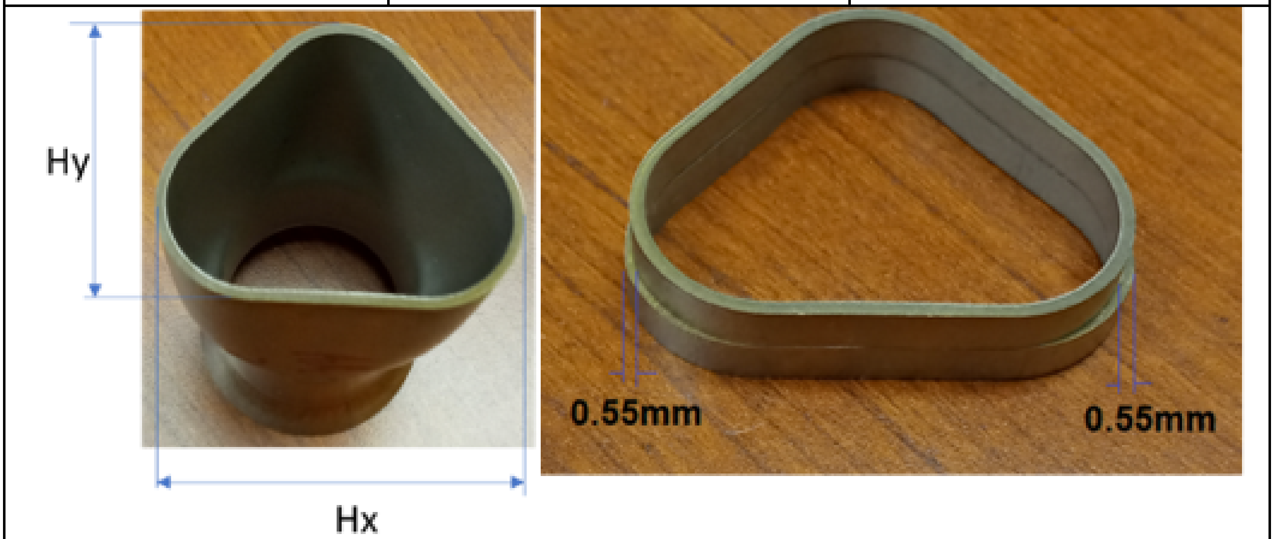

Figure 10. Dual-pressure LP#3: 91 MPa-11 MPa-91 MPa, comparison with CLP (triangular parts).

These findings demonstrate that material formability is largely influenced by the loading path. The dual-pressure THF experimental outcomes reveal that formability is significantly enhanced when internal pressurization levels before and after tube collapse (external pressurization) are carried out at the same pressure level (91 MPa in this case). Loading paths D-LP #1 and D-LP #2 had internal pressurization level 1 set at 70 MPa, and after tube collapse, the pressure was raised to 81 MPa and finally ramped to 91 MPa.

Figure 11 depicts the plastic deformation of the tubular samples under internal pressurization and external pressurization. During internal pressurization, the majority of grains on the tube wall experience tensile stress, while during external pressurization (Figure 11b), the majority of grains on the wall undergo compressive stress. The manner in which plastic deformation occurs has the potential to affect grain orientation and dislocation. The grains subjected to these two different loading conditions may change the shape of the grains and their orientation differently.

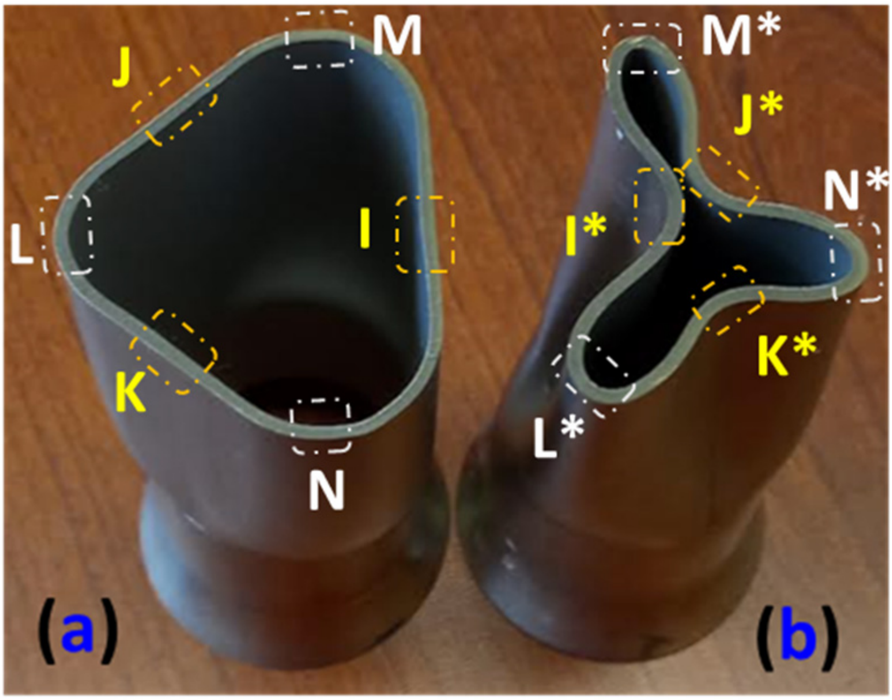

Figure 11. Plastic deformation during (**a**) internal and (**b**) external pressurization. The "*" is used to differentiate between the deformation mode observed during external pressurization and the deformation mode exhibited during internal pressurization.

It should be noted that the observed increase in material formability cannot be attributed to hydrostatic pressure effects since the internal pressure and external pressure did not act simultaneously. In other words, the experimental setup was designed in such a way that, at the tube collapse stage, the internal pressure was dropped to zero. Therefore, it is likely that other mechanisms, such as changes in the microstructure, are responsible for the improved formability observed in the experiments.

When a material is subjected to tensile stresses, the grains in the material begin to elongate and align in the direction of the stress, resulting in a more uniform and continuous grain structure throughout the material. The elongated grains can slide more easily past each other, resulting in increased ductility and a higher degree of stretchability. A similar phenomenon has been observed in bending and unbending tension (BUT) tests that are commonly conducted to simulate material flow in sheet forming using draw-beads [29–31]. In these tests, researchers have discovered an increase in formability and have observed elongated grain morphology in the direction of the drawing load [32]. The inability of load path #1 and #2 to improve formability may suggest that the change in the magnitude of the local state of stress during reverse deformation may have misaligned the grains, reducing the material's ductility.

Upon analyzing the deformation paths of the tube, which underwent internal pressurization followed by external pressurization to collapse the sample, it becomes apparent that regions IJK, as well as regions LMN (as depicted in Figure 11), experienced the highest plastic strain. Considering that the dual-pressure loading paths may involve multiple cycles of pressurization, it is likely that these regions underwent the most significant changes in stress amplitudes. Upon further assessment of these regions, it was observed that during internal pressurization, the IJK regions predominantly exhibited tensile plastic strain, whereas during the collapse stage (external pressurization), these regions primarily exhibited compressive plastic strain (stress reversal).

While the tips of the petals (LMN regions) also experienced tensile plastic strain during internal pressurization, during the collapse stage, these curved petals underwent additional bending. Consequently, it is evident that the outer tube surface encountered tensile plastic strain. It is important to note that for materials with lower formability, the tensile plastic strain induced on the LMN regions may lead to surface fractures. This implies that the collapse level in dual-pressure THF processes needs to be optimized to prevent such failures from occurring. Further analysis of the microstructure can provide additional insights into the underlying mechanisms and help understand the observed behavior.

Figure 12 illustrates the deformation progression in tubular samples during the production of a pear-shaped part using dual-pressure loading paths #4 and #5. The pear shape geometry is commonly employed to evaluate the effectiveness of tube hydroforming lubricants, with the assessment relying on the protrusion height of the pear achieved under a constant internal pressure loading [15]. In this study, this geometry was chosen to investigate the impact of dual-loading paths on both material formability and tribological conditions.

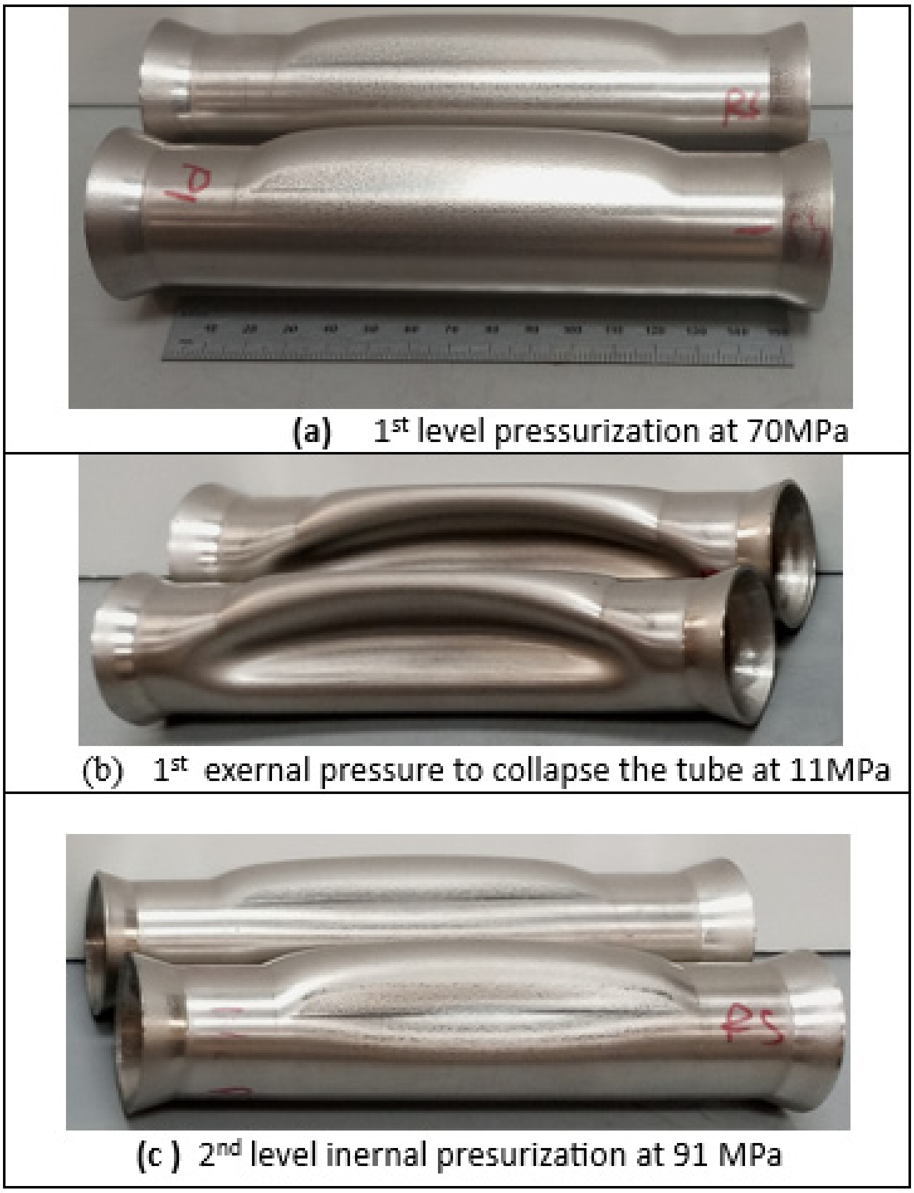

Figure 12. Dual-pressure LP# 4 for pear-shaped parts: (**a**) The tube deformation shape during the first level pressurization loading path at 70 MPa, (**b**) The tube deformation shape observed during external pressurization at 11 MPa, (**c**) The tube deformation shape for the second level pressurization loading path at 91 MPa.

Loading path #4 consisted of two stages of internal pressurization. In the first stage, the tubular sample was partially formed at a pressure of 70 MPa (Figure 12a). Figure 12b illustrates the collapsed tube samples after external pressurization, which was conducted at 11 MPa. In the second stage, the tubular samples were pressurized to 91 MPa.

Similarly to the triangular shape geometry, load path #4 did not demonstrate any improvement in the material formability. However, a significant difference in the protrusion height (Hy) was observed when loading path #5 was employed. The only distinction between these two loading paths is that load path #5 involved two internal pressurization levels set at the same pressure of 91 MPa, with external pressurization set at 11 MPa.

Figure 13 presents two cut sections: the top slice depicts a pear-shaped sample hydroformed using the conventional loading path, while the bottom slice illustrates a pear-shaped sample hydroformed using the dual-pressure loading path. It is evident that the use of dual-pressure tube hydroforming (THF) resulted in an increase in protrusion height (Hy) from 42.76 mm to 44.1 mm, indicating a difference of 1.3 mm. Both internal and external pressurization were conducted using the hydraulic oil SAE 30, which also served as a lubricant. The same mechanisms observed for formability enhancement in the triangular shape parts discussed above can be attributed to this geometry as well.

	Hy
Conventional LP	42.76mm
Dual PLP	44.10mm

Figure 13. Load path # 4: 91 MPa, 11 MPa, and 91 MPa (pear shape using the oil SAE 30).

Although Section 2 presented mechanisms for enhancing both tribological conditions and material formability, the experimental results indicate that the influence of dual-pressure THF on material formability is predominant. One of the reasons for this observation is that the fluid used in external pressurization is not a conventional lubricant, resulting in a relatively low potential for reducing friction stress at the contact surface between the die and the tubular surface. To address this limitation, several hydroforming tests were conducted using Teflon sheets, which have been found to exhibit high lubricity in tube hydroforming and other metal forming processes.

Figure 14 illustrates the protrusion height (Hy) of the pear-shaped part obtained when the tubular samples were lubricated using Teflon sheet and SAE 30. These tests were performed using the conventional THF pressure loading path at 91 MPa. As depicted in the figure, the use of Teflon sheet as a lubricant resulted in a protrusion height that was 2 mm higher than when SAE 30 was used.

Dual-THF experiments were also conducted with the tubular samples wrapped in Teflon sheet. Loading path #5, involving two internal pressurization levels set at 91 MPa, was employed, while the external pressure was set at 11 MPa. It is important to note that although SAE 30 hydraulic oil exerts pressure on the external surface of the tubular sample, the presence of the Teflon sheet significantly governs the lubrication effect due to its low shear strength. As shown in Figure 15, the protrusion height increased from 44.8 mm to 46.1 mm. Remarkably, this increase of 1.3 mm is consistent with the increase observed when hydraulic oil SAE 30 was used for internal and external pressurization.

	Hy
Conventional LP: Oil-SAE 30	42.76mm
Conventional LP: Teflon sheet	44.8mm

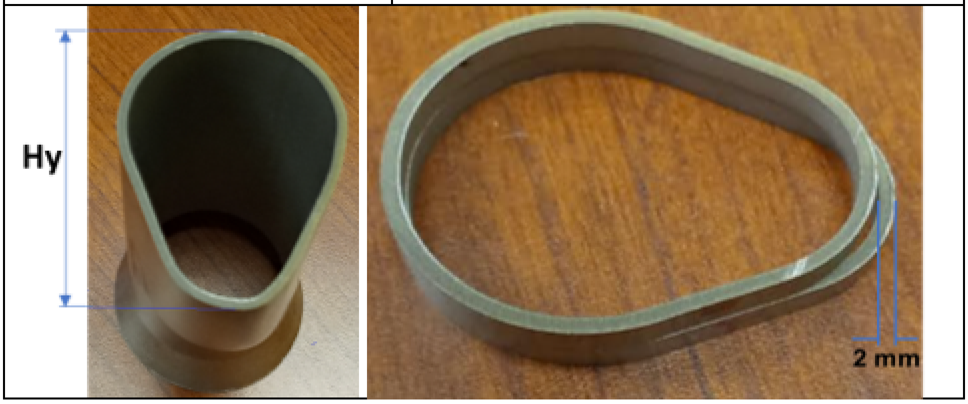

Figure 14. Influence on lubricant on protrusion height [SAE 30 vs. Teflon sheet].

	Hy
Conventional LP	44.8mm
Dual PLP	46.1mm

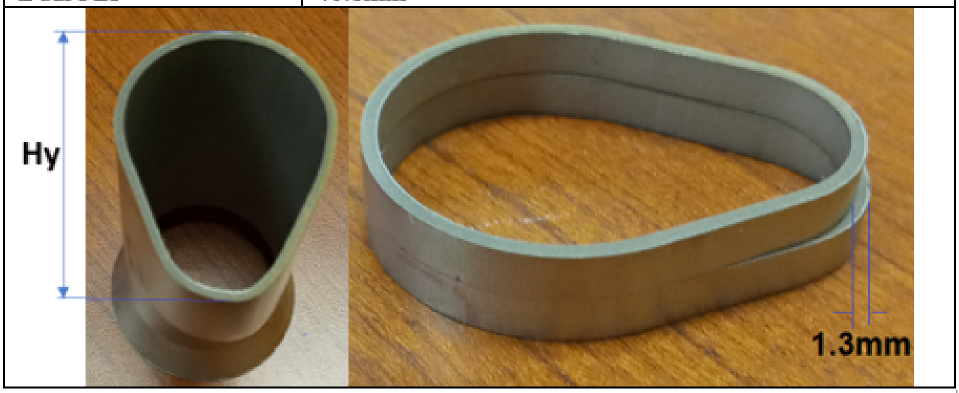

Figure 15. Load path #5: 91 MPa, 11 MPa, and 91 MPa (pear shape using Teflon sheet).

A bar graph presented in Figure 16 summarizes the experimental results for the pear-shaped geometry. The increase in protrusion height of 3.34 mm is attributed to the enhancement of both material formability and tribological conditions. The results clearly indicate that the 1.3 mm increase in protrusion height is primarily due to the improved material formability resulting from dual-pressure THF.

Applications and constraints of dual-pressure THF: The utilization of dual-pressure tube hydroforming (THF) presents unique challenges and opportunities compared to traditional THF die systems. This alternative approach involves both internal and external fluid pressurization of tubular samples, necessitating a more intricate tooling design. However, dual-pressure THF proves advantageous for parts with limited processing windows or tubular materials with low formability.

One concern relates to the additional energy required for external pressurization. Nonetheless, experimental studies indicate that the energy input for external pressurization constitutes only a small fraction of the energy expended for internal pressurization. Surprisingly, a mere 12% of internal pressurization proved sufficient to collapse the tube during external pressurization.

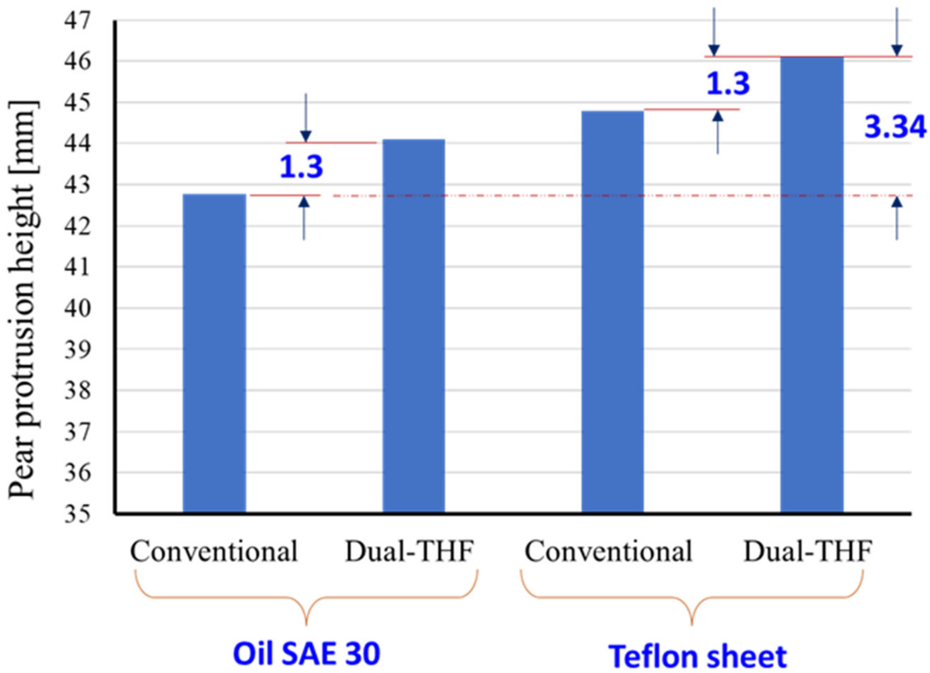

Figure 16. Influence of dual-pressure THF on formability for different lubrication conditions.

To maximize the benefits of increased material formability and enhanced tribological conditions, careful selection of a suitable fluid-based lubricant is crucial for external pressurization. When it comes to tribology, the primary advantage of dual-pressure THF lies in facilitating relubrication. While multiple cycles of tube collapsing and expansion can lead to improved tribological conditions, this study's experimental observations demonstrate that such repetitive deformation may introduce stress states unfavorable for enhancing formability. This effect may arise from grain dislocations and morphological changes induced by varying tensile and compressive loads over time and space.

Additionally, it should be noted that the plastic strain associated with the collapse and expansion of tubular samples, especially in materials with higher strain hardening exponents, can increase the yield stress, thereby reducing material ductility. This work-hardening is mainly due to the movements of dislocations that interact with each other, leading to the accumulation of dislocations and the formation of dislocation tangles. As deformation progresses, the dislocation density increases, resulting in strain hardening and an increase in material strength. The dynamic recovery of strain rate may occur simultaneously with dislocation movement during deformation where dislocations can reorient and rearrange themselves to form low-angle grain boundaries that can act as barriers to further dislocation motion, leading to a decrease in strain hardening.

The repeated change in stress due to collapse and expansion of the tube can result in dislocation annihilation, thereby enhancing strength and ductility. As competing factors come into play, the careful selection of loading paths for dual-pressure THF becomes essential. In this study, employing two levels of internal pressurization at equal maximum pressure values, along with one level of external pressurization, consistently led to improved material formability. Overall, while dual-pressure THF presents challenges in tooling design and requires careful considerations in energy consumption and loading paths, it shows promise in expanding the processing capabilities of tubular materials with low formability or narrow processing windows.

5. Conclusions

Experiments were conducted to investigate the influence of dual-pressure tube hydroforming (THF) on material formability and tribological conditions. This study focused on exploring various pressure loading paths for dual-THF, involving multiple cycles of internal tube pressurization and external pressurization to collapse the tube. Throughout the study, triangular and pear-shaped part geometries were manufactured using the dual-pressure tube hydroforming (THF) technique. The following are the key findings derived from this investigation:

(a) The loading path in dual-pressure THF plays a critical role in improving material formability. The loading path that involved two levels of internal pressurization both set at a maximum pressure of 91 MPa, alternating with external pressurization at 11 MPa, resulted in a significant enhancement in material formability. This formability improvement was consistent for both triangular and pear-shaped parts. Loading paths with three levels of internal pressurization (70 MPa, 80 MPa, and 91 MPa) and two levels of external pressurization did not enhance material formability. This suggests that the change in the state of stress and dislocation behavior, as dictated by the loading paths, may play a major role in improving formability.

(b) The study revealed that using SAE 30 hydraulic oil as a lubricant and as a pressure medium did not result in appreciable improvements in tribological conditions, despite relubrication occurring at the tube–die interface during external pressurization. This lack of improvement is attributed to the non-ideal lubricating properties of SAE 30 oil.

(c) A combined effect of enhanced material formability and improved tribological performance was observed when a Teflon sheet was used as a lubricant during dual-pressure THF. The protrusion height difference between conventional THF and dual-pressure THF for pear-shaped parts was 3.34 mm. Out of this difference, 1.3 mm was attributed to the enhancement of material formability, while 2.1 mm was attributed to the effectiveness of the Teflon sheet in reducing friction stress at the tube–die interface. The selection of lubricants plays a critical role in optimizing the tribological conditions in dual-pressure THF. A high-lubricity liquid lubricant, which also serves as a pressure medium, is crucial to fully exploit the benefits of dual-pressure THF.

(d) Dual-pressure THF presents unique challenges and opportunities. Although the dual-pressure-THF process requires more intricate tooling design and additional energy for pressurization of the outer surface of the tubular specimens, experimental studies have indicated that the energy input for external pressurization constitutes only a small fraction of the total energy expended for internal pressurization. In the present study, it was found that approximately 12% of the energy used for internal pressurization was sufficient to collapse the tube during external pressurization.

(e) Overall, this study demonstrates the potential of dual-pressure tube hydroforming for enhancing material formability and tribological performance, with specific loading paths and lubrication conditions playing significant roles in achieving optimal results.

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References

1. Hwang, Y.; Manabe, K. Latest Hydroforming Technology of Metallic Tubes and Sheets. Technology of Metallic Tubes and Sheets. *Metals* **2021**, *11*, 1360. [CrossRef]
2. Bell, C.; Corney, J.; Zuelli, N.; Savings, D. A state of the art review of hydroforming technology Its applications, research areas, history, and future in manufacturing. *Int. J. Mater. Form.* **2020**, *13*, 789–828. [CrossRef]
3. Ngaile, G. *Tube Hydroforming Chapter: Sheet Metal Forming, Processes and Applications*; Altan, T., Tekkaya, E., Eds.; ASME International: New York, NY, USA, 2012; pp. 179–209.
4. Hartl, C. Review on Advances in Metal Micro-Tube Forming. *Metals* **2019**, *9*, 542. [CrossRef]
5. Hwang, Y.-M.; Tsai, Y.-J. Movable Die and Loading Path Design in Tube Hydroforming of Irregular Bellows. *Metals* **2020**, *10*, 1518. [CrossRef]

6. Hwang, Y. Applications of Movable Dies in Tube Hydroforming Processes, TUBEHYDRO2022. In Proceedings of the 10th International Conference on Tube Hydroforming, Matsue, Japan, 14–17 November 2022; pp. 1–10.
7. Zhu, H.; Lin, Y.; Chen, K.; He, Z. Forming Limit Analysis of Thin-Walled Extruded Aluminum Alloy Tubes under Nonlinear Loading Paths Using an Improved M-K Model. *Materials* **2023**, *16*, 1647. [CrossRef]
8. Khalfallah, A.; Oliveira, M.C.; Alves, J.L.; Menezes, L.F. Constitutive parameter identification of CB2001 yield function and its experimental verification using tube hydroforming tests. *Int. J. Mech. Sci.* **2020**, *185*, 105868. [CrossRef]
9. Schneider, R.; Grant, R.J.; Sotirov, N.; Falkinger, G.; Grabner, F.; Reichl, C.; Scheerer, M.; Heine, B.; Zouaoui, Z. Constitutive flow curve approximation of commercial aluminum alloys at low temperatures. *Mater. Des.* **2015**, *88*, 659–666. [CrossRef]
10. Wang, X.; Fan, X.; Chen, X.; Yuan, S. Cryogenic deformation behavior of 6061 aluminum alloy tube under biaxial tension condition. *J. Mater. Process. Technol.* **2022**, *303*, 117532. [CrossRef]
11. Yuan, S.J.; Fan, X.B. Method for Pressure Forming of Aluminum Alloy Special Shaped Tubular Component by Using Ultra Low Temperature Medium. U.S. Patent 10960452B2, 20 March 2021.
12. Ngaile, G.; Yang, C. Analytical Model for the Characterization of Guiding Zone Tribo-Test for Tube Hydroforming. *ASME J. Manuf. Sci. Eng.* **2009**, *131*, 021008. [CrossRef]
13. Vollersten, F.; Plancak, M. On Possibilities for the Determination of the Coefficient of Friction in Hydroforming of Tubes. *J. Mater. Process. Technol.* **2002**, *125*, 412–420.
14. Dalton, G. The role of lubricants in hydroforming. In Proceedings of the Automotive Tube Conference, Dearborn, MI, USA, 26–27 April 1999.
15. Ngaile, G.; Yang, C. Part 1: Analytical Model for Characterizing the Pear Shape Tribotest for Tube Hydroforming. *Proc. IMechE Part B J. Eng. Manuf.* **2008**, *222*, 849–863. [CrossRef]
16. Galdos, L.; Trinidad, J.; Otegi, N.; Garcia, C. Friction Modelling for Tube Hydroforming Processes—A Numerical and Experimental Study with Different Viscosity Lubricants. *Materials* **2022**, *15*, 5655. [CrossRef] [PubMed]
17. Nikhare, C.; Weiss, M.; Hodgson, P. FEA comparison of high and low pressure tube hydroforming of TRIP steel. *Comput. Mater. Sci.* **2009**, *47*, 146–152. [CrossRef]
18. Yuan, S.; Wang, X.; Liu, G. Control and use of wrinkles in tube hydroforming. *J. Mater. Process. Technol.* **2007**, *182*, 6–11. [CrossRef]
19. Yuan, S.; Yuan, W.; Wang, X. Effect of wrinkling behavior on formability and thickness distribution in tube hydroforming. *J. Mater. Process. Technol.* **2006**, *177*, 668–671. [CrossRef]
20. Lang, L.; Li, H.; Yuan, S.; Danckert, J.; Nielsen, K. Investigation into the pre-forming's effect during multi-stages of tube hydroforming of aluminum alloy tube by using useful wrinkles. *J. Mater. Process. Technol.* **2008**, *209*, 2553–2563. [CrossRef]
21. Mori, K.; Maeno, T.; Maki, S. Mechanism of improvement of formability in pulsating hydroforming of tubes. *Int. J. Mach. Tools Manuf.* **2007**, *47*, 978–984. [CrossRef]
22. Yang, C.; Ngaile, G. Preform Design for Tube Hydroforming Based on Wrinkle Formation. *ASME J. Manuf. Sci. Eng.* **2011**, *133*, 061014. [CrossRef]
23. Cui, X.-L.; Teng, B.; Yuan, S. Hydroforming process of complex T-shaped tubular parts of nickel-based superalloy. *CIRP J. Manuf. Sci. Technol.* **2021**, *32*, 476–490. [CrossRef]
24. Hirsch, J.; Al-Samman, T. Superior light metals by texture engineering: Optimized aluminum and magnesium alloys for automotive applications. *Acta Mater.* **2013**, *61*, 818–843. [CrossRef]
25. Lewandowski, J.J.; Lowhaphandu, P. Effects of hydrostatic pressure on mechanical behaviour and deformation processing of materials. *Int. Mater. Rev.* **1998**, *43*, 145–187. [CrossRef]
26. Cui, X.-L.; Wang, X.-S.; Yuan, S.-J. Deformation analysis of double-sided tube hydroforming in square-section die. *J. Mater. Process. Technol.* **2014**, *214*, 1341–1351. [CrossRef]
27. Jain, N.; Wang, J. Plastic instability in dual-pressure tube-hydroforming process. *Int. J. Mech. Sci.* **2005**, *47*, 1827–1837. [CrossRef]
28. Cui, X.-L.; Yuan, S.-J. Effects of superimposed hydrostatic pressure on bulging deformation and fracture of tubes in double-sided hydroforming. *Arch. Civ. Mech. Eng.* **2019**, *19*, 569–583. [CrossRef]
29. Benedyk, J.C.; Stawarz, D.; Parikh, N.M. A method for increasing elongation values for ferrous and nonferrous sheet metals. *J. Mater.* **1971**, *6*, 16–29.
30. Emmens, W.C.; van den Boogaard, A.H. Incremental forming by continuous bending under tension—An experimental investigation. *J. Mater. Process. Technol.* **2009**, *209*, 5456–5463. [CrossRef]
31. Emmens, W.C.; van den Boogaard, A.H. Cyclic Stretch-bending: Mechanics, Stability, and Formability. *J. Mater. Proc. Technol.* **2011**, *211*, 1965–1981. [CrossRef]
32. Zecevic, M.; Roemer, T.J.; Knezevic, M.; Korkolis, Y.P.; Kinsey, B.L. Residual Ductility and Microstructural Evolution in Continuous-Bending-under-Tension of AA-6022-T4. *Materials* **2016**, *9*, 130. [CrossRef]