ABSTRACT

HUMMEL, STEPHEN DEAN. Development of a Die-Less Hydroforming Process. (Under the direction of Dr. Gracious Ngaile).

Hydroforming has gained increased popularity as a metal forming process to produce parts for the automotive, aerospace, and hardware industries. Currently, tube and sheet hydroforming are the two main processes for creating those parts. Some advantages of these processes are weight reduction, fewer secondary operations, dimensional accuracy, and part consolidation. The current limitations of tube and sheet hydroforming are equipment capacity, cycle time, cost, and ability to produce a large spectrum of complex geometries.

In this study, an innovative die-less hydroforming process is introduced to reduce these limitations. The objective of this study is to determine the process capabilities and feasibility of die-less hydroforming. The proposed process eliminates the need for expensive equipment such as dies and presses which not only reduces cost, but also allows for complex large scale parts to be produced. This process includes the attachment of blank sheets or tubes via welding then using hydraulic fluid to pressurize the area between the welds in order to free-form the material.

To develop a die-less hydroforming process, finite element analysis (FEA) was used to determine the process capabilities. Four geometry families are introduced and classified by their deformed shape and application to industries such as aerospace and construction. Of those, the tubular geometries were then chosen for further investigation due to their applicability to many structures.

Three variations of the tubular geometry are identified based on the deformation characteristics; longitudinal lobe, circumferential lobe, and helical lobe. A parametric design study is performed through numerical analysis. To do this, the initial diameter and thickness was varied on each of the three tubular geometries while a range of forming pressure was applied. It was determined that there is a linear relationship between pressure, diameter, and thickness with the lobe formation and lobe wall thinning for all of the tubular geometries.
The strength-to-weight benefit of the tubular structures was also verified through finite element analysis. The longitudinal lobe hydroformed geometry was able to carry 135% more load than a blank tube under compressive loading at a stroke of 10 mm while carrying 133% more load at a stroke of 3 mm under flexural loading. The circumferential lobe geometry carried 250% more torsional load at a rotation of 17° while carrying 174% more load under flexural loading at a 3 mm stroke. The helical geometry was able to carry 150% more torsional load at an 8° clockwise rotation and 92% more torsional load at an 8° counterclockwise rotation. It was also able to carry 157% more compressive load at a 6 mm stroke.

To test the viability of the die-less hydroforming process, a longitudinal lobe tubular structure was fabricated and formed. A pressure of 9,500 psi (65.5 MPa) was used to deform the tube and the lobe formation showed good agreement with the FEA solution, with the average difference in the major diameter of the lobe being 4.2%.

The results from this study indicate that a die-less hydroforming manufacturing process is viable and capable of producing strong, lightweight parts of complex geometries at a reduced cost to traditional hydroforming processes.
Development of a Die-Less Hydroforming Process

by

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DEDICATION

To my Grandparents, James and Caroline Hummel.
BIOGRAPHY

Stephen Hummel was born in Jacksonville, Florida in 1988. He attended Stanton College Prep then graduated from the University of Central Florida with a BS in Mechanical Engineering in 2010. While at UCF, Stephen was part of and eventually led a grassroots club which encouraged student participation at sporting events. From there he began his graduate studies at North Carolina State University where he joined the Advanced Metal Forming and Tribology Lab under the advisement of Dr. Gracious Ngaile in January 2011. Stephen is still an avid sports fan and enjoys playing or watching sports of any kind.
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First, I would like to acknowledge my Grandparents James and Caroline Hummel. Without their support and encouragement, none of this would have been possible.

I would like to thank my adviser, Dr. Gracious Ngaile, for being supportive and passionate about this research. I would also like to thank Dr. Kara Peters and Dr. Tiegang Fang for serving on my committee.

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CHAPTER 1
INTRODUCTION

1.1. Introduction

The use of hydroforming manufacturing processes has rapidly increased over the past decade due to increased research and technological advances. One of the main benefits of this process is that the initial material is fully utilized so that thinner gage metals can be used while maintaining the necessary strength requirements. Currently there are two primary fluid assisted metal forming techniques; tube hydroforming and sheet hydroforming. For automotive applications, parts such as hoods, fuel tanks, pillars, exhaust manifolds, and chassis components can be produced through hydroforming methods so that they are lighter and equally as strong as compared to traditional manufacturing techniques such as deep drawing and stamping. Although there are an increasing amount of automotive parts produced via hydroforming, there are several limitations preventing the growth of the technology. Equipment cost for a hydroforming setup can often be much more expensive than that of a traditional metal forming operation. Part geometries are limited by the process parameters and by the capacity of the presses. Also, cycle time can be higher than traditional processes.

Hydroformed parts can currently be found in automobiles, aircrafts, and household parts such as fittings. However, there are many other sectors that can benefit from hydroforming technology such as the construction industry. Large shell structures such as columns which support roadways, silos that hold gas or other commodities, or tubular support members for bridges can all be produced to be lighter and stronger through hydroforming. This research proposes an innovative hydroforming process that reduces tooling limitations while producing strong, lightweight, complex structures whose geometry cannot be replicated by any other cold forming operation. By introducing a die-less process, tooling cost can be reduced and press capacity limitations are eliminated.
1.2. Objectives and Approach

The primary objectives of this research are:

a) Identify families of geometries that can be produced through a die-less hydroforming process.

b) Explore fields of application for die-less hydroformed components beyond the current hydroforming applications such as automotive, aerospace, and household appliances.

c) Use finite element analysis as a tool to investigate the process capabilities, forming parameters, and limitations.

d) Use finite element to design complex geometries that can be produced through die-less hydroforming.

e) Design an experimental setup and conduct experiments to demonstrate the viability of a die-less hydroforming process.

Finite element analysis (FEA) is heavily relied upon in the developmental phase of this new hydroforming process. Several classes of geometries are first developed and analyzed using FEA to determine their feasibility of production and benefit to the market. One classification of parts is then extensively studied using FEA in order to determine geometry variation and forming characteristics. To demonstrate the viability of the process, die-less hydroforming experiments are carried out.

1.3. Thesis Organization

Chapter 1 gives a brief introduction to the current and potential applications of hydroforming along with some limitations. The objectives of this study are outlined as well as the approach that is taken to achieve the objectives.
Chapter 2 gives an extensive literature review of the tube and sheet hydroforming processes. This review will cover the state-of-the-art for both processes as well as identifying challenges and limitations.

Chapter 3 provides an overview of the die-less hydroforming process and the process capabilities. This chapter will focus on the benefits, potential applications, and limitations to the process. Several potential complex geometry families with real world applications are introduced. The geometry families discussed in this chapter are unable to be formed through any hydroforming process other than die-less.

Chapter 4 discusses how finite element analysis is used in the design and analysis of parts produced through die-less hydroforming. It is shown how FEA can be used as a tool for designing die-less hydroformed parts. Analysis is performed on a geometry family introduced in Chapter 3 that has several applications to the construction, automotive, and aerospace industries. FEA is used to analyze the forming characteristics of the part based on initial geometry and pressurization as well as determining the increase in strength-to-weight ratio from forming. This analysis can be used to design unique geometries as well as provide an understanding of the forming mechanisms.

Chapter 5 presents the manufacturing procedures that are employed to produce die-less hydroformed parts. This chapter focuses on the equipment needed to perform the operation and the preparation of the blanks. Die-less hydroforming has the capabilities of producing a vast spectrum of geometries, therefore several manufacturing considerations are discussed. Chapter 5 also outlines the procedures and results from a die-less hydroforming trial performed on a geometry introduced in Chapter 3 and analyzed in Chapter 4. The experimental trial serves to confirm the finite element analysis as well as determine the feasibility of the geometries that are introduced.

Chapter 6 provides a conclusion to summarize the works of the study.
CHAPTER 2
LITERATURE REVIEW ON TUBE AND SHEET HYDROFORMING

2.1. Introduction to Tube Hydroforming

Tube hydroforming (THF) is an emerging manufacturing process that is currently used by the automotive and aerospace industries among others. In the automotive industry, applications of hydroformed parts include [Koc et al., 2001; Hartl, 2005]:

- Manifolds, catalytic converters, tail pipes, and other parts pertaining to the exhaust system
- Engine cradles, drive shafts, cross members
- Chassis frames and rear axle parts
- Interior parts such as instrument panels, seat frames, and pillars

Parts manufactured via the hydroforming process exhibit certain characteristics that make them extremely valuable to automotive applications, most notable among these benefits are [Ahmetoglu et al., 2000]:

- Reduction of weight by selectively thinning the tube walls
- Increase in strength and stiffness
- Significant decrease in secondary operations
- Dimensional accuracy
- Efficient use of materials and consolidation of parts used.
2.1.1. Process Overview

Tube hydroforming is the process of conforming a tube to a die in order to create a desired shape through the use of internal and axial pressure. The tube is generally designed to fit a particular die, which acts as a forming tool during the hydroforming process. A hydraulic press is used to encase and clamp the tube between the two dies during forming. Hydraulically powered cylinders are inserted into the open sides of the tube and provide a compressive axial force while supplying an internal pressure via fluid. Figure 2.2 shows the basic steps involved in a THF process. In Stage I, the tube blank is inserted and the press is closed and locked so that there is no separation of the dies. During Stage II, the tube is compressed by the axial punches while pressurized internally through some fluid medium. Stage III represents a calibration phase where the pressure is intensified to conform the tube completely to the die and in Stage IV the press is released and the formed part is removed.

Some of the areas of most interest to researchers in the field of tube hydroforming are materials, process parameters, tribological effects, and equipment.
2.1.2. Loading Path

Tube hydroforming is a unique metal forming process because of its reliance on internal and axial pressure. In order to avoid failure, a proper balance must be struck between the stroke velocity of the axial pistons and the flow rate of the fluid that provides the internal pressure. There are two stages to a typical tube hydroforming process; free forming or pre-forming and calibration [Asnafi et al., 2000].

Free forming and can be characterized by:

- Steady increasing of internal pressure combined with axial feeding.
- High strains and plastic deformation in the expansion zone.
- High frictional effects in the guided zone.
- Increased material inflow to reduce localized thinning.
After the majority of the expansion is completed in the pre-forming stage, the calibration period is initiated in order to finalize the tube. The calibration stage is characterized by:

- Very high, constant internal pressure.
- Minimal or no axial force.
- Increased friction in the expansion zone due to contact with the tool.

During the calibration stage, high internal pressure is used in order to smooth out any wrinkles that occurred in pre-forming and also to fill the corner radii of the die [Lang et al., 2009; Asnafi et al., 2000]. Thinning is often prevalent during calibration, therefore it is necessary to ensure proper axial force during the free forming stage so that material is fed into the expansion zone. Figure 2.3 illustrates a graphical representation of the load path for the free forming and calibration stages. As the figure shows, the axial feed is either reduced or eliminated altogether in the calibration stage as the internal pressure is increased.

Optimization of the loading path has been the focus of several studies. Ghosh proposed a real-time database to predict the forming curve given certain parameters of the tube. To do this, the internal pressure curve was generated through an analytical model while the axial feed curves were configured though FEA by iterating 9 different parameters; strength coefficient, strain hardening exponent, friction coefficient, initial tube diameter, initial thickness of the tube, initial length of the tube, protrusion/bulge position along the length of the tube, protrusion/bulge height, and angle of protrusion. A cubic spline interpolation was used to fit the curves for different geometries and based on the desired geometries characteristics such as number of bulges, bulge height, and degree of bulge, the correct loading path could be predicted [Ghosh et al., 2010].
2.1.3. Materials For Tube Hydroforming

Tube hydroforming is characterized by large plastic strains and deformation under variable axial loading and internal pressure. The formability of each tube is largely dependent on the mechanical properties of the material. Properties such as strength coefficient $K$, strain hardening exponent $n$, and anisotropy parameter $r$ represent the most critical material characteristics effecting formability in a THF process.

Although the listed material properties for commonly used metals are readily available in databases, those values are usually obtained through uniaxial tensile tests of the material while in sheet form. It is known that the flow of a material differs with stress state, therefore, it is often important to find the material properties of a material using a test that accurately reflects the biaxial stress state experienced in tube hydroforming.

One such test that is used to determine material properties is a bulge test. Bulge tests allow for free expansion of the middle of the tube while the ends are fixed in the radial and axial direction by the die and axial cylinders respectively. The tube is then internally pressurized...
by a fluid and will generally form in a matter of seconds, depending on the amount of pressure and thickness. Plane strain conditions apply in a bulge test, therefore the two active strains can be represented as functions of the radius of the bulge and instantaneous thickness of the formed tube. It is then easy to determine the effective stress and strain employing yield criteria and through use of the power law, material properties such as strength coefficient $K$ and strain hardening exponent $n$ can be determined.

Extensive analysis on the influence of different material properties on the formability of tubes during tube hydroforming has been conducted [Carleer et al., 2000; Manabe et al., 2002]. It has been concluded that the anisotropy parameter $r$ and strain hardening exponent $n$ have the greatest effect. Tubes with a higher anisotropy value required more axial feeding in order to achieve the maximum forming, thus allowing for more material to be fed towards the center of the tube thereby reducing thinning and delaying fracture [Manabe et al., 2002].

### 2.1.4. Failure Modes

The three most common failure modes in tube hydroforming are bursting, wrinkling, and buckling [Asnafi et al., 2000; Koc et al., 2002]. A significant amount of research has been done to determine a process window that will avoid failure. Wrinkling, buckling, and bursting can all be controlled through proper axial and internal pressure.

The internal pressure must be high enough to induce yielding in the tube walls, be high enough to avoid buckling and wrinkling which can be caused by axial force, and be low enough as to not cause necking and fracture [Koc et al., 2002]. Similarly, the axial force must be large enough to provide sealing of the fluid, be large enough to overcome friction between the tube and die wall, and be large enough to induce plastic deformation. Figure 2.4 shows a typical process window for a THF process.

By applying a force balance on an infinitesimal section of the tube and assuming the von Mises yield criteria, the pressure required to yield the tube can be expressed as equation (2.1) [Asnafi, 1999]:
where $p_l$ is the internal pressure, $K$ is the strength coefficient, $n$ is the strain hardening exponent, and $\alpha$ is the ratio of the principal stresses.

It is clear that the pressure is directly related not only to the material properties of the tube such as the strength coefficient $K$ and the strain hardening exponent $n$, but also the geometrical parameters such as initial tube diameter $d_o$ and thickness $t_o$.

In order to avoid bursting, an irreversible failure, the plastic instability must be taken into account. The maximum strain where necking will occur can be calculated by taking the derivative of the pressure with respect to the radius of the tube and setting that equal to zero. In a simple case of internal pressure combined with independent axial load, the critical strain can be expressed as equation (2.2) [Jain et al., 2005]:

$$\varepsilon_f = \frac{2n}{\sqrt{3}} \left[ \left( \frac{\sigma_x}{\sigma_0} \right)^2 - \left( \frac{\sigma_x}{\sigma_0} \right) + 1 \right]^{1/2}$$

(2.2)

It can be seen that the stress state induced by both the axial and internal pressure greatly complicates the tube hydroforming process in terms of yielding and failure. Much of the research to date in this field has been concerned with developing process parameters that will increase the safe operating zone. Recently it has been found that inducing wrinkles through axial feeding can force material into the deformation zone and greatly expand the process window as Figure 2.4 shows [Yang et al., 2011].
Figure 2.4: (a) Conventional process window and (b) expanded process window [Yang et al., 2011].

2.1.5. Tribological Effects

During tube hydroforming, frictional effects vary along the length of the tube. It is convenient to simplify the process into three zones. In the guided zone, the tube is in constant contact with the die while material is being fed into the transition zone. The flow of material through the guided zone is critical in the hydroforming process, therefore it is necessary to reduce the amount of friction using lubricants. An analytical model to determine the stress state in the guiding zone was developed using a tribotest seen in Figure 2.5 (b). The coefficient of friction could be related to tube parameters by equation (2.3) [Ngaile et al., 2004]

\[ \mu = \frac{(2\alpha - 1)t_0}{L} \ln\left(\frac{F_f}{\pi r_0 p_i (\alpha - 1)t_0} + 1\right) \]  \( (2.3) \)

where \( \mu \) is the coefficient of friction, \( L \) is the tube length, \( r_0 \) is the initial radius, \( t_0 \) is the initial thickness, \( F_f \) is the frictional force, \( p_i \) is the internal pressure, and \( \alpha \) is \( r_0 / t_0 \).

Tests which determine the coefficient of friction for different lubricants have been developed such as push through test, tube upsetting, and pear shaped tribo test [Vollertsen et al., 2002;
Selection of lubricants is not only dependent on COF, but also environmental safety, ease of application, ease of removal, and cost.

![Diagram](image)

**Figure 2.5:** (a) THF die broken into zones [Ahmetoglu et al., 2000] and (b) setup for a guiding zone tribotest [Ngaile et al., 2004].

### 2.1.6. Equipment for Tube Hydroforming

The necessary equipment to perform tube hydroforming experiments can be grouped into four main categories:

- Presses
- Punches
- Dies
- Hydraulic and pressure system.

#### 2.1.6.1. Presses

The press has one primary function, act as the force resisting the internal pressure so that there is no translation of the tube or separation of the die. Different designs for presses are currently being researched because of their high cost and direct influence on cycle time. Most presses consist of a long stroke vertical hydraulic cylinder that controls the upper die and provides the clamping force. Cycle time is severely dependent on the press because of the
amount of fluid that is needed to drive the long stroke cylinder. The necessary clamping force of the press depends on the part that is being formed. A simple estimation of the clamping force can be approximated by equation (2.4) [Gearing et al., 2008]:

\[
F = \frac{pA}{2000}
\]  

where \( p \) is the maximum forming pressure, \( F \) is the clamping force, and \( A \) is the projected area. An example of the projected area for a square die is shown in Figure 2.6. It is usually safe to add a 30 to 50% factor of safety to this estimate.

![Projected Area](image)

**Figure 2.6: Example of a projected area used in press force calculation.**

### 2.1.6.2. Punches, Die, and Hydraulic Systems

The punches, or axial cylinders, are designed to compress the tube in order to feed material towards the expansion zone while simultaneously distributing the internal pressurizing fluid. Every hydroforming tool is equipped with two punches which act in synchronization according to the desired loading path.

Dies are typically made from tool steel so that they are not penetrated or misshapen during the hydroforming process. There is a high amount of friction between the die and the tube, therefore it is beneficial for the die to have a smooth surface. Much research has gone into determining the effect of the die radius in the transition zone on material flow. Kridli et al. (2003) showed that there is an inverse relationship between die radius and thinning.

The hydraulic systems for hydroforming setups are critical to performance. Typically a stand-alone hydraulic pump is dedicated to the press cylinder to reduce operating time while
a completely separate system is used for the feed actuators [Gearing et al., 2008]. A pressure intensifier is used in order to ramp up the hydraulic pressure to the necessary levels for forming, which can exceed 60,000 psi (413 MPa). There are two factors in determining the pressure intensifier volume; the change in part volume and the compressibility of the fluid. Control valves are often custom fabricated so that they can withstand the immense pressure. Figure 2.7 displays a hydraulic scheme for a typical THF process.

![Figure 2.7: Hydraulic scheme for a typical tube hydroforming system [Gearing et al., 2008].](image)

The control system which operates the hydraulic fluid is of critical importance as well. Open loop systems which consist of only a directional valve are simple and require limited amount of equipment, however there is no feedback or control so the press tonnage can only be approximated. Closed loop systems make use of servo valves, sensors, and a controller that can make adjustments based off the sensor data. This system calls for more components, however is much more reliable and accurate, which can be important in the tube hydroforming process.
A model of a complete system is shown in Figure 2.8. This machine was developed at the University of Stuttgart and has a press capacity of 3,500 tons (35,000 kN). It is seen that the long stroke cylinder controls the upper die movement and is locked into place using spacers controlled by plunger cylinders [Siegert et al., 2000]. Figure 2.8 (a) shows the process begins by loading the tube into the bottom die and lowering the top press through the upper vertical cylinder which is controlled through the hydraulic system. Figure 2.8 (b) shows the hydraulic fluid pressurizing the lower vertical cylinders to lift the lower die into position while the spacer cylinders lock the upper die into place. Figure 2.8 (c) shows the hydraulic fluid is now directed to the axial cylinders so that they can form a tight seal around the tube. Figure 2.8 (d) illustrates the actual forming process where the fluid supply responsible for the internal forming pressure is sent through an intensifier, or booster, while the axial cylinders are pressurized.

Figure 2.8: THF process from start to finish [Siegert et al., 2000].
2.2. Introduction to Sheet Hydroforming

Sheet metal hydroforming (SHF) focuses on the forming of either a single blank or double blank sheet through the use of a fluid medium. The fluid medium can either directly form the blank, known as active hydroforming, or can provide a counter pressure to assist in forming in a process known as passive forming. The advantages of hydroforming of sheet metal blanks as opposed to conventional techniques such as stamping include [Siegert et al., 1999]:

- Larger forming ratios
- Better surface quality
- Reduction of operations
- Reduction in tooling costs due to no female die
- Ability to form conical shapes and complex geometries

Figure 2.9: Applications of sheet hydroforming [Maki, 2003].

2.2.1. Forming Classifications

The main attraction of sheet hydroforming over conventional sheet forming operations is the reduction of tooling costs since the fluid can either replace the die or act as the forming pressure to replace the punch. Therefore, it is most convenient to refer to the sheet
hydroforming process based on the tool that is used. Sheet hydroforming with a punch (SHF-P) encompasses processes in which a solid punch is used to deform the material with fluid aiding as a counter pressure. Sheet hydroforming with a die (SHF-D) makes use of the fluid as the forming medium which pressurizes the sheet or sheets to conform to a die. SHF-D can also be split into single blank forming and double blank forming, also referred to as parallel plate hydroforming.

2.2.2. Sheet Hydroforming With a Punch

For centuries deep drawing of sheet metal blanks has been used in order to create concave geometries that are work hardened. Recently, the use of a fluid medium to assist in this process has been introduced in what is known as hydromechanical deep drawing (HDD). Figure 2.10 shows a comparison of the traditional stamping process with a typical HDD process. The fluid medium provides a counter pressure which is controlled by the stroke of the punch and a pressure release valve. This type of pressurization is known as passive, since the fluid is not solely responsible for deforming the material. The fluid can be externally pressurized in order to form the blank to the punch surface in what is known as active pressurization shown in Figure 2.11.

The hydromechanical deep drawing process provides several advantages versus traditional stamping [Siegert et al., 1999]. The counter pressure from the fluid produces high frictional forces between the blank and the punch, thus reducing stretching and thinning. Also, the counter pressure produces a more favorable stress state which delays the onset of necking. During a stamping or deep drawing operation, the blank experiences biaxial tension in the free expansion section. With the introduction of a counter pressure, the once tensile stress normal to the punch becomes compressive, thus increasing the maximum shear to failure. This counter pressure also provides for a much more uniform thickness distribution over the length of the blank. Lastly, the fluid medium acts as a female die which eliminates the need for expensive tooling.
2.2.2.1. Combination of Processes

Active and passive pressurization are often times combined into one process in order to produce specialized parts. Figure 2.12 shows a scenario in which the blank is pre stretched through active pressurization then hydromechanically deep drawn using passive pressurization. Pre stretching of the blank can provide localized strain hardening and reduce the thinning rate of the material. One application for this is in the production of car hoods, in which pre straining will provide for better dent resistance and buckling resistance [Janchen, 1999; Hoffman et al., 2001].

Another combination process that is widely used involves traditional stamping of the blank followed by active fluid pressurization in a final calibration stage to conform the blank to the punch. This process, as shown in Figure 2.13, can produce more complex parts in one single operation as opposed to multiple stamping operations.
2.2.2.2. Process Design

Extensive research through the use of experimentation and numerical solutions has been done to determine the effect of the counter pressure on limiting draw ratio and other parameters. Rosen et al. (2001) showed that the pressurization of the fluid can have a drastic effect on the thickness of the blank during the drawing operation. Using a conical punch, it was shown that a linear pressurization curve coupled with an increased pressure buildup in the beginning of the operation (due to pre stretching) is the most beneficial to thickness distribution. Having a high pressure initially causes high friction between the blank and the punch lending to less stretching. A slow buildup of pressure can lead to wrinkles and other unwanted defects.
For more complicated shapes, a higher counter pressure is required to form the blank to the punch or die therefore increasing the force required by the press. Also, the draw gap, which is the gap between the punch and the blank holder, plays a significant role in hydromechanical deep drawing. A common defect from this is bulging against the drawing direction, which is shown in Figure 2.14. This bulging can cause unwanted rupture or tearing. In order to combat this, a chamber of “support pressure” through the use of seals between the upper binder and the punch was developed [Aust, 2001]. This support pressure proved to increase the limit draw ratios of cups with varying punch geometries.

![Diagram](https://via.placeholder.com/150)

**Figure 2.14: a) Bulging against drawing direction and b) Proposed pressure support chamber [Aust, 2001].**

### 2.2.3. Sheet Hydroforming With a Die

Figure 2.15 shows the principle idea behind SHF-D in which fluid acts as the forming pressure in order to conform the blank to some female die shape. This process involves very high fluid pressures and thus it requires high blank holder forces. This process holds obvious advantages over traditional stamping with a punch and female die because this reduces the need for a punch, thus reducing cost, and also replacing the punching force with a fluid which reduces friction and allows for more even thickness distribution. Also, higher tolerances and better surface quality can be achieved [Kleiner et al., 2001]. A modification of
this process is also used as a bulge test to determine material properties. This form of SHF-D does not require a female die and only relies on free expansion of the sheet.

![Figure 2.15: Single blank SHF-D [Kleiner et al., 2001].](image)

### 2.2.3.1. Double Blank Sheet Hydroforming

Double blank, or parallel plate hydroforming, has recently found several applications amongst the automotive industry including B-Pillars, engine cradles, and fuel tanks [Maki, 2003; Rosen et al., 2001; Birket et al., 2001]. The principle idea behind double blank sheet hydroforming is shown in Figure 2.16. There are several benefits to double blank hydroforming, primarily the ability to produce multiple geometries during the same operation with the use of two different female die. Also, the blanks could be made of different materials to produce two completely separate parts in during the same process.

![Figure 2.16: Double blank SHF-D [Siegert et al., 2000].](image)

### 2.2.3.2. Process Design

There are significant challenges in sealing the blanks at the blank holder and introducing the fluid between the blanks. There are two primary modes of docking; introduction of the fluid
between one blank and introduction of the fluid between both blanks, as shown in Figure 2.17 [Hein et al., 1999].

The fluid can be introduced through one sheet either in the flange or in a connecting branch within the die cavity. When introduced in the flange, the sheet blanks are typically welded together thus reducing draw in which causes stretching of the material. When introduced through a connecting branch in the die cavity, the sheets can remain unwelded however there is some additional tooling that needs to be considered since the branch must move freely with the blank as it is being formed [Krei, 1999].

The fluid can be introduced through both sheets through the use of a rigid seal system or a lancing system [Bobbert et al., 2001]. The sealing system uses a ring channel in the blank holder in order to limit draw-in while the fluid is introduced between the two unwelded sheets in the flange as shown in Figure 2.18 [Krei, 1999]. A lance system can also be used in which a tool shaped as an arrowhead penetrates between the two unwelded sheets and is sealed by the blank holder force. It has been shown through experimentation and numerical simulation that the lance can cause wrinkling and increase the force needed from the press [Bobbert et al., 2001].

![Figure 2.17: Docking systems for parallel plate hydroforming [Hein et al., 1999].](image-url)
2.2.4. Materials For Sheet Hydroforming

Similarly to tube hydroforming, mechanical properties of the blank are important in determining formability for SHF process. In order to determine the material properties of a given sheet, a popular method using sheet hydroforming has been implemented. The hydraulic pressure bulge test is similar to a traditional limiting dome height test, however uses fluid as the pressurizing medium instead of a punch. This test creates a biaxial stress state, which allows for much greater strain than in a tensile test [Gutscher et al., 2004]. A system was developed at the ERC/NSM which instantaneously captures the bulge height which can easily help solve for the flow stress of the material. It is not uncommon for materials to have varying properties depending on the place of production or time of production. Therefore, it can be extremely beneficial as a quality control measure in a plant or for establishing accurate data for numerical modeling.
2.2.4.1. Anisotropy

For most steels, it is acceptable to model a sheet hydroforming operation under the assumption that the material exhibits isotropic behavior. However, with the ever increasing demand on weight restrictions for automobiles and other manufactured items, lightweight materials such as aluminum and magnesium are becoming more popular. These materials both exhibit anisotropic properties which can lead to plenty of issues in regards to sheet hydroforming. The anisotropic constant in aluminum is less than 1, meaning the strain in the thickness is greater than the strain in the width during yielding. This of course can lead to thinning and premature fracture before an adequate draw depth. Abedrabbo et al. (2005) investigated at length the effect of anisotropy in aluminum sheet hydroforming operations in regards to wrinkling. In order to do this, Barlat’s anisotropic yield model was implemented [Barlat et al., 1997]. This model proposes a yield function $\Phi$ that is defined:

$$\Phi = \alpha_1|S_2 - S_3|^\alpha + \alpha_2|S_3 - S_1|^\alpha + \alpha_3|S_1 - S_2|^\alpha = 2\bar{\sigma}^\alpha$$

(2.5)

where $\alpha$ is 6 for BCC metals and 8 for FCC metals.

The isotropic plasticity equivalent stress for plane stress is then introduced.
The coefficients $c_1, c_2, c_3, c_6, \alpha_1, \alpha_2, \alpha_3$ describe the anisotropy of the material and can be solved through experimentation. This yield criterion is then used in tandem with an energy approach to create an upper bound solution to the wrinkling problem. After analysis, a pressure profile is obtained which will prescribe the optimum pressure versus punch depth that will not induce wrinkling.

### 2.2.5. Equipment For Sheet Hydroforming

#### 2.2.5.1. Presses

It has been previously noted that the benefits of sheet hydroforming comes at a tremendous cost of press capabilities. In the case of SHF-P, the press not only needs to have enough pressure to deform the material, but also to overcome the counter pressure exerted by the fluid. At the Institute for Metal Forming Technology (IFU) at the University of Stuttgart, a 35 kN press once designed for tube hydroforming was retro fit for use in sheet hydroforming [Beyer, 1999].

The press concept, as shown in Figure 2.20, involves a long stroke cylinder at the top of the press which controls the primary closing motion. There are then two “spacers” which will lock the long stroke cylinder into place during the forming, as shown in position B in Figure 2.20. Three short stroke cylinders are then used to press the die onto the material while the press frame remains locked and provides the necessary blank holder force.
2.2.5.2. Blank Holder Solutions

At the Department for Forming Technology (LFU) in the University of Dortmund, a massive 100 MN press has been constructed to perform SHF-D processes on large scales [Kleiner, 2003]. A multipoint blank holder system was developed in order to promote realtime calibration of the blank holding force [Kleiner, 2003]. A draw in sensor is attached at the location where the flange transitions in the free forming body, which is tied into a control system that can adjust the pressure in a certain location of the blankholder. The blankholder is segmented into 10 smaller local blank holders that are controlled individually by a short stroke cylinder. Figure 2.21 shows a schematic of the 100 MN press and Figure 2.22 (a) shows a die insert complete with the multipoint blankholder system.

At the IFU, a similar approach is taken. The segmented elastic blankholder system incorporates segmented blank holders that are forced via pyramid shaped pin cushions to control the blankholder force and multiple locations as shown in Figure 2.22 (b) [Siegert, 2003].
Figure 2.21: LFU SHF-D 100 MN press [Kleiner, 2003].

Figure 2.22: (a) LFU multipoint blankholder system and die insert and [Kleiner, 2003]. (b) hydraulic multipoint cushion blankholder system [Siegert, 2003].

The relationship between the blank holder force, stroke of the punch, and counter pressure are all interrelated and must be optimized to produce a defect free part. A process window showing the potential defects due to improper pressurization and blank holder force is shown in Figure 2.23.
2.3. Limitations of Hydroforming

From the literature reviews for both THF and SHF discussed in this chapter, it can be seen that there are clear limitations to both of the processes. Chief among these are:

- Cost of presses and tooling
- Press capacity
- Process time
- Spectrum of complex geometries

The most obvious limitation of THF is the inability to create any shape other than hollow round or box parts without other operations. Complexity of the parts made is not only limited by the tube geometry, but also by the capacity of the press and required calibration pressure. Tight corners and small die radii require a very high calibration pressure which increases the load on the press.
The equipment involved in tube hydroforming can become extremely expensive depending on the complexity and size of the part. A traditional 120 kN press can cost $6.5 million alone [APT]. Also, because of the hydraulic control system and process window, THF processes generally have a long cycle time. Figure 2.24 shows a breakdown of the time required to create an engine cradle.

Figure 2.24: Cycle time for a tube hydroforming process for a common automotive part [Osen, 1999].

In sheet hydroforming, the primary limitations are:

- Need for immense press capacity
- Cycle time
- Spectrum of complex geometries that can be produced
- Wrinkling due to anisotropy and blank holding issues
- Costly custom presses designs needed

Similar to tube hydroforming, capacity and cost of the press, hydraulic system, and punches/dies can become exorbitant. Also it has been reviewed that there are significant
issues involved with blank holding and complex solutions in order to reduce failure rates. Complex shapes are again limited by press capacity and frictional effects from the dies and punches. Overall, it is relatively expensive and time consuming to create parts using sheet hydroforming versus conventional stamping or deep drawing.

There is a clear need in the hydroforming industry for a manufacturing process that reduces the need for complex equipment, thereby drastically reducing cost and eliminating some forming limitations. Also, with the elimination of presses and hydraulic equipment, cycle time will be greatly reduced. To address some of the limitations of the current hydroforming process, a new hydroforming process is introduced. As discussed in detail in the next chapters, this new process can create complex structures whose geometry cannot be replicated by any other forming operation. In this process, the use of a press and dies is eliminated.
CHAPTER 3
DIE-LESS HYDROFORMING AND PROCESS CAPABILITIES

3.1. Introduction and Objectives

There is a clear need in the hydroforming industry for a manufacturing process that reduces the need for complex equipment, thereby drastically reducing cost and eliminating some forming limitations. In order to bypass the limitations of the current hydroforming technology, a new die-less hydroforming process is introduced in this study. Die-less hydroforming holds several advantages over traditional tube and sheet hydroforming:

- Ability to create complex geometries that cannot be produced by current hydroforming processes
- Elimination of dies and press thereby drastically reducing cost
- Forming pressure and part geometry is not limited by press capabilities

A major benefit of die-less hydroforming is that the un-deformed part can begin as any geometry, it is not limited to a tubular shape or blank sheet. This freedom of geometry allows for the die-less process to create custom, complex geometries that are not possibly formed by other metal forming processes.

In industry, dies experience significant wear due to frictional effects which hinder formation and require either re-working of the dies or replacement. Significant amounts of time and resources have to be dedicated to die development to reduce wear and frictional effects during forming. Therefore the benefits of a die-less process are not only in formation of the part, but also reduction of cost plus research and development time.

As discussed in Chapter 2, the hydroforming industry has dedicated lots of time and money in the development of state of the art presses that reduce cycle time and can withstand the forces created during forming. Even with modern control and hydraulic systems, there is still
a limit on load capacity and time for the press to load and unload a part. It is often not practical for smaller companies to produce parts through the hydroforming process because of the cost of building and maintaining the press. The elimination of a press in the die-less hydroforming process therefore may be the largest contribution to the industry since it not only drastically reduces cost and service time, but also can help reduce cycle time.

In order to develop a die-less hydroforming process that is most beneficial to the metal forming industry, several objectives must be met:

- Versatile process that can create a number of different complex geometries
- No dies or press, only equipment necessary is that which provides the fluid under pressure
- Opportunity for large volume production with low cycle times
- Minimum scrap i.e. full utilization of material

The development of this process begins with a classification of geometries that can be produced through die-less hydroforming based on their formed shape. Finite element analysis is then used not only as an analysis tool, but also in the parametric design of complex parts.

### 3.2. Process Overview

The concept behind die-less hydroforming is to attach multiple blanks together by welding or through a series of welds and introducing fluid pressure between the welds. The initial step in the die-less hydroforming process is to cut the sheet blanks into an initial geometry which is determined by the desired final form. Two matching blanks are then welded in some fashion so that the area between the welds is completely sealed. A hole or holes are created on one sheet blank where the fluid will be introduced between the welds allowing the material to form freely. Through this process, the two primary variables that can be manipulated in order to create different geometries are initial blank shape and pattern of the weld.
3.3. Classification of Geometries

One of the primary benefits of a die-less hydroforming process is the ability to create complex geometries that are not possible through other methods. In developing this process, it is convenient to organize potential geometries into families based on their shape and application. In this study, three different classifications of geometries are explored. Each of these geometries has several real life applications and can be formed through die-less hydroforming. Table 3.1 displays the family of geometries.

Table 3.1: Die-less hydroforming potential geometry families.

<table>
<thead>
<tr>
<th>Geometry Family</th>
<th>Model</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1.png" alt="Model Image" /></td>
<td><img src="image2.png" alt="Application Image" /></td>
</tr>
<tr>
<td>2</td>
<td><img src="image3.png" alt="Model Image" /></td>
<td><img src="image4.png" alt="Application Image" /></td>
</tr>
</tbody>
</table>
3.3.1. Geometry Family 1

This classification of part is characterized by either a square or circular base where the fluid enters and multiple outstretched appendages similar to that of a ceiling fan. Geometry 1A shown in Figure 3.1 contains a circular mid-section of radius 20 mm with four arms.
extending from the base, while Geometry 1C was sketched with a smaller mid-section of radius 15 mm and a thin strip connects the mid-section with the arms. Geometry 1B has a square mid-section with fillet radii connecting the appendages and the base. It also has flared appendages that increase in width as they extend away from the mid-section.

In order to hydroform, each geometry must consist of two blanks, one with a hole and one solid sheet. These blanks are then welded together along their outer edges to provide a sealed inner area which is free to expand when fluid is introduced. The forming medium is injected through the hole in one of the blanks, with the surface surrounding the inner edge of the hole as the only area that is constrained. This geometry is of interest because of the potential deflection of the appendages during hydroforming.

The inspiration for this geometry family is a product known as the Plopp Stool, which is created using an inflating method similar to the one introduced in this chapter, however with air as the forming medium instead of fluid. It is seen in Figure 3.2 that the formed part resembles the Plopp Stool, however the appendages do not show significant deflection. It was later concluded that the Plopp Stool is fabricated by inflation between the welds and manual pulling of the legs into the shape [Zieta].

These shapes were investigated using finite element analysis in order to determine the feasibility of forming and to determine important parameters such as thinning, plastic strain experienced, and deflection in the appendages. The results from some of the simulations are shown in Figure 3.2. It can be seen that complex shapes can be created using a die-less hydroforming depending on initial geometry.
Figure 3.1: Varying family 1 geometries. (a) Circular base geometry 1A, (b) square base geometry 1B, (c) circular base Geometry 1C, (d) tri legged Geometry 1D.

Figure 3.2: Deformed family 1 geometries. (a) Circular base geometry 1A, (b) square base geometry 1B, (c) circular base Geometry 1C, (d) tri legged Geometry 1D.
3.3.2. Geometry Family 2

The second family of geometries is characterized by a circular shape, like that of a steering wheel. Unlike the Geometry Family 1 where rotation of the arms was closely monitored, the wheel was merely expected to inflate and create a hollow round shape. This shape could be utilized in several real world applications that involve circular structures, such as pulleys or cams. An obvious application of this family of geometries is rims for car or bike tires. Most alloy rims are produced through CNC machining which can be time consuming and wasteful of material. Through a die-less hydroforming process, any rim shape can be made without the use of expensive CNC or water jet machines.

![Image of rim geometry](image)

(a) Out of plane deflection on formed geometry and (b) thickness distribution of two holed blanks.

Figure 3.3: (a) Out of plane deflection on formed geometry and (b) thickness distribution of two holed blanks.

Another benefit to using hydroforming is the work hardening experienced by the geometry. To display the strain hardening effect die-less hydroforming had on the circular geometry, Abaqus Standard was used to apply a static load to a circular geometry that included work hardening and one of the exact same geometry with the pre-defined stress attached to the nodes. A concentrated compressive load of 50 N was applied to the top of the wheel while the bottom edge was constrained. The results showed that the rim not formed by die-less
hydroforming experienced 300% more deflection due to the 50 N load. These work hardened rims could prove extremely useful for large commercial or combat vehicles which can weigh several tons.

Table 3.2: Comparison of the structural integrity of hydroformed vs. non-hydroformed parts.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Concentrated Load</th>
<th>Maximum Mises Stress (Mpa)</th>
<th>Maximum Plastic Strain</th>
<th>Maximum Vertical Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel during Forming</td>
<td>50</td>
<td>1352</td>
<td>0.9</td>
<td>4.6</td>
</tr>
<tr>
<td>Wheel w/o work hardening</td>
<td>50</td>
<td>55.14</td>
<td>1.50E-03</td>
<td>0.13</td>
</tr>
<tr>
<td>Wheel with work hardening</td>
<td>50</td>
<td>813</td>
<td>0.9</td>
<td>3.91E-02</td>
</tr>
</tbody>
</table>

Figure 3.4: FEA results of crushing the (a) wheel not formed through hydroforming and (b) wheel formed through die-less hydroforming.

3.3.3. Geometry Family 3

This family of geometries will be investigated most extensively in this study because of their versatility and application. The geometry family is characterized by tubular structures that
feature several different welding configurations for different uses. These structures, like all others created through hydroforming, are work hardened and exhibit a higher yield strength after forming. Due to the forming mechanism of inflating between the welds, the tubular structures in this geometry family show hollow nodules which can be utilized in different ways. It also drastically reduces the weight of many structures considering thin walled tubes withstand formed through die-less hydroforming can replace much thicker tubes of the same material. Figure 3.5 shows some of the configurations that are possible in this geometry family.

Figure 3.5: Die-less hydroforming tubular structures.

Figure 3.6 shows some possible applications for the tubular structures in geometry family 3. Large steel columns are often used in the construction industry for supporting roadways, bridges, and buildings. These columns are usually used as a base for concrete that is surrounds the outer and inner wall of the tube. Large shell structures like the silo pictured in Figure 3.6 (c) typically need to be supported along the internal wall to prevent buckling. Similar structure could be made through die-less hydroforming which would not require additional support. Through the die-less hydroforming technique, all of these structures can be produced easily while reducing the weight and increasing strength. Also, the unique look to die-less hydroformed tubes could be desired by architects.
In addition to the several applications in the field of construction, these tubular structures could also greatly benefit the aerospace industry. Due to the stress endured during a landing, the landing gear assembly must be one of the strongest components on a plane. Landing gear assemblies, like that shown in Figure 3.6 (b), make use of tubular components to house the pistons and dampers. Oleo Struts could be made lighter and stronger with the use of a die-less hydroformed structure.

Figure 3.6: Potential applications to Geometry Family 3. (a) Steel columns for roadway, (b) Grumman HU-16A landing gear, (c) grain silo, (d) transmission towers.

There are also several potential applications for these geometries in the automotive industry. Tubular structures are often used to reduce weight and also handle provide rigidity especially against compressive loading. Figure 3.7 shows one automotive application in which the die-less hydroformed tubular structures could be used. Hollow chassis cross members are used to
provide rigidity between the chassis box frame. The use of the die-less hydroformed tubes will reduce weight since thin walled material could be used while maintaining the strength required for even heavy utility trucks. The hollow nodules that form as shown in Figure 3.7 (b) can also be utilized for component wiring or other applications. A square cross member is often used in box chassis frames, and this shape can be achieved using this process by varying the size of the nodules as shown in Figure 3.7 (c).

Figure 3.7: (a) Chassis for a typical automobile. (b) Cross sectional view of a die-less hydroformed chassis cross member. (c) Square cross section created using different size nodules.
3.3.4. Geometry Family 4

The fourth family of geometries could be very beneficial to the construction industry. Arches are used in many structures because of their ability to bear load and for aesthetic purposes. Large arches or similar structures like those seen in Figure 3.8 can be produced through die-less hydroforming without the need to bend or roll tubes. Curved sheets can be welded together then hydroformed into arch like structures that can be lighter, stronger, and produced faster than current processes. Figure 3.9 shows the unique cross section of an arch that could be manufactured by using die-less hydroforming.

![Figure 3.8: (a) Arapaho bridge in Addison, Texas and (b) Shenxigou Bridge in Dujiangyan, Sichuan, China.](image)
Figure 3.9: (a) FEA model of an arch created by die-less hydroforming and (b) view of cross section A-A.

3.4. Conclusions

A die-less hydroforming process can eliminate many of the challenges and limitations experienced through other metal forming processes. Several different types of complex geometries can be produced in this way that are unobtainable through other metal forming processes. The geometry variations can be controlled through initial blank design and welding techniques. The cost of production for this process can be drastically lower than tube and sheet hydroforming because of the lack of necessity for expensive dies and presses. With no press limitations, large scale products such as 30 foot tall tubular columns can be made easily in one process instead of multiple steps.

There are limitations to the process however. Secondary operations such as welding, rolling, or trimming or an integral part of the die-less hydroforming process and can add greatly to cycle time. Also, since the fluid pressure can reach very high levels, the welds must contain very few flaws in order to create a tight seal. Material flow through the welds is also hard to predict and can affect deformation.

The tubular geometry family introduced in this chapter provides some of the most intriguing applications and will be the focus of the rest of this study.
CHAPTER 4
DESIGN OF TUBULAR GEOMETRIES

4.1. Introduction

Thin walled cylindrical shell structures have been heavily researched in the past 50 years because of their application to several industries. Rockets, aircraft fuselages, cooling towers, silos, pipelines, chimneys, masts, and tanks are a few of the everyday applications of shell structures spanning multiple industries [Rotter, 1998]. These structures are used primarily because of their excellent strength to weight ratio and ability to handle multiple loading states.

In many applications, thin walled shells are used for large structures in which the radius and length are magnitudes larger than the thickness. These structures can also be subjected to different loading scenarios such as axial compression, axisymmetric pressure, torsion, or internal pressure. Owing to the geometry of shells, instability and buckling is a concern, especially for large structures or ones that experience mixed loading. In order to prevent buckling, stiffeners of various shapes can be attached to either the internal or external wall. Even with stiffeners, shell buckling can still occur under certain loading conditions as seen in Figure 4.1

![Figure 4.1: Buckling in a (a) wine holding tank and (b) fuel silo.](image-url)
Development of analytical models to accurately describe the buckling phenomena in shells has been attempted by several researchers. Different analytical models such as membrane theory, linear shell bending theory, linear eigenvalue analysis, and non-linear analysis have been developed to describe and predict, to varying degrees of success, buckling in shell structures [Rotter, 1998].

Elastic analysis of ring-stiffened shells first introduced by Bryant and Kendrick describe the critical buckling pressure as shown in equation (4.1) [Tian et al., 1999; Kendrick, 1953; Bryant, 1954];

\[ p_c = \frac{E h}{R} \left( \frac{n^4 R^4}{L^4} \right) \left( \frac{n^2 + 2 R^2}{2 L^2} - 1 \right) + \frac{E I (n^2 - 1)}{L (N+1)} \]  

(4.1)

Where \( E \) is the elastic modulus, \( I \) is the second moment of area, \( L \) is the length of the shell, \( h \) is the thickness of the shell, \( R \) is the radius, \( n \) is the number of circumferential waves, \( N \) is the number of stiffeners, and \( \Omega \) is defined as equation (4.2) for Kendrick’s formula and equation (4.3) for Bryant’s:

\[ \Omega = R^3 \]  

(4.2)

\[ \Omega = \left( R + \frac{h}{2} \right) \left( R + e_c \right)^2 \]  

(4.3)

where \( e_c \) is the eccentricity of the stiffeners and shell. Non-linear buckling analysis has become increasingly popular with the advancement of computational ability. An energy approach can be taken where a parameter can be defined as in equation (4.4) [Bushnell, 1970];

\[ H_n = U_s + \sum_{k=1}^{M} U_r^k - \left( T_s + \sum_{k=1}^{M} T_r^k \right) + \sum_{i=1}^{K+1} U_c^i \]  

(4.4)

where \( U_s \) is shell strain energy, \( U_r^k \) is strain energy of the \( k \)th ring stiffener, \( T_s \) is the shell kinetic energy, \( T_r^k \) is the kinetic energy of the \( k \)th ring stiffener, and \( U_c^i \) is the \( i \)th set of...
constrain conditions. The energy terms are functions of stress, strain, geometry, and displacements. This can be treated as an Eigen value problem where an extremum solution to the parameter $H_n$ can be found. This extremum value can correspond to the critical pressure which causes buckling.

With the advancement of finite element capabilities, much research has been done on the benefit of different shapes, sizes, and quantity of stiffeners [Prusty et al., 1999]. FEA can provide accurate numerical solutions to shell problems that are difficult or impossible to develop closed-form solutions to. Due to the multiple loading conditions that shells can be subjected to, FEA is not always a convenient design tool for stiffened shell structures. For this reason, generic standards have been created which give a basis for design, however are far from all-encompassing [Rotter, 1998].

It can be seen that although shells are useful in many applications, design and analysis of the structures has proven to be very difficult. Stiffeners must be added to many shell structures for support, however, they significantly add to the complexity of the analysis.

Shell structures formed by die-less hydroforming such as those introduced in Chapter 3 can provide a solution to the complex shell buckling problem. Due to strain hardening and increase in the moment of inertia, which as seen through the analysis and equation (4.1) has an effect on buckling, die-less hydroformed structures can improve the strength to weight ratio and remove the need for stiffeners. The goal of this chapter is to analyze the benefit of creating shell structures through a die-less hydroforming process and provide a parametric study on some of the design criteria for different geometries using finite element analysis.

### 4.2. Numerical Modeling of Die-Less Hydroforming of Tubular Structures

The unique tubular structures that can be created using die-less hydroforming are formed by attaching two tubular blanks through welding and using fluid pressure between the welds. The deformed areas between the welds are referred to as lobes in this study and will be a
primary focus of the investigation. By altering the welding pattern, lobe formation can drastically change and create different tubular geometries.

In this study, there are three different tubular geometries that will be investigated. These geometries can be classified by the lobe characteristics as shown in Table 4.1.

Table 4.1: Classification of tubular geometries.

<table>
<thead>
<tr>
<th>Name</th>
<th>Weld Pattern</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Lobes</td>
<td>Blanks are welded together along the length of the tubes</td>
<td></td>
</tr>
<tr>
<td>Circumferential Lobes</td>
<td>Blanks are welded together circumferentially around the tubes.</td>
<td></td>
</tr>
<tr>
<td>Helical Lobes</td>
<td>Blanks are welded together in a helical pattern that travels the length of the tubes.</td>
<td></td>
</tr>
</tbody>
</table>
In order to analyze the structures, the geometrical, material, and process variables which affect forming must be defined and are given in Table 4.1.

Table 4.2: Variables for die-less hydroforming of tubular structures.

<table>
<thead>
<tr>
<th>I. Geometrical Variables</th>
<th>II. Material Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_o^u$ = Initial outer radius</td>
<td>$K$ = Strength coefficient</td>
</tr>
<tr>
<td>$r_i^u$ = Initial inner radius</td>
<td>$n$ = Strain hardening exponent</td>
</tr>
<tr>
<td>$r_n^u$ = Initial radius at the neutral line</td>
<td>$\nu$ = Poisson’s Ratio</td>
</tr>
<tr>
<td>$d_0$ = Initial outer diameter</td>
<td>$E$ = Elastic modulus</td>
</tr>
<tr>
<td>$l_0$ = Initial length of the tube</td>
<td>$\rho$ = Density</td>
</tr>
<tr>
<td>$t_0$ = Initial thickness of the blank</td>
<td></td>
</tr>
<tr>
<td>$\alpha$ = Helical angle</td>
<td></td>
</tr>
<tr>
<td>$r_o^d$ = Outer radius after deformation</td>
<td></td>
</tr>
<tr>
<td>$r_i^d$ = Inner radius after deformation</td>
<td></td>
</tr>
<tr>
<td>$r_n^d$ = Radius at the neutral line after deformation</td>
<td></td>
</tr>
<tr>
<td>$l_f$ = Final length of the tube</td>
<td></td>
</tr>
<tr>
<td>$t_f$ = Final thickness of the blank</td>
<td></td>
</tr>
<tr>
<td>$d_{major}$ = Major diameter of the formed lobe</td>
<td></td>
</tr>
<tr>
<td>$d_{minor}$ = Minor diameter of the formed lobe</td>
<td></td>
</tr>
<tr>
<td>$\lambda$ = Forming ratio for the vertical lobed geometry</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.2 (a) illustrates the undeformed geometry where the inner and outer blank are welded together in some pattern at $r_n^u$. The thickness $t_0$ refers to the thickness of the individual blank, therefore when the structure is welded the total thickness will be $2t_0$. Figure 4.2 (b) and (c) represent the deformed geometry and lobe parameters respectively. FEA can be used to investigate the formation of the lobes under different loading conditions.
4.2.1. Pre-Processing

All simulations presented in this study were performed on Abaqus 6.7 teaching license, which limits the assembly to 20,000 elements. For each simulation, the two blanks are modeled as cylinders of the same diameter with the distinction of being the “inner blank” or “outer blank”. The tubular blanks are partitioned according to the welding pattern for the
particular geometry. The partition creates several individual sections on the tube that can be constrained, meshed, and loaded separately.

The blanks are modeled using S4R shell elements, which adhere to classical shell theory for thin walled structures such as sheets. To simulate the attachment of the tubes, the tie constraint in Abaqus is used. Through this feature, the nodes along the partition lines of the inner blank are attached to the nodes on the corresponding partition line on the outer blank so that they rotate and translate as one node.

Since portions of the surface of the blanks will be tied together, a shell surface reference offset is used so that the reference surface of the shell does not represent the midpoint, but rather the top or bottom surface depending whether it is the inner or outer blank. The inner blank shell is offset in the positive normal direction similar to Figure 4.3. With the shell offset, the surface that is meshed represents the surface that will actually be in contact with the outer blank.

For all of the simulations, the material is assumed to be stainless steel 304 and the plastic flow follows the power law.

\[ \bar{\sigma} = K \bar{\varepsilon}^n \]  

(4.5)
Table 4.3: Material properties for the simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>207,000 MPa</td>
</tr>
<tr>
<td>$v$</td>
<td>0.27</td>
</tr>
<tr>
<td>$\rho$</td>
<td>7.85E-08 g/mm$^3$</td>
</tr>
<tr>
<td>$K$</td>
<td>1450 MPa</td>
</tr>
<tr>
<td>$n$</td>
<td>0.56</td>
</tr>
</tbody>
</table>

4.2.2. Finite Element Simulation of the Forming Process

Due to the complex nature of die-less hydroforming, numerical analysis is used in order to predict the deformed geometry and analyze the structures.

Since there is no die, there are very little constraints on the workpiece during forming. The only portion of the geometry that will not be free to form is the area directly surrounding the holes on the outer tube where the fluid is introduced. The boundary conditions for this geometry were selected under the assumption that the forming at the ends of the tubes are not of interest and that there will be a transition point where the forming will become homogenous along the length of the tubes. In other words, after formation of the geometry the ends of the tubes will be scrapped and the remaining part will be formed homogeneously. Under that assumption, all translational and rotational degrees of freedom were constrained at one end of the tube. Figure 4.4 shows the boundary condition used in all simulations.

An equal and opposite uniform pressure is applied to the partitioned surfaces of the inner and outer blanks. For the inner blank, the pressure is applied to the outer surface in the direction towards the middle of the tube. For the outer blank, the pressure is applied to the inner surface in the outward normal direction. A linear loading path is used for all simulations in this study and all pressure values mentioned refer to the maximum pressure which occurs at the end of the time step.
4.3. Evaluation of Strength-to-Weight Ratio for Tubular Geometries

In order to assess the strength of the hydroformed tubular structures, FEA simulations which mimic possible loading scenarios are performed on the formed parts and compared with a blank tube. These simulations are performed to show the increase in strength-to-weight ratio from die-less hydroforming. After the forming simulations, the deformed geometries are imported into a new simulation environment with the stress and strain values still attached to the nodes. This ensures that the strain hardening effects are still considered in the strength tests. Due to the limited forming capabilities at the ends of the tubes and the unique geometry of the lobes, creative boundary and loading conditions must be applied. Three loading scenarios are simulated; flexural, compression, and torsional.

For the flexural scenario, two semi-circular rigid dies are used to hold the tube while a third semi-circular die loads the tube perpendicular to its length. The holding dies are 10 mm in width and are separated by a 46.5 mm gap. The die used for loading is also 10 mm in width and is in the center of that gap. This setup is used to simulate a common three point bend test. This is an important measure of the tubes strength since there are many applications in the construction industry where this type of loading occurs.

For the compression simulations, one end of the tube is constrained in all directions while the opposite end is loaded towards the constrained end. The constraint is applied to the area around the tube 10 mm from the bottom edge since lobe formation does not occur there.
Also, instead of applying a concentrated load to the edge of the tube it is applied to a 10 mm long surface to negate the limited forming effects around the edge of the tube. This is achieved by coupling the degrees of freedom of the nodes on the 10 mm long surface with a rigid die that is prescribed a displacement. This accurately simulates a compression test where a die is used to apply the load instead of crushing the tube between two flat plates. is done

The torsional loading simulation is performed in the same way as the compression test, however the loading die is prescribed an angular rotation instead of translational. Figure 4.5 shows the coupling between the die and tube surface used for loading and the boundary condition on the other end of the tube.

![Figure 4.5: Loading and boundary condition for the torsional and compression tests.](image)

Each of the three tubular geometries is subjected two of the strength simulations and compared with a tubular blank. For consistency, the initial diameter and thickness of the formed tubes and blank tube are the same. The initial thickness for each of the blanks of the welded geometry is 2 mm, thus making the entire thickness of the structure 4 mm. Therefore, the blank tube used as a baseline for these simulations was assigned a thickness of 4 mm. With the same initial geometrical parameters, the weight of the formed tubular structures and the blank tube can be considered equal.

Table 4.4 shows the geometrical and loading conditions of the strength simulations. The stroke for the compression and flexural simulations along with the rotation or the torsional
simulation are heavily exaggerated in order to observe the failure mode of the parts. In reality, the part would fail before the end of the prescribed stroke.

<table>
<thead>
<tr>
<th>Table 4.4: Parameters for the strength tests.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Outer Diameter (mm)</td>
</tr>
<tr>
<td>40</td>
</tr>
</tbody>
</table>

### 4.3.1. Tubular Geometry with Longitudinal Lobes

The longitudinal lobed tubular structure subjected to the different loading scenarios is formed using a maximum pressure of 65 MPa. Figure 4.6 shows a cross sectional view of the formed lobes and the plastic strain achieved during formation. It can be seen that a maximum strain of 0.4 is experienced during formation with the average strain in the inner lobe reaching 0.25.

![Image](image.png)

**Figure 4.6: Plastic strain in the longitudinal lobe geometry during forming.**

**Compression Loading**

The tubular structure with longitudinal lobes shows considerable strength when subjected to compressional and flexural loading. As Figure 4.7 shows, the longitudinal lobed geometry was much more resistant to deformation during compressive loading than the blank. It is
observed that in the low stroke range, which is most applicable to real life scenarios, the longitudinal lobe geometry is able to carry significantly more load than the blank. At 10 mm stroke, the hydroformed geometry carries 135% (98,665 N) more load than the blank. Due to the geometry of the lobes, the structure begins to fail before the blank tube. After a stroke of 13.5 mm, failure is observed and the load begins to drop rapidly because of localized buckling at the top and middle of the tube as shown in Figure 4.8 (a). At this failure stroke, the load for the longitudinal lobed geometry is 91% (82,820 N) higher than the blank tube. Failure for the blank begins to occur at a stroke of 21 mm when wrinkles begin to emerge as shown in Figure 4.8 (b). In an actual compression test, the blank tube would experience buckling due to geometric imperfections which were not implemented in this code.

Figure 4.7: Compression load capacity for the longitudinal lobed structure.
Figure 4.8: (a) Longitudinal lobe geometry failing under compression at a stroke of 13.5 mm. (b) Blank tube failing under compression at a stroke of 21 mm.

**Flexural Loading**

For the flexural simulation, the blank and longitudinal lobed geometry exhibited similar load-displacement curves which are plotted in Figure 4.9. Again it can be seen that the lobed structure shows an increase in strength, particularly at lower stroke. At a stroke of 3 mm, the hydroformed part carries 133% (16,040 N) more load than the blank tube. Figure 4.10 (a) and Figure 4.10 (b) show the cross sectional view of the longitudinal lobed and blank tube respectively at a stroke of 9 mm. The hydroformed part shows good rigidity and retention of tubular shape. Figure 4.10 (c) shows the longitudinal lobed structure at the end of the bend test.
Figure 4.9: Bending load carrying capacity for the longitudinal lobed structure.

Figure 4.10: Cross sectional view during bending loading for the (a) longitudinal lobed geometry and (b) blank tube and an (c) overall view of the test.
From the finite element analysis it can be concluded that the longitudinal lobed geometry formed via die-less hydroforming has a significantly higher strength-to-weight ratio than a blank tube. A much greater load must be exerted on the hydroformed structure in order to deform it through compressive loading or bending loading versus a blank tube.

### 4.3.2. Tubular Geometry with Circumferential Lobes

The tubular geometries with circumferential lobes was subjected to torsional load and bending load simulations. The geometry was formed using a maximum pressure of 95 MPa and reached plastic strain values of 0.49 as shown in Figure 4.11. The average strain around the lobe is 0.24.

![Figure 4.11: Plastic strain in the circumferential lobe geometry during forming.](image)

**Torsional Loading**

For the torsion loading simulation, the circumferential lobed structure requires a significantly higher torque in order to deform through twisting as compared to the blank tube. As shown in Figure 4.12, at 17° twist, the load required for the circumferential lobed geometry is 250% (1438 N-m) higher than the blank tube. Again it is seen that the hydroformed part fails before the blank. At an angle of 62°, the hydroformed part begins to misshapen as shown in Figure 4.13 (a) and cause the torque to drop. At this failure however, the circumferential lobed
geometry is being subjected to a 106% (1234 N-m) higher torque. For the blank tube, failure occurs at 134° as shown in Figure 4.13 (b).

![Torsion Loading diagram](image)

**Figure 4.12:** Moment carrying capacity for the circumferential lobed structure.
Flexural Loading

For the flexural loading simulations, the hydroformed part once again showed higher strength than the blank tube as illustrated in Figure 4.14. The circumferential lobed geometry required over 10,000 N of force more than the blank tube in order to achieve the same stroke for the duration of the trial. At a low stroke of 3 mm, the hydroformed part required 174% (21,086 N) more load. This indicates that a die-less hydroformed circumferentially lobed tube will withstand a significantly larger amount of load before deflection.
4.3.3. Tubular Geometry with Helical Lobes

The helical lobed geometry was subjected to torsional loading and compression loading simulations. The geometry was formed using a maximum pressure of 125 MPa and reached a maximum plastic strain value of 1.01 as shown in Figure 4.15. The average strain throughout the lobe is 0.26.
**Torsional Loading**

Unlike the circumferential lobed geometry, the helical part did not show a failure mode when a moment was applied in the clockwise direction. As shown in Figure 4.16, the helical geometry deforms very differently when subjected to a torsional load in the clockwise direction versus the counter clockwise direction. Figure 4.16 (a) shows the geometry with a clockwise load in which the diameter of the tube slightly increases as the weld lines straighten out. On the other hand, Figure 4.16 (b) shows a counter-clockwise load where the diameter shrinks in the middle.

Figure 4.17 shows that the helical geometry exhibits much better strength when the load is applied in the clockwise direction. The helical lobed structure was able to carry more load at each degree of twist while remaining in tubular shape, particularly in the early onset of torsion. At an angle of 8°, the helical geometry carried 150% (854 N-m) more load than the tubular blank under clockwise torsional load and 92% (531 N-m) under counter-clockwise loading. The counter-clockwise torsional loading capacity is surpassed by the blank after 50°, in which case the tube is likely fractured.
Figure 4.16: Deformation of the helical lobed geometry when subjected to a (a) clockwise torque and a (b) counter-clockwise torque.

Figure 4.17: Moment carrying capacity for the helical lobed structure.
Compression Loading

For the compression loading scenario it is again seen that the hydroformed part exhibits much higher strength at initial loading. As shown in Figure 4.18, at a stroke of 6 mm, the helical geometry is subjected to 157% (105,018 N) more load than the blank tube. The helical tube does begin to fail early though. At a stroke of 7.5 mm, localized buckling near the loaded edge begins to occur as shown in Figure 4.19.

![Figure 4.18: Compression load carrying capacity for the circumferential lobed structure.](image-url)
4.4. Parametric Study To Establish Design Window for Die-Less Hydroforming

The forming profile of each of the tubular geometries is dictated by the welding pattern. In order to be able to describe the forming quantitatively, the lobes must be analyzed using data from FEA solutions. The lobes are used not only to describe the forming characteristics of the tubes, but also can be used for design purposes. When designing a tubular structure for a particular application, two critical geometrical components are inner and outer diameter. Since the hydroforming of the tubes can drastically change the profile, it is necessary to determine the relationship between variables such as initial diameter, initial thickness, forming pressure, and forming profile. Once these relationships are established through finite element analysis, the results can be used to create a process window in which the forming pressure and lobe formation of a tube of a certain diameter or thickness within the range tested in this study can be predicted.

The approach to investigate the effects of the initial parameters on forming is to apply several different forming pressures to each tubular geometry while varying the initial radius and
thickness. Table 4.5 shows the design matrix for the different geometries. After forming, the coordinates around one of the formed lobes is plotted in order to determine the forming profile. Also, the maximum thinning is taken into account as well with the assumption that a thinning of greater than 20% indicates failure.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>$d_0$ (mm)</th>
<th>$t_0$ (mm)</th>
<th>$P_t$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
<td>1</td>
<td>65,75,85,95,105,115,135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>65,85,105,125,140,220</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>65,85,105,135,175,200</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>40</td>
<td>1</td>
<td>65,75,85,95,105,115</td>
</tr>
<tr>
<td>Lobes</td>
<td></td>
<td>1.5</td>
<td>65,85,105,125,145,165</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>65,85,105,125,145,165,185</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1</td>
<td>65,75,85,95,105,115,125,135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>65,75,85,105,115,125,135</td>
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<td></td>
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<td>2</td>
<td>65,75,85,95,115,130,145</td>
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<tr>
<td>Circumferential</td>
<td>30</td>
<td>1</td>
<td>35,45,55,65,75,85,95</td>
</tr>
<tr>
<td>Lobes</td>
<td></td>
<td>1.5</td>
<td>65,75,85,95,105,115,125,145</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>Helical Lobes</td>
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<td></td>
<td></td>
<td>2</td>
<td>65,85,105,125,145,165</td>
</tr>
</tbody>
</table>

Table 4.5: Simulation matrix for the tubular structures.
4.4.1. Tubular Geometry with Longitudinal Lobes

The longitudinal lobe tubular geometry attaches the inner and outer tube blanks by a weld along the length of the tubes as shown in Table 4.1. For this study, the welds were started every 45° around the diameter of the outer blank. In order to determine the deformation characteristics based on initial parameters, a range of pressures was applied while varying the thickness and diameter as shown in Table 4.5. Before this analysis, it is necessary to determine the effect of the length to diameter (L/D) ratio on the forming capabilities of the tubular geometry. This is critical information because of the wide range of applications which can call for tubes of very different sizes. Finite element simulations are performed on structures with an L/D ratio of 2, 5, and 8 with \( t_{\ell} \) 1 and 2 mm to determine the effect of the length of the tube on formation capabilities. A maximum pressure of 65 MPa and an initial diameter of 50 mm is held constant for each simulation for consistency. To track the deformation of the lobe, a path is created including the nodes around the lobe and the coordinates are plotted. Figure 4.20 (b) shows a cross sectional area for a formed geometry with an L/D of 5 and the nodal path that is used to plot the forming profile. The forming profiles for the different L/D ratios and thicknesses are shown in Figure 4.21.

As the results show, varying the length of the tube does not change the forming characteristic of the lobes. These results indicate that the length of the tube does not affect forming and is therefore not a limitation to the die-less hydroforming process.
Figure 4.20: (a) Deformed geometry and (b) path used to track the coordinates of the lobe.

Figure 4.21: L/D effect on forming of the longitudinal lobed geometry.
4.4.1.1. Lobe Forming Characteristics

To investigate the forming characteristics of the longitudinal lobe geometry, an L/D ratio of 5 is held constant. Figure 4.22 and Figure 4.23 illustrate the lobe formation for a longitudinal lobe specimen of 30 mm diameter with 1 mm and 2 mm thickness respectively. It can be seen from the figures that the lower portion of the lobe, which corresponds to the inner blank, exhibits a different forming characteristic than the upper portion. There is a deep bulge in the middle while the area close to the welds remains relatively flat. Also, since the bottom portion of the lobe experiences more expansion than the upper portion, the tied nodes which correspond to the weld shift downwards, allowing for the upper portion of the lobe to maintain the same outer radius from the center of the tube. The 2 mm thick blanks require a much higher pressure in order to see significant deformation of the lobes. Figure 4.22 shows that between 105 MPa and 135 MPa the bottom portion of the lobe begins to deform more rapidly than at lower pressures. This is due to the change in stress state experienced by the inner tube when the curvature approaches zero then concaves inward toward the center of the tube. After that release of strain energy, the lobe begins to deform linearly with pressure as is seen in the 1 mm thickness plot. A similar pattern of lobe formation is seen for the other sets of diameters and thicknesses, therefore they are listed in Appendix A.
Figure 4.22: Lobe forming profile for the longitudinal lobe geometry with an initial diameter of 30 mm and thickness of 1 mm (L/D=5).

Figure 4.23: Lobe forming profile for the longitudinal lobe geometry with an initial diameter of 30 mm and thickness of 2 mm (L/D=5).
In order to quantitatively define the deformation of the lobe, a forming ratio is introduced as equation (4.6)

\[ \lambda = \frac{d_{\text{minor}}}{d_{\text{major}}} \]  

(4.6)

From this definition it can be inferred that a forming ratio of 1 indicates a circular lobe. Figure 4.24 illustrates the forming ratio versus pressure for each of the diameter and thickness variations. As expected, the forming ratio at a given pressure increases with increasing diameter. This indicates that tubes with smaller initial outer diameters, such as the 30 mm one tested in this study, can require over 200 MPa in order to achieve forming ratios of above 80%. Also, as the individual tubes become thicker the pressure must be increased in order to form. Each variation was initially formed using 65 MPa then from those results a pressure window was determined. It can be seen that in this pressure range, the forming ratios linearly increase with increasing pressure. This is an important characteristic for design of tubular geometries. It can also be seen that there is a linear relationship between the forming ratio, pressure, and initial diameter.

Figure 4.24: Forming ratio versus pressure for vertical weld geometry with initial blank thickness of (a) 1 mm (b) 1.5 mm and (c) 2 mm.
4.4.1.2. Lobe Wall Thinning Characteristics

It is also important to determine the relationship between thinning and the initial geometrical parameters in order to predict a safe range of pressures in which failure will not occur. Figure 4.25 shows the thinning percentage for a path around the lobe. It was seen earlier that the inner and outer portion of the lobe experience different forming mechanisms, therefore it is expected that they would exhibit different thinning characteristics. The inner portion of the lobe begins the forming process under compression and thus does not show as much thinning as the outer lobe. The greatest thinning occurs near the tie constraint which simulates the weld as expected.
Figure 4.26 shows the thinning versus pressure curves for each diameter and thickness set. The thinning value for this figure corresponds to the highest thinning percentage experienced by the part. Again there is a linear relationship noted between the thinning percentage and the pressure until the thinning percentage reaches above 20% when the relationship becomes exponential as seen in Figure 4.26 (b). As the forming ratio approaches 1, the upper portion of the lobe begins expanding rapidly thus leading to a high thinning rate. The thickness versus pressure curves are pivotal to understanding the maximum forming ratio that is allowed and at what pressure it is safe to form.

Figure 4.25: Thickness distribution for a longitudinal lobe geometry of $d_0=30$ mm, $t_0=1$ mm, and forming pressure of 95 MPa.
Figure 4.26: Thinning versus pressure for longitudinal lobe geometry with initial blank thickness of (a) 1 mm (b) 1.5 mm and (c) 2 mm.
It is shown that there is a linear relationship between initial diameter, initial thickness, and pressure with thinning percentage and forming ratio. This linearity is useful in the design of a particular part since the data can be easily interpolated. A safe forming window for this geometry can be estimated for tubes of different initial diameters and thickness.

4.4.2. Tubular Geometry with Circumferential Lobes

The circumferential lobed tubular geometry attaches the inner and outer blanks together through circumferential welds along the length of the tubes as shown in Table 4.1. For this structure, the number of welds and the length of the tube determines the spacing in between the welds, and therefore determines the forming pattern. In order to maintain consistency for this study, the same number of welds and the length of the structure are held constant for each different diameter. Each set geometry variation will consist of welds that are 15 mm apart and the length of the structure is kept at 150 mm since it was determined that L/D ratio does not affect forming. Figure 4.27 shows the deformed geometry of the circumferential lobe tubular structure.

![Figure 4.27: Deformed circumferential lobe geometry.](image-url)
4.4.2.1. **Lobe Forming Characteristics**

Figure 4.28 and Figure 4.29 display the forming profile for a circumferential welded tubular structure of diameter 30 mm and thickness 1 and 2 mm respectively. From the forming profile it can be seen that the lobes of the circumferentially welded structure deforms differently from the vertically welded structure. The primary difference is that the inner and outer portions of the lobe deform nearly symmetrically about the initial neutral line $r_n^u$. Also, due to the radial bulging of the lobes, the entire structure experiences a drastic change in length. For this set of simulations, the edge at $l=150$ mm is constrained, therefore the length shrinks in that direction. It is seen from the forming profile that as the pressure is increased and the forming ratios become more significant, the Z-coordinates also increase. A similar pattern of lobe formation is seen for the other sets of diameters and thicknesses, therefore they are listed in Appendix B.

Similar to the longitudinal lobe, the circumferential lobe geometry also shows a linear relationship between forming ratio and thickness as shown in Figure 4.30. However, there is not a clear relationship between diameter and forming ratio for different thicknesses. While the forming ratio is higher for a larger diameter at a given pressure, the difference is not as significant as was seen in the longitudinal lobe geometry.
Figure 4.28: Lobe forming profile for the circumferential weld geometry with an initial diameter of 30 mm and thickness of 1 mm.

Figure 4.29: Lobe forming profile for the circumferential weld geometry with an initial diameter of 30 mm and thickness of 2 mm.
Figure 4.30: Forming ratio versus pressure for circumferential weld geometry with initial blank thickness of (a) 1 mm (b) 1.5 mm and (c) 2 mm.
4.4.2.2. Lobe Wall Thinning Characteristics

The circumferential lobe geometry exhibits a unique thickness distribution as well. Figure 4.31 shows the thinning percentage of the inner and outer lobe of one geometry with the parameters given in the figure. The outer lobe experiences up to 18% thinning while the inner lobe thickens by over 12%. This can be attributed to the compressive stress state in the inner lobe and the tensile stress state in the outer lobe. Also, as Figure 4.32 shows, greater thinning is achieved at lower diameters as opposed to the longitudinal lobe geometry.

![Thickness Distribution; $d_0=30$ mm, $t_0=1$ mm, $P_i=95$ MPa](image.png)

Figure 4.31: Thickness distribution for a circumferential lobe geometry of $d_0=30$ mm, $t_0=1$ mm, and forming pressure of 95 MPa.

![Circumferential Lobe Thinning; $t_0=1$ mm](image.png)

Figure 4.32: Thinning versus pressure for circumferential weld geometry with initial blank thickness of (a) 1 mm (b) 1.5 mm and (c) 2 mm.
4.4.3. Tubular Geometry with Helical Lobes

The helical geometry features 6 welds that wrap around the length of the tube in a helical manner. The welds begin every 45° around the diameter and complete a 315° rotation around the tube. In order to model this, a different approach to the partitioning strategy is employed. A python script is used in order to generate datum points that outline each of the helix patterns, then a shortest distance partition is used. The script used for this study is listed in Appendix D. Like the vertical weld geometry, a L/D ratio of 5 is held constant for the helix analysis.
4.4.3.1. Lobe Forming Characteristics

The helical lobe geometry provides one of the most interesting forming mechanisms. As the lobes are pressurized, a twisting of the tube occurs which can be seen from the forming profiles in Figure 4.33. The profile of the formed lobes for two different thicknesses is shown in Figure 4.34 and Figure 4.35. It can be seen that the lobes translate with the increasing pressure as the tube begins to twist while simultaneously increasing the forming ratio. Also, the upper and lower portion of the lobes form almost symmetrically about $r_0^\mu$. The forming profiles for all sets of diameters and thicknesses exhibit a similar forming pattern, therefore they are listed in Appendix C.

Figure 4.33: (a) Deformed helical lobe geometry and. (b) Cross sectional cut of the deformed geometry.
Figure 4.34: Lobe forming profile for the helical weld geometry with an initial diameter of 30 mm and thickness of 1 mm.

Figure 4.35: Lobe forming profile for the helical weld geometry with an initial diameter of 30 mm and thickness of 2 mm.

As shown in Figure 4.36, the forming ratios are again linear with pressure for each diameter and thickness set. For this structure, forming ratios of over 0.8 were achieved without significant thinning.
Figure 4.36: Forming ratio versus pressure for helical weld geometry with initial blank thickness of (a) 1 mm (b) 1.5 mm and (c) 2 mm.
### 4.4.3.2. Lobe Wall Thinning Characteristics

The thickness distribution for the helical lobe geometry follows the same pattern as the other structures in that the outer lobe experiences thinning while the inner lobe thickens. For this geometry, there is not a significant amount of thickening in the inner lobe as shown in Figure 4.37. The thickness versus pressure for each of the diameter and thickness sets is shown in Figure 4.38. It is seen again that as the thinning percentage exceeds 20% it becomes exponential with increasing pressure. A linear relationship is again noticed at levels under 20% thinning.

![Thickness Distribution](image)

**Figure 4.37:** Thickness distribution for a helical lobe geometry of \( d_0 = 30 \text{ mm}, t_0 = 1 \text{ mm}, P_i = 105 \text{ MPa} \).
Figure 4.38: Thinning versus pressure for helical weld geometry with initial blank thickness of (a) 1 mm (b) 1.5 mm and (c) 2 mm.
4.5. Conclusions From Analysis

The finite element simulations have shown that the tubular geometries that are able to be formed through die-less hydroforming are strong, unique structures that can be designed for several applications where traditional shell structures are required. Each of the structures showed excellent strength to weight ratios in a variety of loading scenarios and provided much more resistance to deformation than a blank tube. The effect of the lobe formation on the strength of the structure can reduce or eliminate the necessity for stiffeners which will reduce cost, secondary operations, and complexity of analysis.

Three different types of tubular geometries were introduced; longitudinal lobe, circumferential lobe, and helical lobe. The longitudinal lobe geometry has a unique lobe forming mechanism where the lower portion of the lobe deforms more rapidly than the top portion. Forming ratios of over 0.9 were achieved, however at the expense of a thinning percentage exceeding 20%. A linear relationship between pressure, diameter, and thickness was observed until the forming ratio approaches 1.0 when there is an exponential rise in thinning percentage. The longitudinal lobe geometry proved to be beneficial in cases of compressional and flexural loading. In compression, the longitudinal lobe geometry was able to carry 135% more load at a 10 mm stroke than a tubular blank. During flexural loading, the geometry carried 133% more load at a 3 mm stroke.

For the circumferential geometry, the inner and outer lobes form symmetrically about the neutral line. Due to the radial bulging, as the lobes form the tube length reduces in the direction of the constrained end. A linear relationship is seen between pressure and forming ratio, however increasing of the tube diameter does not affect the forming ratio as was seen with the longitudinal lobe geometry. Forming ratio of 0.7 was achieved for the 1 mm thick blanks at pressured of over 90 MPa, however significant thinning was seen at higher forming ratios. The circumferential lobe geometry showed excellent strength in torsional and compressive loading. For torsional loading, the geometry carried 250% more load than a tube blank at 17° rotation while carrying 174% more load at 3 mm stroke in compression.
The helical lobe geometry provided the most unique forming characteristics of the tubular structures. Owing to the welding pattern, the tube experienced a rotation during forming. The lobe formation showed a linear relationship between pressure and forming ratio as well as forming ratio and initial diameter. As the diameter of the tube increased, higher forming ratios were achieved at lower pressures. Forming ratios of over 0.8 were seen at pressures of 100 MPa for the 1 mm thick blank of 50 mm diameter. At higher blank thickness, pressures exceeding 200 MPa are required to achieve high forming ratios. The helical lobe geometry proved to be beneficial in torsional and compressive loading. The strength of the tube did vary depending on the direction of the applied moment for torsional loading however. With a clockwise applied moment, the helical lobe geometry carried 150% more load than a blank tube at 8° while carrying 92% more load when a counter-clockwise moment was applied. For compressive loading, a 157% higher load carrying capacity was seen at a stroke of 6 mm.

For each of the geometries, the same thickness distribution was observed where the inner lobe would become thicker and the outer lobe experienced significant thinning. This is due to the compressive stress state induced in the inner lobe as it is being deformed against its natural radius of curvature.

The linearity observed between forming ratios, thinning, and pressure based on initial geometrical parameters is extremely useful in design of the tubular geometries. Process windows can be easily constructed to help estimate the proper forming pressure for desired part geometries.
CHAPTER 5
SYSTEM REQUIREMENTS, MANUFACTURING PROCEDURES AND EXPERIMENTAL TRIALS

5.1. Introduction

In order to verify the viability of die-less hydroforming, a detailed look at the manufacturing process is necessary. While the required hardware is similar to other hydroforming processes, there are new challenges presented with die-less forming. Also, blank preparation is important because it directly affects the forming characteristic of the part and is crucial to successful forming. Experimental trials are also needed to discuss the feasibility of production, accuracy of the finite element analysis, and structural benefit of parts produced by die-less hydroforming.

5.2. Die-Less Hydroforming Hardware

One of the largest benefits to die-less hydroforming is the reduction of complexity and cost of experimental setup. The necessary hardware can be slightly different depending on the geometry, however there are common components required for every operation. Figure 5.1 shows a schematic of the die-less hydroforming process.

The control computer is used to input the loading path and control the hydraulic pressure. A control system is necessary in order to accurately pressurize the component. This control system can contain no feedback, in which case external pressure gauges must be mounted in order to determine the pressure. This system is less accurate, however is sufficient for many forming operations. A more complex control system can be implemented by the use of pressure sensors along the hydraulic fluid path.

A hydraulic system like those used in tube and sheet hydroforming is necessary in order to provide the forming fluid. This hydraulic system typically consists of a pump and a pressure intensifier to achieve the fluid pressure required in forming. The control computer relays the information to a control circuit unit which activates and controls the pump. High pressure
fluid lines must be used in order to carry the high pressure fluid from the pump to the workpiece. Fittings between the hoses and equipment may have to be custom made in order to accommodate size and pressure requirements. For the tubular geometries or any geometry with multiple points of fluid entry, several lines must be utilized.

One way of making this process efficient is to have one line bring the fluid from the hydraulic system to a distributor that will distribute the fluid evenly between the attachments on the workpiece. This distributor can be fabricated to hold many more lines than is necessary for experimentation by using plugs to seal the unused lines. Alternatively, independent pressure controlling can be achieved by having multiple lines attached directly to the fluid control system.

Since the process contains no die, the workpiece must be formed in a closed container for safety purposes. Unlike traditional hydroforming processes when fluid is contained by the die, if bursting occurs in die-less hydroforming the fluid will be released freely and could become dangerous. The enclosure also allows for a collection device to recycle the unused fluid. The unused fluid collected at the bottom of the enclosure can be returned back to the pump and reused for forming, thereby decreasing waste.

![Figure 5.1: Schematic of the die-less hydroforming system.](image-url)
5.3. Blank Preparation

Preparing the blanks to be hydroformed is the most time consuming part of the die-less hydroforming process. This preparation can be done in a number of ways and depends on the desired geometry. In Chapter 3, four different families of parts were introduced, each one requiring different operations to prepare the blank. The blanks for Geometry Family 1 and 2 can be prepared by simply machining the blank sheets then welding them together along the edges. For high volume manufacturing, advanced machining devices such as CNC mills/lathes or water jet cutting can be utilized to decrease time and increase accuracy. Advanced welding techniques such as laser welding can also be used to reduce time and create fluid tight welds that will not leak. Other welding processes such as TIG and resistance seam welding can be used as well. In addition to machining the geometry and welding the edges, a fluid entry point must be designed. One way of doing this is to have a hole in one of the blanks and welding a stud with a matching hole size to the blank. This procedure adds to the cycle time, however it is critical that it is designed properly so that the fluid does not leak during forming.

The arch geometries of Geometry Family 4 are prepared by cutting the blanks into an arch shape. There is a two stage forming process to obtain the tubular shape of the arches through the use of sheet blanks. Figure 5.2 illustrates the forming process that takes place in a cross section of the arch. Four blanks are used to create the structure and are assembled in pairs as shown in Figure 5.2 (a). The pair of blanks are welded together along the length of the middle of the plates then the pairs are connected by welding the outer edges. A fluid pressure is then used to form the blank pairs into a tubular shape. After a tubular shape is achieved, the area between the blank pairs is pressurized as shown in Figure 5.2 (b).
Figure 5.2: (a) First stage and (b) second stage used in the formation technique used for the arch geometry.

Depending on the welding configuration and access to machinery, the blanks for the tubular geometry in Geometry Family 3 can be prepared in tubular form or in sheet form. To prepare the blanks while in tubular form, the inner tube remains solid while the outer tube is cut into slices corresponding to the desired welding pattern. These slices are then welded onto the solid tube and studs are placed over the holes punched through the slices. Another way that can create more complex welding patterns such as the helix is to cut a sheet into slices and weld those onto a solid sheet. Once completely attached, the sheets can be rolled into a tube and then welded again along the seam. This process is obviously more time consuming and can limit the thickness and diameter of the blanks due to rolling constraints. Also, the material will likely have to be annealed after the process to release the stresses from the rolling and welding. Figure 5.3 illustrates the blank preparation of the tubular geometry in sheet form. Since it was shown that L/D ratio does not affect forming and that an increase in diameter lowers the required pressure to form, die-less hydroforming can be used to create high volume large tubular structures that exhibit superior strength and unique geometry.
5.4. Experimental Trials

To demonstrate the viability of the process, a tubular geometry with circumferential lobes is hydroformed. Because of rolling limitations, the only way to prepare the blank is to begin with them in tubular form. To begin, two stainless steel 304 tubes with 50 mm outer diameter and 2 mm thickness are machined to the same length of 200 mm. One tube is then marked every 60° along the length and cut using a slitting saw on a milling machine. A 0.36 inch hole is then drilled into each of the slices near the top edge so that the fluid can enter.

Before welding the slices onto the solid tube, the studs which provide the fluid must be welded onto the slices using a TIG welder. Because the tubes are thin walled structures, special attention needs to be paid to providing enough shield gas and controlling the heat so there is no burn through. To protect the back side of the slice, angle iron and aluminum tape are used to create an enclosure while Aragon gas is purged through the tube as shown in Figure 5.4. Aragon is used as a shielding gas to minimize the effects of the atmospheric gasses which can negatively impact the quality of the weld. For this experiment, left hand threaded stainless steel screws are used as the studs to provide the fluid. A 0.36 inch holes is cut down the center of the screw and it is then attached to the slice with the holes aligned.
Once the stud is attached, the slice is then welded onto the solid tube. Since the tube blanks were originally the same diameter, there is some gap that is needed between the slices as shown in Figure 5.5 (a). The ends of the solid tube are sealed off with aluminum tape and Aragon gas is purged through the center of the tube to shield the inner surface. After the welding is completed, the assembly is annealed in a furnace for one hour at 1900°F to relieve the residual stresses incurred from machining and welding. The complete assembly is shown in Figure 5.5 (b).

Figure 5.4: Purging of Argon during welding of the stud on the slice.

Figure 5.5: (a) Welding of the slices on the tube and (b) final assembly.
5.4.1. Experimental Setup

The hydraulic system used for this study was originally designed for a tube hydroforming process. Figure 5.6 (a) shows the hydraulic equipment used to provide the forming fluid. The pump sits directly above the hydraulic fluid tank and is capable of producing pressures up to 20,000 psi. The fluid travels directly from the pump to a fitting that is attached to the control box. Due to the high pressures produced in this system, special fittings and hoses that are rated for use above ksi have to be used. A high pressure line is connected to the fitting on the outside of the control where it connects directly to the distributor as shown in Figure 5.6 (b).

![Figure 5.6: Hydraulic system consisting of (a) the pump, oil reservoir, and (b) high pressure line that leads to the distributor.](image)

The distributor consists of a main hose attachment and 8 threaded holes for tubes that go to the work piece to connect as shown in Figure 5.7. A pressure gauge is mounted to one of the openings since there is no feedback control system in this setup. Six lines are then attached to the distributor on one end then tightened to a connector on the other. The connector is used to
connect the hose to the left hand threaded screw that is welded onto the assembly. The screw must be left hand threaded so that as the connector is rotated counter clockwise it will tighten onto both the hose and the screw. A sealing system is used between the screw and the connector so that leakage does not occur. The sealing system is shown in detail in Figure 5.8. The entire assembly is shown in Figure 5.9.

Figure 5.7: Distributor with attached hoses.

Figure 5.8: Sealing system which connects the stud to the hose.
5.4.2. Experimental Results

A maximum forming pressure of 10,000 psi was set due to the limitations of the hoses. For safety purposes, a maximum pressure of 9,500 psi was used. Figure 5.10 shows the forming results from the experimentation. It can be seen that one lobe experienced more deformation than the other lobes. It was observed in the early stages of pressurization that this lobe was forming more rapidly than the others. This is likely caused by a larger gap between the slice and the solid tube which allowed for the fluid to easily cover the entire forming surface. Figure 5.10 (a) shows the outer view of the tubular structure with the studs most removed. The high arcs corresponding to the lobes coupled with the valleys from the weld provide a unique, complex geometry. Figure 5.10 (b) shows the deformation of the lobes toward the center of the cylinder. As predicted by the FEA results, formation in the bottom lobe is much greater than the outward portion of the lobe. With the end of the assembly cut off, the complete forming profile of the lobes can be seen. As shown in Figure 5.10 (c) the forming patterns of the lobes are relatively consistent with each other and a unique hollow structure is formed.
In order to accurately represent the experimental setup, a modified FEA model was created.
Instead of tying the nodes along a line to simulate the weld, a 3 mm surface is tied between
the two blanks in order to simulate the weld gap in the experiment. This provides more
realistic forming ratios and thinning percentages. Using the new model, the experimental
results show good agreement with the finite element simulations. The bottom portion of the
lobe exhibits the deep bulging in the center and flat section near the welds that was shown in
the FEA results. Figure 5.11 and Figure 5.12 show a comparison of the FEA model with the
experimental results. It can be seen that there is good agreement between the model and the workpiece in terms of deformation of the lobes.

![Comparison of the deformation of the body of the tube between the FEA results and the experiment.](image1)

Figure 5.11: Comparison of the deformation of the body of the tube between the FEA results and the experiment.

![Comparison of the deformation of the lobes between the FEA results and the experiment.](image2)

Figure 5.12: Comparison of the deformation of the lobes between the FEA results and the experiment.

To quantitatively validate the FEA model with the experiment, the major and minor diameter of each of the lobes is measured. Since the FEA model shows uniform deformation in each lobe, only one lobe is analyzed. The measured values are listed in Table 5.1. The largest
discrepancy occurs in the lobe that formed more rapidly than the others. However, it can be seen that there is a good agreement between the experiment and finite element analysis.

Table 5.1: Forming results comparison between experiment and FEA results.

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<th>$d_{\text{Major}}$ (mm)</th>
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<th>$d_{\text{Minor}}$ % Difference</th>
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<td>0.53</td>
<td>8.34</td>
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</tr>
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</tbody>
</table>

5.5. Conclusions

It is shown that die-less hydroforming is a viable and cheap process that is capable of producing complex geometries. The manufacturing aspects of die-less hydroforming present several challenges due to the combination of processes such as welding, cutting, and rolling that can be required to prepare the blank. Blank preparation is especially significant in this process as the initial shape and weld of the blanks determines the forming characteristics. Depending on the welding and preformed geometry of the blank, cycle time can be high for blank preparation in this process.

While there are several challenges, large scale production is still achievable with modern manufacturing equipment. Several different geometries are capable of being produced with a minimal amount of hydraulic and control equipment. The tubular geometry used for experimentation in this study could be prepared quickly with the use of robotic welding and cutting. Like other hydroforming processes, forming time is not a significant portion of the entire cycle.

The experimental trial confirmed the viability of die-less hydroforming as a process to create a unique work hardened structure. Furthermore, it is shown that the results from the
experiment match well with the FEA solutions allowing for deeper investigation into forming capabilities and geometry variations.
CHAPTER 6

CONCLUDING REMARKS AND FUTURE WORK

The analysis and experimental trials done for this study indicate that a new die-less hydroforming manufacturing process is feasible and can be advantageous to many industries. It has been shown that conventional hydroforming processes are limited by equipment, cost, and geometrical complexity of the part.

The die-less hydroforming process proposed in this study requires minimal equipment and can produce a wide variety of parts. A basic hydraulic pressurization system is all that is needed in order perform the die-less hydroforming process. The shape of the formed part is controlled through the blank preparation. Blank preparation includes cutting the blanks, welding them together, and providing an entrance for the fluid. It is critical that the blanks are precision welded so that fluid does not escape and cause a failure of the part. By welding the blanks together in different patterns, very different looking geometries can be produced.

A few of the possible geometries that could be produced through die-less hydroforming were introduced and organized into families. These geometries included fan like, circular, tubular, and arch like structures. The fan like geometry could be produced easily by blank sheet metal into the desired shape, welding along the edges, and pressurizing between the blanks. This produces a work hardened, hollow, and complex structure that cannot be produced through other forming operations. The circular family of geometries can be produced in a similar way, however the blank is cut into a flat circular shape. The arch geometry can be produced in a two stage hydroforming process without the need for bending or rolling the material into a tubular shape. This could be a huge benefit for the construction industry since bending and rolling is difficult for large diameter and long tubular structures. Also, the unique cross section and work hardening makes the arches formed from die-less hydroforming have a high strength to weight ratio.

Die-less hydroforming can be used to produce unique tubular structures which can improve upon current shell structures which require stiffeners for support. Different tubular
geometries are able to be produced by varying the welding pattern which attaches the two blanks. The forming of these structures is thoroughly investigated in this study.

Finite element analysis is used to determine the feasibility of the parts as well as a parametric design tool. In order to design the tubular parts for specific applications, the relationship between the deformed geometry and the initial conditions needs to be understood. The area between the welds which is subjected to the fluid pressure forms a circular like lobe which is used in this study to describe the formation of the part. Three tubular geometries are selected for design based on their lobe development: longitudinal lobes, circumferential lobes, and helical lobes. The geometry of these lobes is controlled by the welding pattern. FEA simulations are then performed on each of the three geometries. For each geometry, diameters of 30, 40, and 50 mm are used along with initial blank thickness of 1, 1.5, and 2 mm in order to provide the relationship between initial geometrical parameters with lobe formation. For each set of diameter and thickness, the pressure is iterated in a safe operating range. The formation of the lobes is described by measuring the major and minor diameter and creating a forming ratio. It is shown through the FEA simulations that there is a linear relationship between forming ratio, initial diameter, initial thickness, and pressure. Also it is shown that the thinning of the structure is linearly dependent on the initial geometry and thickness as well as the pressure. This linear relationship allows for a process window to be created easily through interpolation. With a developed process window, the forming pressure and forming ratio can be predicted for tubes of all sizes.

Finite element analysis is also used to verify the increase in strength to weight ratio of the die-less hydroformed structures versus a tubular blank. Each of the geometries was subjected to torsional loading, flexural loading, and compressive loading to determine how the tubes would respond to normal loading situations. The longitudinal lobe geometry was able to carry 135% more load at a 10 mm stroke than a tubular blank during compressive loading and 133% more load at a 3 mm stroke during flexural loading. The circumferential lobe geometry showed the same strength in bending and torsion, with a 250% higher torsional load carrying capacity than a tube blank at 17° rotation while carrying 174% more load at 3
mm stroke in compression. The helical lobe geometry showed excellent strength in compression and torsion, however had a different response to clockwise and counterclockwise applied torque in the torsion test. For a clockwise torque, the lobes begin to straighten out along the length of the tube and create an expanded radius which proved to be very resistant to torsion. A counterclockwise applied moment constricted the tube and decreased the diameter, in which case the load to failure was significantly lower yet still comparable to a tube blank. With a clockwise applied moment, the helical lobe geometry carried 150% more load than a blank tube at 8° while carrying 92% more load when a counter-clockwise moment was applied. For compressive loading, a 157% higher load carrying capacity was seen at a stroke of 6 mm.

Experimental trials proved the feasibility of the die-less hydroforming process and confirmed the finite element analysis. A longitudinal lobe geometry was produced by first cutting a blank tube into six slices then welding those onto a solid blank tube of 50.8 mm diameter and 2 mm thickness. A tube hydroforming hydraulic system was used to provide the fluid pressure and a unique pressure distribution and sealing system was designed to inject the fluid between the welded blanks. A pressure of 9,500 psi (65.5 MPa) was used to form the part. The lobe formation showed good agreement with the finite element solution, with the average difference in the major diameter being 4.2%.

The finite element analysis and the experimental trial were used to verify the feasibility of a die-less hydroforming process. The process can provide significant benefit to the metal forming industry by reducing cost and creating complex geometries that require several operations to form using other manufacturing techniques.

Since the die-less hydroforming process is just being introduced in this study, significant research can still be done to fully understand the process. In the immediate future, experimental trials can be performed on structures from each of the geometry families in order to determine feasibility and identify possible issues. Also, since it is established that there is a direct relationship between initial tube geometry and lobe formation, a more complete process window spanning sizes of tubes can be constructed to determine the
scalability of the die-less hydroforming process. Experimental trials can be done to verify the accuracy of the process window.

In order for this process to be viable to the metal forming industry, high volume manufacturability should be investigated. A heavy emphasis should be placed on identifying optimum blank cutting and welding techniques in order to reduce process cycle time.
REFERENCES


[Schuler] Schuler Hydroforming.  


APPENDIX A

Forming profiles for the longitudinal lobe geometry of varying diameter and thickness.
Longitudinal Lobe Forming Profile; $d_0=50\text{ mm}$, $t_0=1\text{ mm}$

- $65\text{ MPa}$
- $75\text{ MPa}$
- $85\text{ MPa}$
- $90\text{ MPa}$
- $95\text{ MPa}$

Longitudinal Lobe Forming Profile; $d_0=50\text{ mm}$, $t_0=1.5\text{ mm}$

- $65\text{ MPa}$
- $75\text{ MPa}$
- $85\text{ MPa}$
- $95\text{ MPa}$
- $105\text{ MPa}$
- $115\text{ MPa}$
- $125\text{ MPa}$
- $135\text{ MPa}$

Longitudinal Lobe Forming Profile; $d_0=50\text{ mm}$, $t_0=2\text{ mm}$

- $65\text{ MPa}$
- $75\text{ MPa}$
- $85\text{ MPa}$
- $95\text{ MPa}$
- $115\text{ MPa}$
- $130\text{ MPa}$
- $145\text{ MPa}$
APPENDIX B

Forming profiles for the circumferential lobe geometry varying diameter and thickness.

Circumferential Lobe Forming Profile
\( d_0 = 30 \text{ mm} \) \( t_0 = 1 \text{ mm} \)

Circumferential Lobe Forming Profile
\( d_0 = 40 \text{ mm} \) \( t_0 = 1 \text{ mm} \)

Circumferential Lobe Forming Profile
\( d_0 = 30 \text{ mm} \) \( t_0 = 1.5 \text{ mm} \)

Circumferential Lobe Forming Profile
\( d_0 = 40 \text{ mm} \) \( t_0 = 1.5 \text{ mm} \)

Circumferential Lobe Forming Profile
\( d_0 = 30 \text{ mm} \) \( t_0 = 2 \text{ mm} \)

Circumferential Lobe Forming Profile
\( d_0 = 40 \text{ mm} \) \( t_0 = 2 \text{ mm} \)
Circumferential Lobe Forming Profile

- **d₀=50 mm, t₀=1 mm**

- **d₀=50 mm, t₀=1.5 mm**

- **d₀=50 mm, t₀=2 mm**
APPENDIX C

Forming profiles for the helical lobe geometry of varying diameter and thickness.
Circumferential Lobe Forming Profile

\( d_0 = 50 \text{ mm} \) \( t_0 = 1 \text{ mm} \)

\( d_0 = 50 \text{ mm} \) \( t_0 = 1.5 \text{ mm} \)

\( d_0 = 50 \text{ mm} \) \( t_0 = 2 \text{ mm} \)
APPENDIX D

Python script used to generate datum points for the helical lobe geometry

```python
from abaqus import *
from abaqusConstants import *

Mdb()

rad = 20.0
zFactor = 2.0

mdb.Model('Model-1')
mySketch = mdb.models['Model-1'].ConstrainedSketch(name='__profile__', sheetSize=200.0)
mySketch.CircleByCenterPerimeter(center=(0.0, 0.0), point1=(rad, 0.0))

p = mdb.models['Model-1'].Part(name='Part-1', dimensionality=THREE_D, type=DEFORMABLE_BODY)
p.BaseShellExtrude(sketch=mySketch, depth=200.0)

xyz=
for i in range(101):
x = rad*cos(i/21.1)
y = rad*sin(i/21.1)
z = i*zFactor
xyz.append( (x,y,z) )

for i in range(101):
x = rad*cos(0.785398+(i/21.1))
y = rad*sin(0.785398+(i/21.1))
z = i*zFactor
xyz.append( (x,y,z) )

for i in range(101):
x = rad*cos(1.5708+(i/21.1))
y = rad*sin(1.5708+(i/21.1))
z = i*zFactor
xyz.append( (x,y,z) )
```

for i in range(len(xyz)):
dtm = p.DatumPointByCoordinate(coords=xyz[j])

for k in range(100):
w = k+2
e = k+3
mdb.models['Model-1'].parts['Part-1'].PartitionFaceByShortestPath(faces=
    mdb.models['Model-1'].parts['Part-1'].faces.getSequenceFromMask(['#1 '],
    ),
    point1=mdb.models['Model-1'].parts['Part-1'].datums[w], point2=
    mdb.models['Model-1'].parts['Part-1'].datums[e])

session.viewports['Viewport: 1'].setValues(displayedObject=p)
```