

Experimental Verification of the Process Windows for a Conical Shape Part Manufactured by Hydromechanical Deep Drawing Process

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Introduction

Hydromechanical Deep Drawing Process

The hydroforming process was introduced as a novel method to overcome the limitations of the limiting drawing ratio (LDR) encountered in sheet metal parts manufactured by classical forming techniques. Compared to conventional methods, hydroforming enables the manufacture of more complex and challenging geometries in fewer steps and with higher quality, utilizing fluid pressure as a forming medium. A significant advantage of this process is its potential to reduce die costs by up to 90%.

Hydromechanical Deep Drawing (HMDD) is an advanced manufacturing technique and a type of hydroforming process that differs from the classical deep drawing process by utilizing high-pressure fluid instead of a female die. In this method, the punch moves the sheet metal blank controllably into the high-pressure fluid, which forms the material. The blank holder secures the sheet against the die, controlling material flow and ensuring sealing during the process. As the punch advances into the fluid, the fluid pressure increases. This enhances the friction force between the punch and the sheet material, thereby preventing localized thinning. Despite its benefits, the widespread adoption of HMDD is limited by two main challenges: the difficulty in determining the optimal fluid pressure and blank holder force loading profiles, and the complexity of controlling these profiles accurately on the press.

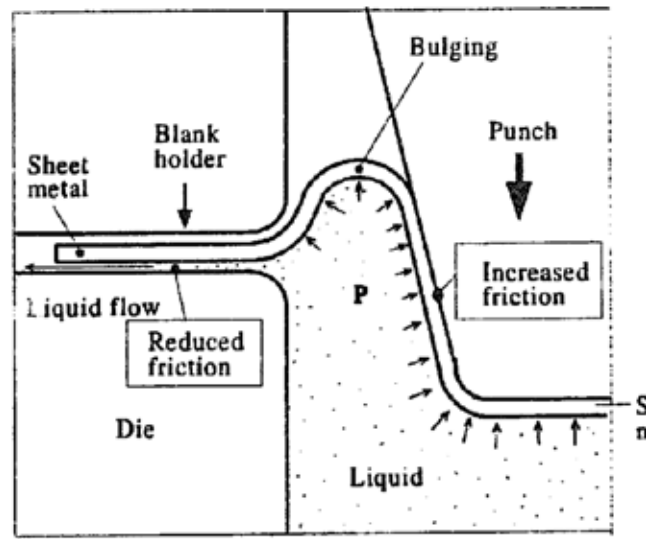
The foundational development of hydroforming technology is credited to Japanese researcher Y. Kasuga, who initiated detailed research and development in 1955. His work culminated in the period from 1958 to 1964 with the introduction of “pressure-lubricated deep drawing.” Following this, in the 1970s, K. Nakamura and T. Nakagawa advanced the field further by working on the “hydraulic counter-pressure fluid forming process.”

Their continued research led to the development of the “radial-pressure deep drawing method” to facilitate the production of deeper parts, as documented by Nakamura et al. (1987).

In their 2011 study, Halkacı et al. demonstrated that the success of the HMDD process is highly dependent on parameters such as fluid pressure (P), blank holder force (BHF), pre-bulging height, sheet thickness, and friction. They highlighted the critical interaction between fluid pressure and blank holder force, noting that excessively high values of both P and BHF lead to sheet tearing, while insufficient values result in wrinkling. Corroborating this, Akay (2014) also emphasized the necessity of determining the optimal P and BHF for successful part formation. A summary of these effects occurring during HMDD is illustrated in Figure 1.

Figure 1

Effects in HMDD (Nakagava et al., 1997)



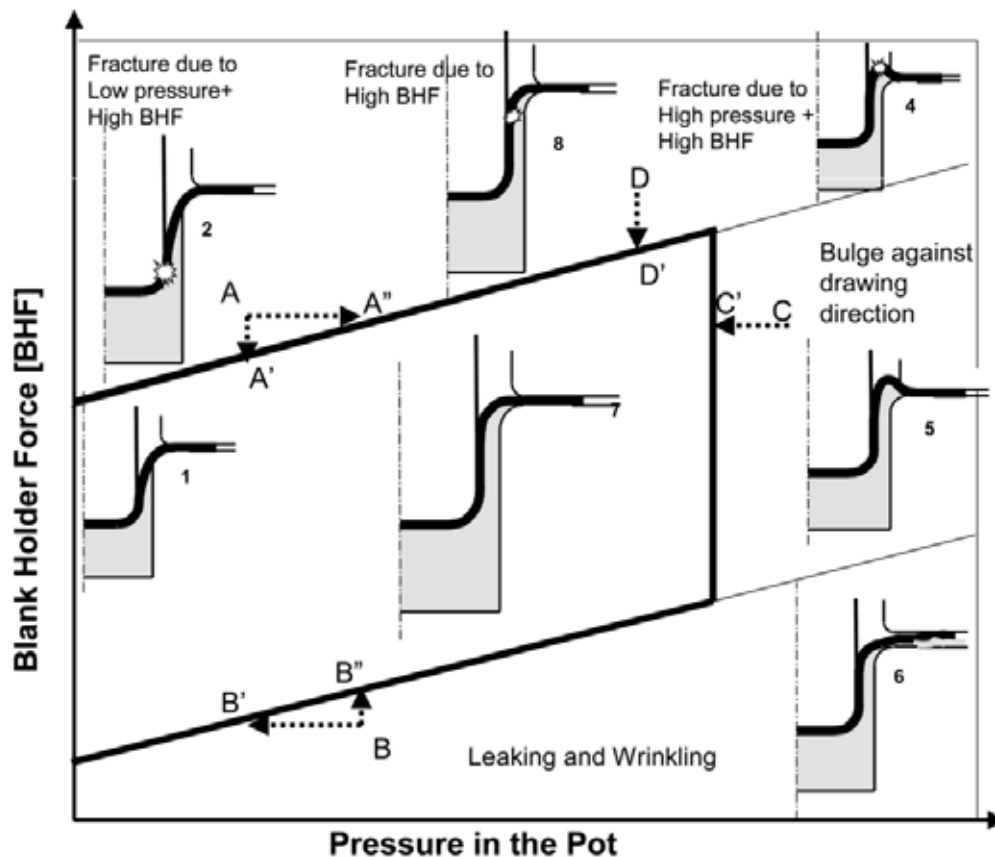
Process Window

Process Windows (PWs) are graphical representations that define the acceptable ranges of key parameters in manufacturing processes. Typically depicted in diagrams that vary at least two critical parameters, they identify a central region of feasible operation, bounded by limits where the process fails, such as by tearing or wrinkling in forming operations. These windows are specific to a part's material and geometry, serving as essential guides for successful production. The concept of process windows is well-established in various manufacturing technologies, including hot forging, ring rolling, friction stir welding, and hydroforming. In HMDD, the use of process windows is crucial. Achieving successful part manufacturing is directly dependent on determining the optimal loading profiles for fluid pressure and blank holder force, which a well-defined process window effectively provides.

A process window is typically divided into four distinct regions: a safe zone, tearing, wrinkling, and leakage. In the preparatory phase, parameters such as sheet metal thickness, part geometry, the limiting drawing ratio (LDR), and the punch and die radii are predetermined. When constructing the process window, the punch velocity and fluid pressure are the primary variables utilized, as these can be actively controlled to define the optimal forming limits. A representative HMDD process window, established based on these relationships, is presented in Figure 2.

Figure 2

Process window in a HMDD Process (Braedel et al., 2005)



The purpose of the process window is to show at which parameters successful results can be obtained, to express it graphically in an understandable way, and to perform the process along the desired line towards the wrinkling-tearing region in a minimum or maximum manner.

1. The process window or process maps can be obtained with multiple analyses, provided that they are experimentally verified.
2. For the parameter optimization of a new process, a process window must be established to determine the constraints that need to be known.
3. In the stage following the obtaining of the process window, obtaining the optimum loading curve becomes a complementary and important study.
4. Especially if, by the nature of the process, at least one parameter changes

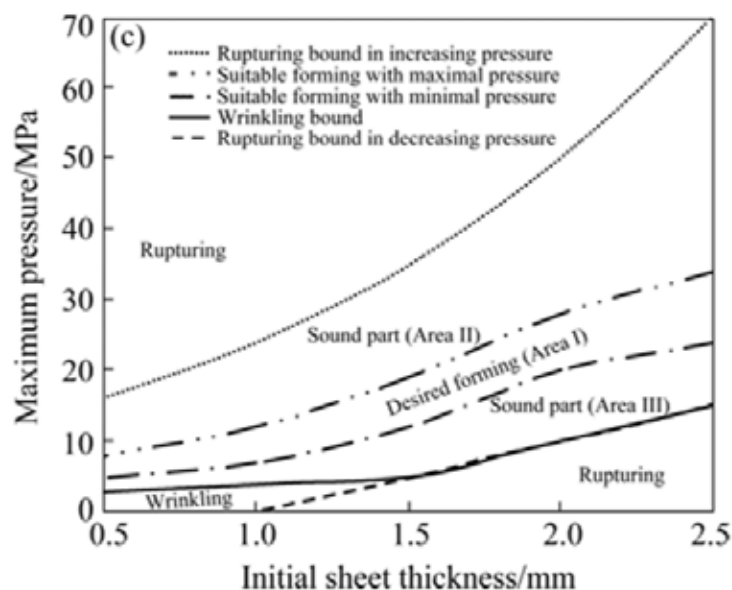
throughout the process, an optimum loading profile that provides suitable forming must be found.

In hydroforming, the process window depends on friction, the geometry of the part to be manufactured, the mechanical properties of the sheet metal, fluid pressure, and the blank holder force.

In their 2015 study, Hashemi et al. developed Process Window Diagrams (PWDs) for aluminum, copper, and steel materials in radial pressure-assisted hydrodynamic deep drawing. The PWD of the steel was shown in Figure 2.8. These diagrams enable rapid assessment of sheet metal manufacturability while reducing the need for extensive experimental work through finite element analysis. For steel, results demonstrated that lower initial sheet thickness and higher strength correlate with improved formability and more uniform thickness distribution. The PWD successfully predicts the feasible forming zone and potential failure modes under various loading conditions (Hashemi et al., 2015).

Figure 3

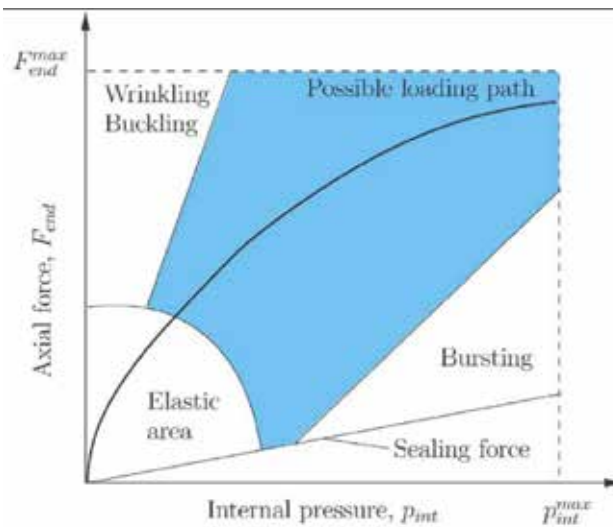
Steel material (St 14) process window (Hashemi et al, 2015).



Aydemir et al. (2005) gave an optimal loading curve for tube hydroforming processes, as illustrated in Figure 4. It is possible to see suitable parameter levels for a successful forming process.

Figure 4

The process window for tube hydroforming (Aydemir et al., 2005).



Sadegh-yazdi et al. (2018) used an adaptive simulation that is integrated with the fuzzy control system with the artificial bee colony (ABC) algorithm to determine the optimized radial and chamber pressure paths in hydrodynamic deep drawing assisted by radial pressure process (Figure 5). They compared the sheet material they had pre-studied with SE analysis to minimize tearing and wrinkling before and after optimization, and they succeeded in obtaining a wrinkle-free product with minimum thinning after optimization (Figure 6).

Figure 5

The hydrodynamic deep drawing assisted by radial pressure process (Sadegh-yazdi et al. 2018).

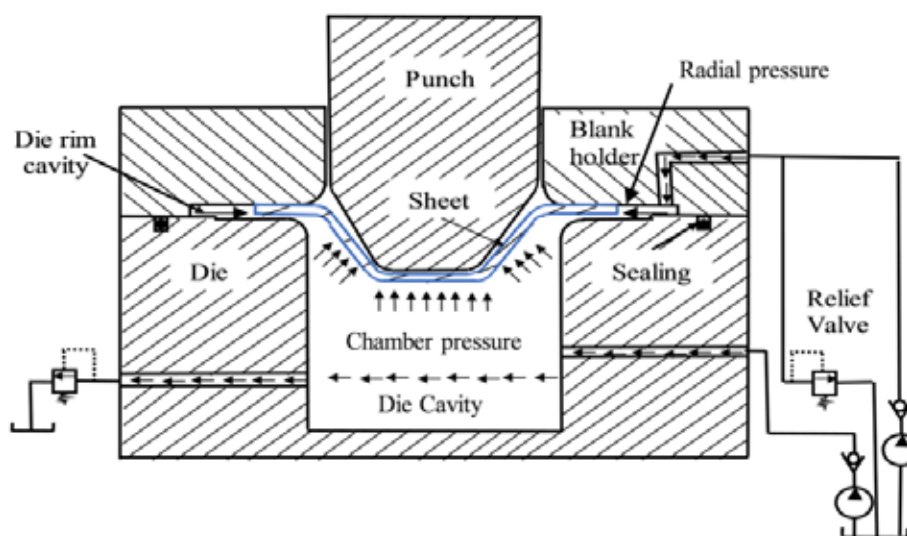
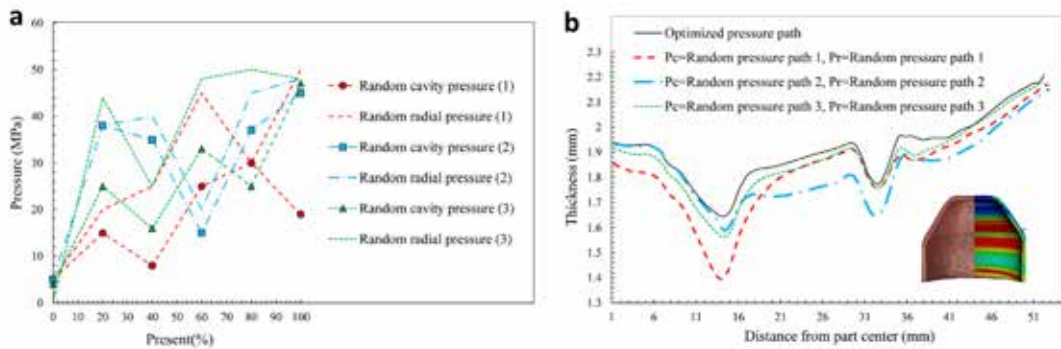


Figure 6

a) Random pressure paths b) Appropriate thickness distribution curve by optimizing the pressure paths (Yazdi et al. 2018)



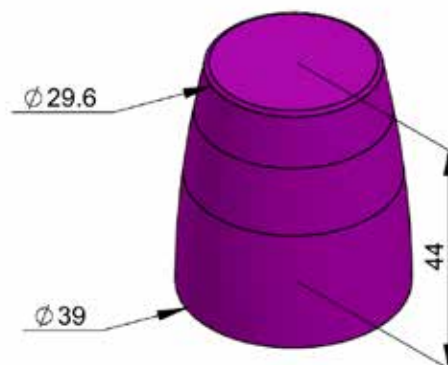
In summary, the literature shows that successful part manufacturing by the hydroforming method predominantly requires the optimization of fluid pressure and blank holder force loading profiles. Process windows have been investigated for various methods, including female die forming, male die forming (HMDD), and tube hydroforming. Previous research on process windows in HMDD has notably not utilized stainless steel and has primarily focused on cylindrical parts. In this study, the process window for a conical shape part from AISI 304 stainless steel was determined experimentally and numerically, and the numerical process window was verified. Consequently, the optimal process parameters will be determined to successfully manufacture the conical part via the HMDD method without sidewall wrinkling.

Determining the Process Window

In this study, separate process windows were determined for liquid pressure and blank holder force (BHF) for a conical shape part (Figure 7) by Finite Element Analysis (FEA) then they were validated by Hydromechanical Deep Drawing (HMDD) experiments. Determination of the process window was explained in a previous study (Özçelik and Türköz, 2019).

Figure 7

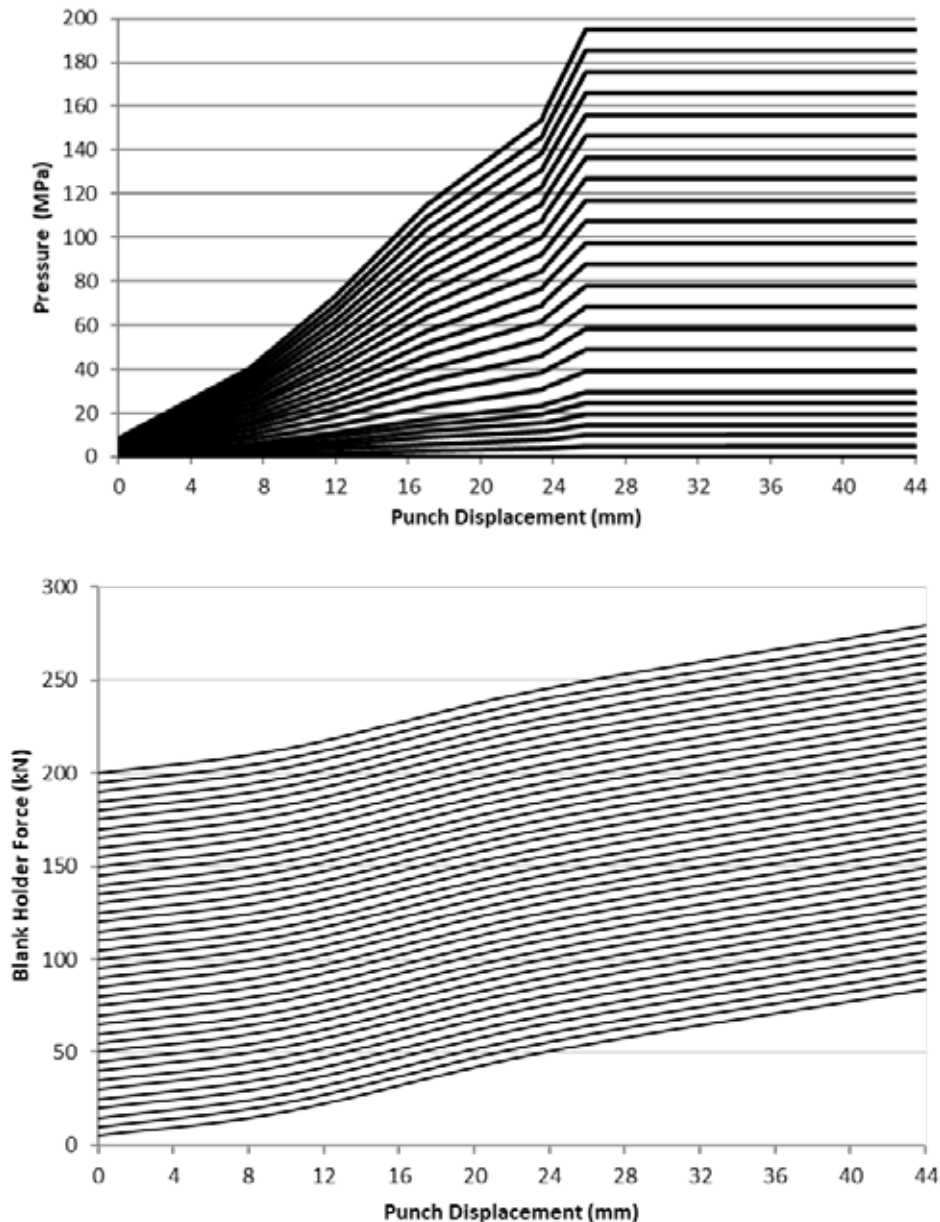
Process window determined conical shape part for HMDD Process



90 analyses were conducted for liquid pressure and 80 for BPK. To determine the liquid pressure process window, constant-pressure, linearly increasing, and increasing curves with different characteristics were tested, and the pressure values at which tear and wrinkling damage occurred, depending on the stamp position, were determined. Constant-pressure curves were applied in 10 MPa increments, starting from 0 MPa to 300 MPa. The linearly increasing and different characteristics liquid pressure and BHF curves are shown in Figure 8. As a result of the analyses, the stamp positions at which tear and wrinkling damage criteria occurred and the corresponding liquid pressure values were determined.

Figure 8

Loading profiles used to create the process window a) For liquid pressure b) For BHF



Experimental Procedure

The process window constructed from the FE analyses was validated by HMDD experiments by using a hydroforming press located in the Hydroforming Laboratory of Konya Technical University. The press has a capacity of 60 tons for both the blank holder and punch forces, and can achieve fluid pressure up to 1600 bar (Figure 9). It was equipped with a Hydraulic Numerical Control (HNC) system, the press enables precise control of the blank holder force, punch position and velocity, and fluid pressure. AISI 304 sheet metal with a thickness of 0.18 mm was used. The sheets were laser-cut to a diameter of 85 mm. To facilitate smooth material flow between the die and blank holder, both sides of the blank were lubricated with paraffin.

Figure 9

The hydroforming press used in the experiments.



For the HMDD experiments, four different fluid pressure profiles and four distinct BHF levels were selected to generate varying forming outcomes within the process window. The actual failure modes observed in the formed parts were compared with the failure modes predicted by the process window, confirming the accuracy of the developed process windows.

Results and Discussion

The stress-strain curves of the AISI 304 material are presented in Figure 10. Using the material's flow curve in Finite Element (FE) analyses of the HMDD process for the conical part, the process windows for pressure and blank holder force were determined, as shown in Figures 11 and 12, respectively. The methodology for conducting the FE analyses is explained in Özçelik and Türköz (2019).

Figure 10

Engineering and true tensile test curves at rolling direction (RD), diagonal direction (DD), and transverse direction (TD)

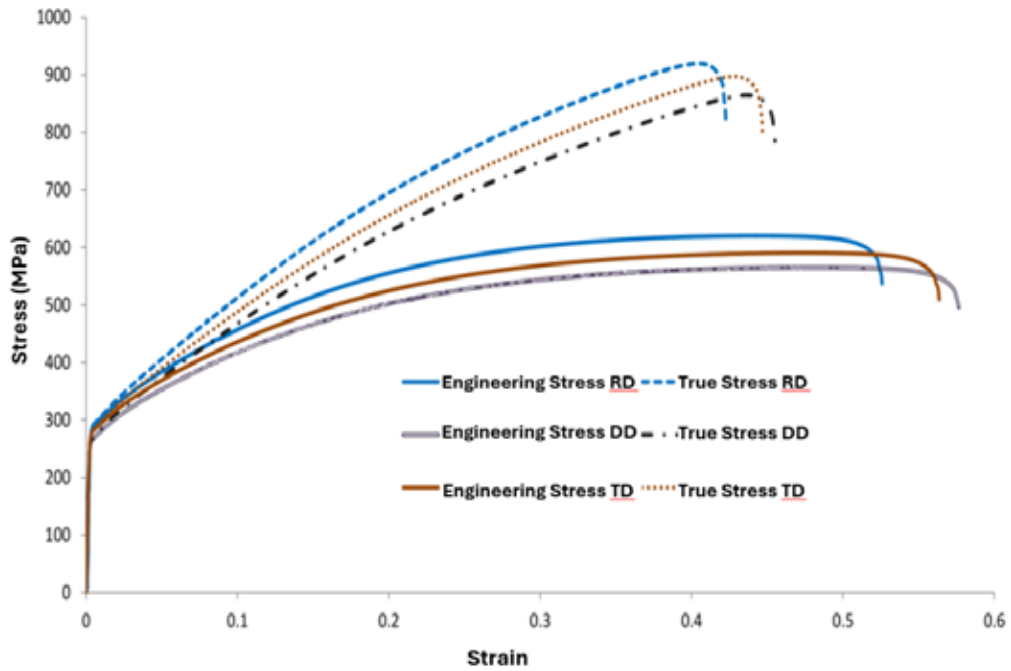


Figure 11

The process window for the fluid pressure

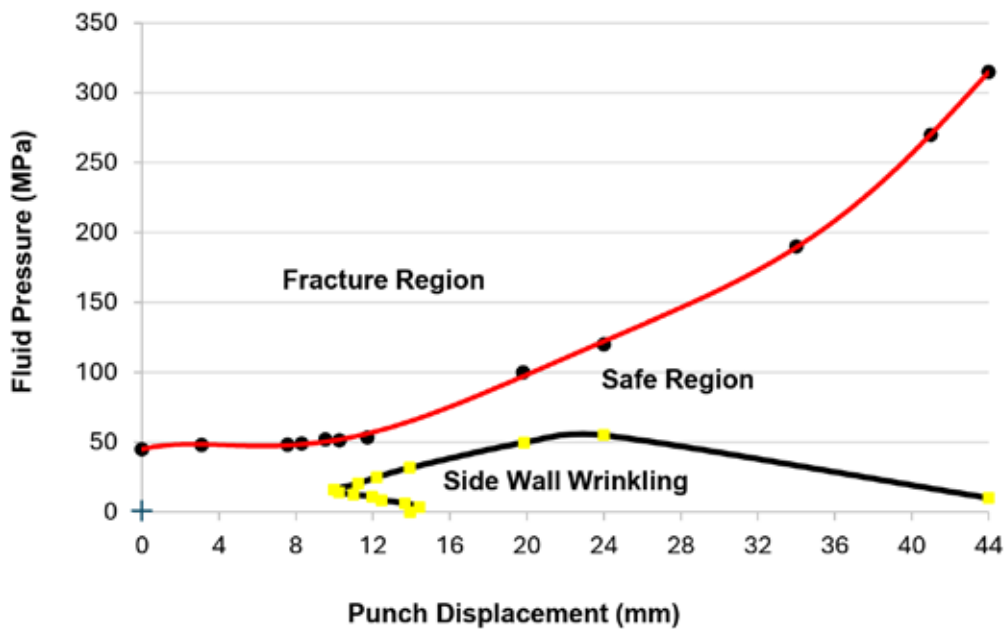
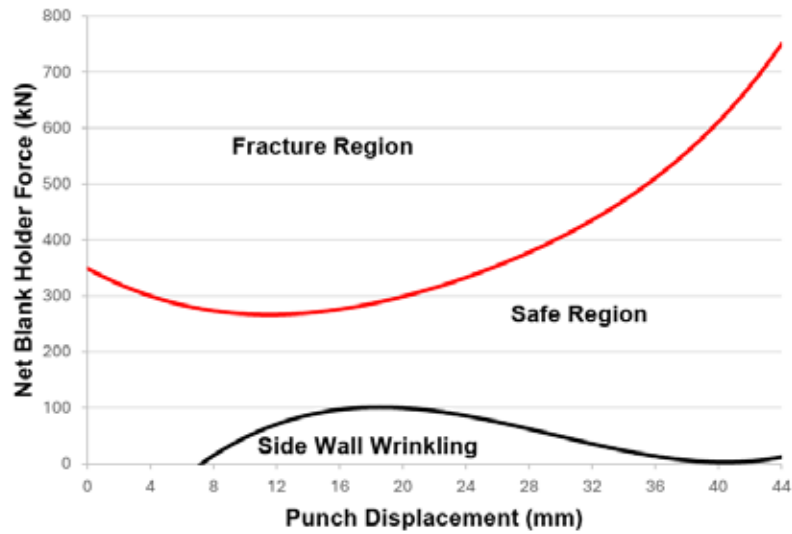


Figure 12

The process window for the blank holder force



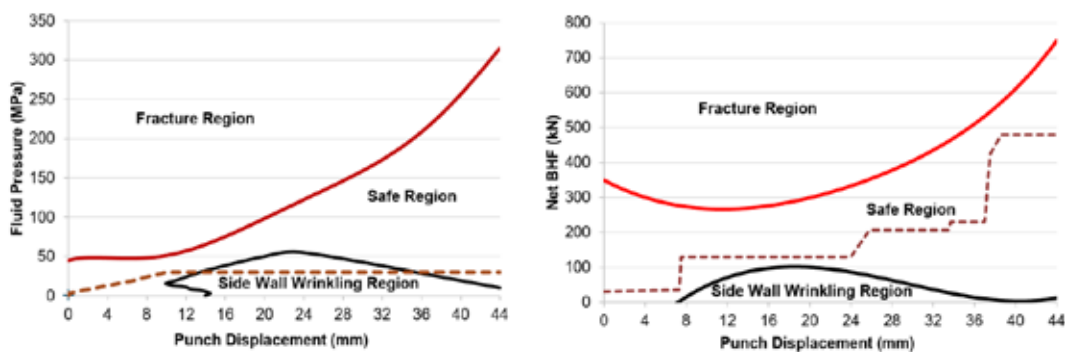
Verification of the Process Windows

HMDD experiments were conducted to validate the obtained process windows. Each experiment was repeated three times to verify its reliability. Experimental results that proved successful in all three repetitions were considered to validate the process window.

The first three experiments were performed to validate the fluid pressure process window. In these experiments, fluid pressure loading profiles were applied as they passed through the wrinkling and fracture regions, and blank holder force (BHF) loading profiles were applied through the safe region. So Experiment 1 was conducted using a pressure curve passing through the wrinkling region while maintaining the blank holder force (BHF) within the safe zone (Figure 13). Consequently, as shown in Figure 14, wrinkling defects occurred in the specimens, confirming the accuracy of the predicted wrinkling boundary.

Figure 13

The fluid pressure and net BHF loading profiles used in Experiment 1 were used to validate the wrinkling region of the fluid pressure process window.



In Experiment 2, validation was performed using a different profile passing through the

boundary of the wrinkling region, as shown in Figure 15. For this experiment, the BHF curve used in Exp 1 that passes through the safe zone was employed. Experimental results again revealed wrinkling defects in the specimens, as illustrated in Figure 16. Based on the outcomes of Experiments 1 and 2, it was concluded that the wrinkling boundary of the fluid pressure process window was accurately determined.

Figure 14

Wrinkling defects occurred at Experiment 1 as expected



Figure 15

The fluid pressure loading profile used in Experiment 2 to define boundary of the fluid pressure process window.

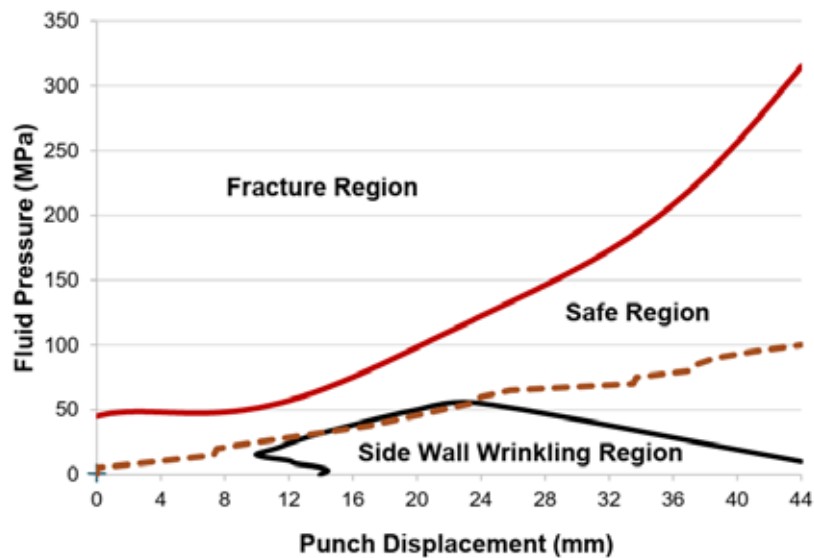


Figure 16

Wrinkling defects occurred at Experiment 2



In Experiment 3, a pressure curve passing through the fracture region was applied while maintaining the BHF curve within safe zone boundaries, as shown in Figure 17. As anticipated, fracture damage occurred in the product, as shown in Figure 18.

Figure 17

The fluid pressure and net BHF loading profiles used in Experiment 3 to validate the fracture region in the fluid pressure process window.

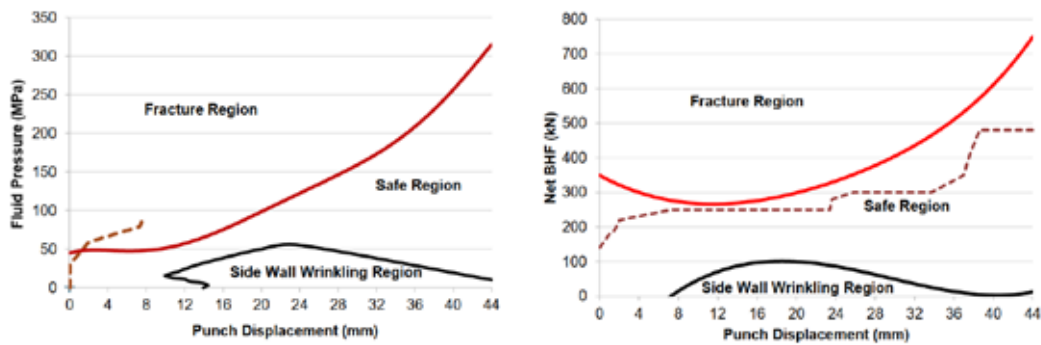


Figure 18

The parts were fractured after applying the loading curves in Figure 16 at Experiment 3



The first 3 experiments were conducted to verify the fluid pressure process window.

After the fluid pressure curves were verified, the latter experiments were performed to verify the BHF process window. So in Experiment 4, the loading profiles were applied as shown in Figure 19. In here to protect against the leakage of the fluid, the fluid pressure curve was passed through the lower boundary of the safe zone. BHF profiles were passed through the wrinkling zone. So the parts were formed with wrinkling defects as expected, as shown in Figure 20.

In Experiment 5, the pressure curve was maintained within the safe zone while the BHF curve was deliberately routed through the fracture boundary (Figure 21), with the expectation of inducing product fracture. As shown in Figure 21, the experiment resulted in specimen fracture as anticipated. Similar fractures occurred in Experiment 6 when the BHF loading profile was routed through the fracture boundary of the BHF process window, as shown in Figure 23. This confirms that the fracture regions for the blank holder force were accurately determined.

Figure 19

The fluid pressure and net BHF loading profiles used in Experiment 4 to validate the wrinkling region of the BHF process window.

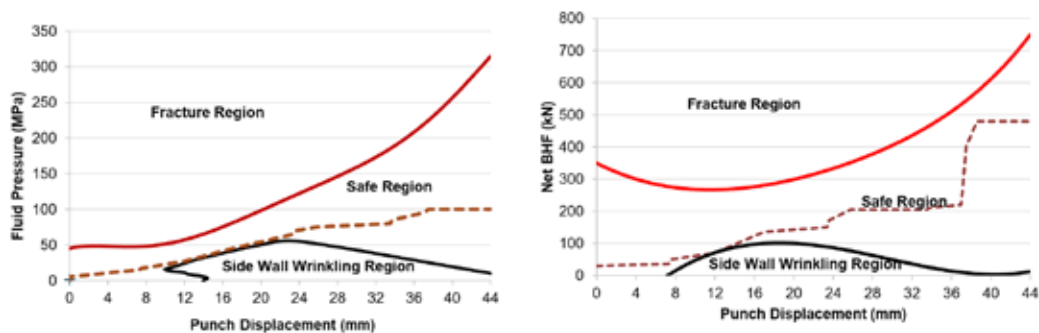


Figure 20

The parts were formed with wrinkling defects after applying the loading profiles in Figure 19 at Experiment 4.



Figure 21

The fluid pressure and net BHF loading profiles used in Experiment 5 to validate the fracture region of the BHF process window.

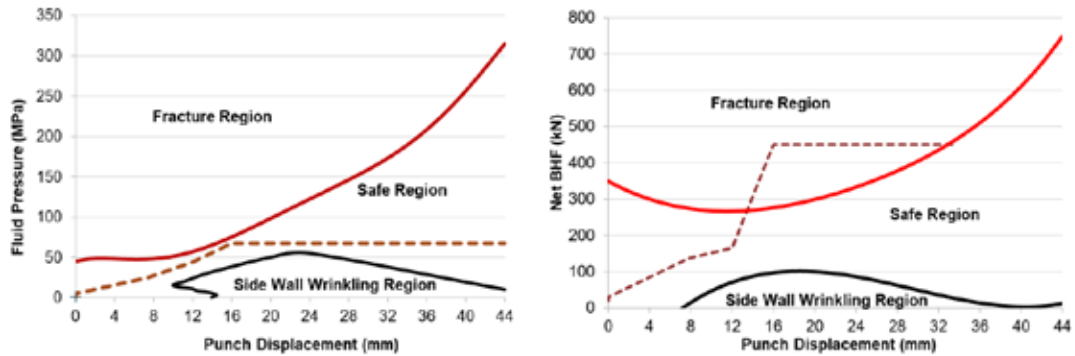


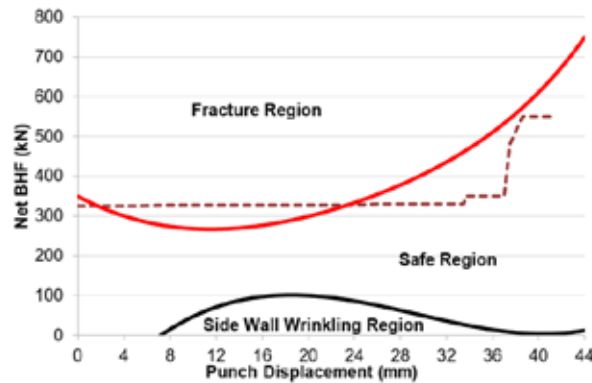
Figure 22

The parts were formed with fracture defects after applying the loading profiles in Figure 19 at Experiment 5.



Figure 23

The BHF loading profile applied in Experiment 6 to validate the boundaries of the fracture region in the BHF process window and fractured specimens.





The final experiments (Experiment 7) were conducted to verify the safe zones of both process windows. Therefore, loading profiles were applied as shown in Figure 24. The experimental results demonstrated that specimens could be manufactured without any wrinkling or fracture damage, as illustrated in Figure 25.

Figure 24

The loading profiles passed through the safe regions of both the fluid pressure and BHF process windows to successfully manufacture the part in Experiment 7.

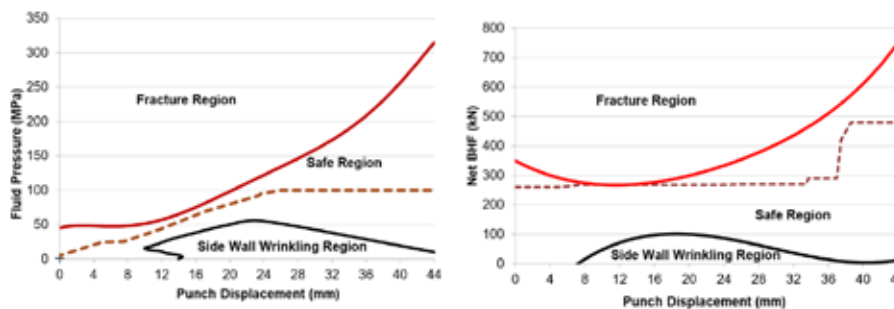


Figure 25

The specimens formed without wrinkles or defects in Experiment 7, using the loading profiles shown in Figure 24.



Conclusions

This study established and experimentally validated process windows for fluid pressure and blank holder force to prevent wrinkling and fracture defects in conical parts manufactured from AISI 304 stainless steel sheets via Hydromechanical Deep Drawing (HMDD).

Developing process windows is a time-consuming and challenging procedure that varies significantly with part geometry, material, and sheet thickness. It requires extensive trials across a wide parameter range to identify values ensuring successful part production. Given the high cost and time associated with experimental determination, numerical methods prove to be the most effective approach for establishing process windows. In this study, individual process windows for fluid pressure and blank holder force—key controllable parameters critical to successful forming—were developed as functions of punch position for a sample part produced by HMDD.

The key findings of this study are summarized below:

- The process windows developed for a specially shaped part were experimentally validated, confirming the effectiveness of the proposed methodology.
- Flawless part production was demonstrated using the established process windows.
- The safe zone in the fluid pressure process window was significantly narrower than that of the blank holder force window, indicating that fluid pressure requires much more precise control in the HMDD production of industrial parts.
- The process windows delineate the parameter limits for potential defects such as fracture, wall wrinkling, and flange wrinkling. The choice of failure criteria substantially influences the shape and boundaries of these windows.
- The absence of a standardized methodology and the case-specific nature of process windows position them as valuable know-how, particularly suitable for industrial applications.

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