ABSTRACT

GIBSON, M. CHRISTOPHER. Investigation of Tube Hydroforming Process Envelope for Macro/Meso Scalability. (Under the direction of Dr. Gracious Ngaile.)

The tube hydroforming (THF) process requires the internal pressurization of a tube stock while the ends are axially fed inside a die cavity. As a result of this internal pressurization, the tube deforms to fill the die cavity. The objective of this study was to investigate the scalability of tube hydroforming and determine the potential for hydroforming at the micro and meso scales. This was accomplished by establishing trends which were identified at the macro scale and using these results to predict the formability at the meso and micro scale. To establish these trends, first the effect of material properties, tube geometries, die geometries, forming pressures and friction coefficients on the formability of the tubes was studied. From these results a pentagon die geometry was selected as the forming die, and stainless steel was selected as the tubing material for the scalability study. For the scalability study, five tube diameters ranging from 0.250 in to 2.250 in were selected. Tube thicknesses for each tube were scaled as a percentage of the outer tube diameter ranging from 1.25% to 5.00%. The forming operation was considered complete once the tube walled experience 20% thinning. For each simulation, the wall thickness and R/t ratio were calculated. The results from these simulations indicate that that trends exist in the formability of tubes as the scale of the tube is reduced. The forming pressures required to reach 20% thinning increased linearly as the tube wall thickness ratio was increased. The tube diameter did not impact the formability of the tube. The wall thickness percentage was shown to be the critical factor when changing the scale of tubes for hydroforming.

To verify the simulation results, experimental testing was performed. Because of the high forming pressures required for stainless steel tubing, copper tubing was used for the experimental testing. Both materials have an identical strain hardening exponent of 0.46, but the strength coefficient for copper is much lower than that of stainless steel. The results from the experimental testing, indicate that FEM can be used to predict the THF process. The measured tube thickness profiles align very consistently with the simulation results. There is an offset in most cases but this can be attributed to variation in tube tolerances due to the manufacturing process. The measured R/t ratios followed the trends of the simulation data, though there was a variation in the values. In all cases, the measured values from the experiment had a smaller corner radius than the simulated tubes. This is most likely a result of inaccurate material properties taken from the literature. The FEM simulations only considered plastic deformation. All elastic behavior was ignored.

The results from this study indicate that tube hydroforming is feasible on the micro and meso levels. However, there are still many issues which must be addressed in the manufacturing process, such as sealing techniques, alignment of the axial cylinders, and potentially high forming pressures as a result of tubes on the micro scale having higher wall thickness to diameter percentages.

INVESTIGATION OF TUBE HYDROFORMING PROCESS ENVELOPE FOR MACRO/MESO SCALABILITY

by

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CHAPTER 1

INTRODUCTION

1.1 Tube Hydroforming Introduction

Tube hydroforming (THF) is a manufacturing process in which a stock tube is internally pressurized while contained inside a die cavity. The tube plastically deforms to fill the cavity while axial compressive forces are used to simultaneously feed the tube end. The THF process overview is illustrated in Figure 1-1.

Figure 1-1: THF Process (adopted from [1])

To start the THF process, a blank tube is first placed into the tooling and the forming dies are closed. The tube ends are then sealed and the tube is filled with fluid. The

internal fluid pressure is increased, forcing the material into the deformation zone. While this occurs, axial feeding and the internal pressure are controlled to improve material shaping capabilities. Once forming is completed, the fluid is evacuated from the tube and the formed tube is removed from the tooling [1,2].

Using this process, parts with higher strength, lower weight, and lower cost can be produced. Many unique shapes can be formed that were previously only achievable by combining multiple metal working processes such as stamping and welding [3]. Large production volumes of the automotive industry promote innovation in the areas of new manufacturing processes to reduce cost. The low waste and high strength of the THF process make it desirable for high production manufacturing.

Figure 1-2: Hydroformed Exhaust Parts [4]

Typical forces employed during the THF process are illustrated in Figure 1-3.

Figure 1-3: Active Forces in THF (P_i =Internal Pressure, F_a =Axial Force, F_q =Counter Punch Force, R_c =Corner Radius, R_e =Fillet Radius) [5]

Typical THF materials include stainless steel, mild steel, copper, aluminum and brass. Other materials can be formed, but the work hardening of the material determines the formability of the tube. Depending on the application, the internal pressures can vary from 2000 bar (30ksi) to 10,000 bar (150 ksi) [5]. As important to the internal pressure is the pressurization profile of the process. The rate of change of the internal pressure is as important to the process as the absolute value of the pressure. Large strain rates begin to reduce formability when operations become too rapid in deformation.

Three primary modes of failure are observed in THF: buckling, wrinkling and bursting, Figure 1-4. Buckling of the tube occurs when too high an axial force is used at the beginning of the forming operation. Wrinkling occurs as a result over feed from the axial cylinders during the forming process. A minimum amount of axial force is required to seal the tubes ends during the forming process. Bursting occurs as a result of excessive thinning during the forming process [6].

Figure 1-4: THF Failure Modes [4]

The process window which results in forming parts without defects due to wrinkling, buckling, or bursting takes place in the shaded region of Figure 1-5.

Figure 1-5: THF Process Window (adopted from [7])

To prevent failure due to bursting, the forming is considered complete once the tube has experienced a set amount of thinning of the tube wall. For this study 20% thinning will be used for complete forming.

1.2 *Process parameters in THF*

1.2.1 Loading Paths

To accurately manufacture a part using the THF process, an appropriate loading path must be determined. The internal pressurization profile and the axial feeding of the tube ends must be specified and coordinated to ensure proper forming of the part. The internal pressure must be:

- High enough to prevent buckling due to excessive compressive axial force,
- High enough to start deformation of the tube walls (Typically the yield strength),
- High enough to allow the material to form into the die cavities (Dependent on ultimate tensile strength, corner radius and tube thickness),
- High enough to prevent the tube from wrinkling as a result of high compressive axial force
- Low enough to prevent the tube from bursting [8].

Currently much research is being done to accurately define appropriate internal pressurization profiles for the THF process. These methods include analytical models, FEM, and trial and error approaches. Because of the unique and complex parts manufactured in the THF process, analytical models and FEM are limited in their ability to predict internal forming pressures. However, these methods have proven helpful during the design process.

In conjunction with the pressurization profile, the axial compressive force on the tube ends must be considered. The requirements for the axial cylinders are that they:

- Seal the ends of the tube to counteract the internal pressure applied to the tube walls,
- Provide enough force to overcome the frictional forces between the die and tube walls,
- Feed the tube with enough force to provide plastic deformation to the tube walls, and
- Act in coordination with the internal pressurization to ensure the tube is properly formed [8].

During the forming process, axial force must be continuously applied to the tube ends to prevent excessive thinning by moving additional material into the expansion region. If the initial force applied to seal the tubes ends is too high, buckling occurs. When the tube is fed at too high a rate during the forming process, tube wrinkling occurs. If the tube feed rate is not high enough, excessive tube thinning will occur resulting in tube bursting.

Figure 1-6 illustrates an example loading path for the THF process. The internal pressurization is shown in blue, and the clamping load is shown in green. During the filling phase, the load on the axial cylinders remains constant to keep the tube ends sealed. After the tube is filled, the internal pressure increases to form the tube. The clamping load is also increased to feed the tube during the forming process.

Figure 1-6: Loading Path (adopted from [2])

1.2.2 Tube Materials

To accurately predict forming in the THF process, the material properties of the tube must be known. Limited data exist for the material properties of tubes used in THF. Some designers currently use material properties from the flat sheet from which the tube is rolled. However during the rolling, welding, and sizing operations the formability and the stress-strain behavior of the tube changes from those of the original flat sheet. A typical method for evaluating the material properties is the tensile test. This test applies a uni-axial loading to the tube. The THF process places the tube under biaxial or tri-axial stress [9]. Using the uni-axial material definition for bi-axial forming can lead to inaccuracies in FE results. The material properties of a rolled tube depend on the material composition, the rolling process, and the state of the heat treatment. Small differences among these factors can lead to large differences in the forming operation.

To accurately determine the material properties for THF, free expansion testing is completed. This process involves plastically deforming a tubular specimen, analytically determining the material properties, and using computer simulations to refine the analytically determined values. This method can be used to determine the stress-strain parameters for a tube of a given size and material subject to bi-axial loading. The deformation of the tube is completed by bulging the tube with internal pressure. The required pressure depends on the strength of the material and the thickness of the tube. The tube is placed into the bulging apparatus, and internal pressure is applied until the tube is bulged to a pre-determined height. Once forming is completed, the tube measurements are recorded and the flow stress, initial yield stress (σ_0), strength coefficient (K), and strain hardening exponent (n) are calculated [10].

1.2.3 Tribological Aspects in THF

Friction is also an important variable in the hydroforming process. In modeling the THF process, Coulomb friction is frequently used. Three zones of friction characteristics have been identified in the hydroforming process. These are the guided, transition and expansion zones. An illustration of the three friction zones are shown in Figure 1-7.

Figure 1-7: Three Friction Zones in the Tube Hydroforming Process [11]

The guided zone is the area where the tube is fed through the die by the axial cylinders. Full contact between the tube and the die are maintained throughout this zone. Material deformation is limited to wall thickening as a result of the compressive axial force applied to the tube ends.

The expansion zone is the region where the material forms to the die geometry. Each zone experiences different friction characteristics during the forming operation. The three major parameters affecting the friction coefficient are the tube material, the die material and die surface characteristics, and the lubricant. [12]

1.3 FEA Modeling of Tube Hydroforming

Finite element Analysis (FEA) has been used for years by the metal forming industry. Three dimensional simulations give more accurate results, but two dimensional simulations are simple to use and effective in producing accurate

results for basic simulations. Recently two dimensional simulations have been used in predicting the forming characteristics in the THF process. Experiments performed by Koc and Altan show that the 2D FEA simulation results for the expansion and calibration zones are in good agreement with experimental outcomes [13]. Hwang and Chen performed similar experiments, comparing the forming pressures and forming results between FEA simulations and experimental measurements for tube expansion in a square die [14]. The latter simulations were performed using the commercially available Finite Element code DEFORMTM 2D.

Experimental results performed by Kridli et al., were compared to 2D simulations performed using ABAQUS/Standard®. These experiments validated the FEA simulations that were performed prior to testing, when the eccentricity of the tube circumference along the tube length was mapped into the FEA model [15]. Using results from previous research indicates that the use two dimensional FEA is adequate for predicting hydroforming for pure expansion.

1.4 Effect of Scale on Formability and Friction

The effect of miniaturization on flow stress was investigated using geometrically similar tensile and upsetting tests. These experiments demonstrated that the flow stress decreases as the scale of the part decreases. This is a result of the '*Surface Layer Model*' shown in Figure 1-8. This model is based upon the fact that at small scales, the material can no longer be considered a homogenous continuum. This is a result of the ratio of the grain size to the billet dimension. The percentage of

grains on surface layer become high when compared to the volume grains. Figure 1-9 illustrates the decreasing flow stress as the scale is reduced [16,17]

Figure 1-8: Relationship between Surface and Volume Grains as Scale is Reduced [16]

Figure 1-9: Flow Stress as Scale is Reduced [17]

Frictional effects of scale were investigated by Geiger et al. using a ring test. The results from these tests are shown in Figure 1-10. As the scale of parts is reduced, the Coulomb friction coefficient (μ) increases. This is a result of the contact area of the large grain size in the small specimen during the forming process. In the small specimens, the ratio of closed lubricant pockets to open lubricant pockets is very low resulting in higher friction coefficients.

Figure 1-10: Effect of Coulomb's Friction as Scale is Reduced [17]

1.5 Potential for Tube Hydroforming at the Micro / Meso Scale

Macro scale tube hydroforming is widely used in commercial manufacturing, however limited research has been conducted on the feasibility of forming at the micro and meso scales. Current trends in miniaturization indicate probable requirements for smaller scale THF in the electronic, biomedical, telecommunications, and avionics industries. Possible uses within these fields include micro scale fuel cells, micro pumps, micro chemical reactors, micro nozzles, etc. The high dimensional accuracy possible with tube hydroforming lends itself to applications where multi-scale technology is applied. Multi-scale technologies include processes where the overall scale and the scale of features of the individual products are different. THF devices have high dimensional accuracy, which allows for interface with micro scale devices, thus avoiding the requirements for MEMS type fabrication.

CHAPTER 2

OBJECTIVE AND APPROACH

2.1 Objective

The objective for this study was to investigate the scalability of tube hydroforming and determine the potential for hydroforming at the micro and meso scales. Previous research has shown that material properties, tube geometries, die geometries, forming pressures and friction coefficients can affect the formability of the tube. The goal of this effort is to establish trends in the formability of tubes in the macro scale and use these trends to predict the formability for tubes in the micro and meso scales.

2.2 Approach

The finite element method (FEM) was used to study the influence of material properties, tube and die geometries, forming pressure and interface friction on formability. The tube mesh was created using quad 4-node elements. Each tube was meshed with a minimum of four elements across the tube wall thickness, with nodes spaced in a uniform radial distribution. Plane strain, Figure 2-1, was assumed with coulomb friction prescribed at the tool-workpiece interface. The region of the formed tube has a length of 4 in.

Figure 2-1: Plane Strain Assumption [18]

Internal hydraulic pressure was applied as a distributed normal force on the internal surface. Symmetry was used where possible to reduce simulation runtime and data analysis requirements.

The following assumptions were made for all FEM simulations:

- The tube is a perfect cylinder with uniform wall thickness,
- The tube material is isotropic,
- The dies are completely rigid, and
- The coefficient of friction is constant along the tube wall, die contact regions [15].

As the objective of this study was to investigate the scalability of tube hydroforming, formability and scaling must be defined. Figure 2-2 illustrates examples of a Macro scale THF part, a Meso scale THF part, and a Micro scale THF part.

Figure 2-2: Macro / Meso / Micro Scaling for a THF Part

For the purpose of this study, formability of a THF part is defined as the ability of a part to completely fill the die cavity without experiencing failure due to excessive thinning. To quantify the formability of a part, the R/t ratio once the part has reached 20% thinning is used, Figure 2-3. This value is the ratio between the formed corner radius, and the initial tube thickness. The industry standard for complete forming is in the range of $R/t = 2$ to 3 [15,19]. This R/t ratio has been established through a trial and error approach. The goal of this research is not necessarily to improve upon these forming ratios, but to determine trends related to tube geometries. A part that has formed to this R/t ratio while remaining at or below 20% thinning is deemed to have sufficiently filled the corner without significantly weakening.

Figure 2-3: Definition of Nomenclature to Define Formability

To quantify the formability of the formed part, the following terminology is used: D = initial tube outer diameter, t_0 = the initial tube wall thickness, R = the minimum corner radius formed, $t_{\max}$ = location of maximum tube thinning. Using these parameters

the following ratios are defined: $\frac{R}{t} = \frac{R}{t_{\max}}$, and $t_d = \frac{t_0}{D}$. These two ratios are used

throughout this scalability study.

Formability was studied by observing the following parameters:

- (1) Variation of tube to diameter ratios (t_d) vs. pressure loading path for different friction values, die geometries and tube materials.
- (2) Tube wall thinning vs. pressure loading profile for different friction values, die geometries, and materials.
- (3) Radius to thickness (R/t) ratio vs. pressure loading profile for different tube to diameter ratios (t_d).
- (4) Pressure loading path vs. tube outer diameter for different t_d ratios.
- (5) Pressure loading path vs. tube wall thickness.
- (6) Radius to thickness ratio (R/t) vs. tube to diameter ratios (t_d).

CHAPTER 3

TOOLING GEOMETRY DETERMINATION FOR MACRO/MESO SCALABILITY STUDY

3.1 *Introduction*

The first step in this investigation was to determine an acceptable die geometry, tube material, and friction coefficient to use in the scalability study. After completion of these simulations, a single die geometry, tube material and friction coefficient were selected for the scalability simulations. A broad range of initial simulations were performed to generate data, which could be used to refine the simulation matrix so the formability trends could be established.

3.2 *FEA Simulation Parameters for Geometry Determination*

In order to determine the necessary range of parameters to be included in the scalability study, an initial set of simulations was performed. For these initial simulations, several tube materials, tube diameters, and tube walls thicknesses were selected. Stainless Steel SS304, Aluminum 6061, and 1008 Steel were selected as the three tube materials. For each material, tubing with outer diameters of 1.00 in and 2.0 in were chosen. Two tube thicknesses of 0.035 in, and 0.065 in were selected. With the tubing dimensions established, the potential die geometries could be evaluated. The purpose of the first set of simulations was to determine the

impact of corner angle, corner radii, tube/die interface friction, tube material and tube thickness and their effects on formability.

The three different tube materials used for this study were selected because they are widely used in industry. It should be noted, however that these materials have different formabilities. It is common to express flow stress of a material using the power law

$$\sigma = k \cdot \epsilon^n \text{ - Equation: 3-1,}$$

where k is the strength coefficient, n is the strain hardening coefficient, and epsilon is the strain. The higher the value of n indicates better formability. Typical values for k and n for Aluminum 6061, 1008 Steel and Stainless Steel 304 are given in Table 3-1.

Table 3-1: Strength Coefficients (K) and Strain Hardening Exponents (n) for Materials used in Scalability Study

Material	k (MPa)	n
Aluminum 6061	410	0.05
Steel 1008	610	0.20
Stainless Steel SS304	1275	0.45

To determine the optimum geometry for the tooling, three geometries were chosen for the simulations: a square die, a trapezoid die, and a pentagon die. Geometry one, shown in Figure 3-1 is a square die. This geometry was chosen as a baseline configuration with which the other geometries could be compared. Geometry two shown in Figure 3-2 is a symmetrical pentagon shaped die. The angles between the walls of the die are 120° .

Figure 3-1: Square Tooling

Figure 3-2: Pentagon Tooling

Geometry three shown in Figure 3-3 is a trapezoid die with corners of 85°, 87.5°, 92.5°, and 95°. This design was selected to investigate the effect of corner angles on the corner radii, and tube thinning.

Figure 3-3: Trapezoid Tooling with 4 Unique Angles

Simulation matrices, which were then designed incorporate each material, tube outer diameter, tube thickness, die geometry and friction coefficients of $\mu = 0.05$, 0.15 , and 0.25 . The simulation matrix for Aluminum 6061 is shown in Table 3-2. Identical simulation matrices were created for Stainless Steel SS304, and Steel 1008.

Table 3-2: Sample Simulation Matrix

Material	Geometry	Diameter (in)	Thickness (in)	Friction Coefficient μ
Aluminum 6061	g1	2	0.035	0.05
				0.15
				0.25
			0.065	0.05
				0.15
				0.25
		1	0.035	0.05
				0.15
				0.25
			0.065	0.05
				0.15
				0.25
	g2	2	0.035	0.05
				0.15
				0.25
			0.065	0.05
				0.15
				0.25
		1	0.035	0.05
				0.15
				0.25
			0.065	0.05
				0.15
				0.25
	g3	2	0.035	0.05
				0.15
				0.25
			0.065	0.05
				0.15
				0.25
		1	0.035	0.05
				0.15
				0.25
			0.065	0.05
				0.15
				0.25

A linear pressure curve was used with a forming time of 10 seconds to reach 20,000 psi. Using the approach outlined in Chapter 2, the initial simulation matrix was completed for the three materials for a total of 108 simulations. The results from these initial simulations were then analyzed and the final parameters for the scalability study were chosen based on these results.

3.3 *Simulation Procedures*

Geometries for FEA models were first prepared using AutoCAD®. The tube designs were then imported into ANSYS® for meshing using quad 4-node elements. Each tube was meshed with a minimum of four elements across the tube thickness, and a uniform radial distribution. The forming process was simulated using the commercially available FEA code DEFORM™ 2D. An example of a meshed tube and the workpiece geometry is shown in Figure 3-4. For the square die simulations, one quarter of the tube was modeled. For the pentagon simulations, one half of the tube was modeled. The entire tube was modeled for the trapezoid die because no symmetry exists in the trapezoid.

Figure 3-4: Square Tooling Mesh (D=2, t=0.035)

After creation of appropriate boundary conditions, each simulation was set up to run 1,000 steps with a linear change in pressure at each time step. Results were recorded every 10 steps for a total of 100 data points, the results are shown in Figure 3-5. The 1,000 time steps were set up to occur over a process time of 10 seconds.

Figure 3-5: Tube forming at various steps in 108° Pentagon corner

Tube thinning was calculated by tracking the nodes along the inner and outer surfaces of the tube. Using nodes which lay on a path perpendicular across the tube wall, the tube thickness was calculated along the tube diameter. Nodes are selected along the outer surface of the tube from the location in which the tube first contacts the die wall until the second location of contact, spanning the entire corner to be filled as shown in Figure 3-6.

Figure 3-6: Point Tracker

The node locations were then exported for each recorded time step and the percent thinning from the initial thickness is calculated. The maximum wall thickness is then used to determine where the simulation reaches the predetermined formability limit of 20%.

The corner radius of the formed tube was calculated by extracting three points along the outer curvature of the tube as shown in Figure 3-7. Using these three points, the

corner radius of the formed part is calculated. The location of maximum thinning at 20% is then used to determine the minimum formed corner radius of the tube.

Figure 3-7: Corner Radius Node Extraction

To better visualize the forming process, the calculated R/t ratio and tube thinning are plotted versus the forming pressure as shown in Figure 3-8. The tube thinning indicates the completeness of the forming. Once the 20% thickness reduction is reached, the forming can be considered complete. The linear pressure profile allows the pressure to continue to rise beyond the established forming limit. As seen in the forming plot, the thinning curve remains at zero for a period of time, until the pressure reaches the yield stress of the tube. Once the forming begins, thinning initially occurs very rapidly and slows as the forming progresses. Plotting these curves, allows the relationship between the forming and thinning to be established.

Figure 3-8: R/t and Percent Thinning vs. Pressure

Figure 3-10 shows that wall thinning reaches 20% at a pressure of approximately 80,000 psi. At this point, the R/t ratio was calculated to be 2.78. The R/t and pressure at 20% thinning were extracted for each simulation performed.

3.4 FEA Simulation Results and Discussion

After completion of the simulations from the Simulation Matrix shown in Table 3-2, data extraction and analysis was completed to determine the minimum corner radius formed at 20% thinning. To determine these values, the R/t ratio and tube thinning percentages were plotted versus the pressure in the same manner shown in Figure 3-8. These plots were generated for each of the 108 simulations, and the corner

radius at 20% thinning were determined when possible. Because of the linear pressure profile from 0 to 20,000 psi, not all of the simulations reached 20% thinning. In these cases, the percent thinning and corner radius were taken at the final time step. The results for the three materials: Aluminum 6061, Steel 1008, and Stainless Steel SS304 are discussed below. For each material simulated, the results were grouped using the tube geometry and friction coefficient. The results were then plotted to produce a direct comparison between the three die geometries. From these results, a single die tooling geometry and tube material were selected for the scalability simulations.

3.4.1 Forming Characteristics of Aluminum 6061 Tubing

A total of 36 simulations were completed which, resulted in 12 plots comparing the three die geometries. The first example is shown in Figure 3-9.

Figure 3-9: R/t and Percent Thinning for Aluminum Tubing

From this plot (D=2 in, t=0.035 in, $\mu=0.15$) the R/t ratios at 20% thinning were extracted for the three die geometries. The R/t ratio for the Square die geometry was estimated to be 9.83, for the Pentagon die geometry was estimated to be 3.54, and for the Trapezoid die geometry was estimated to be 15.22. These trends were similar for each of the tubing geometries and friction coefficients for the Aluminum 6061. The forming simulations completed in the pentagon tooling demonstrated significantly less thinning than those completed in either the trapezoid or the square

tooling. The limiting factor in the thinning of the trapezoid tooling was the 85° corner. The pentagon also showed less variation between the two tube diameters and tube thicknesses. For the square tooling simulations, the R/t ratios ranged from 3.20 (D=1.0 in, t=0.065 in, $\mu = 0.05$) to 10.13 (D=2.0 in, t=0.035 in, $\mu = 0.15$) both at 20% thinning. The trapezoid tooling simulations ranged from 3.33 (D=1.0 in, t=0.065 in, $\mu = 0.05$) to 15.22 (D=2.0 in, t=0.035 in, $\mu = 0.15$) both at 20% thinning. The pentagon tooling simulations ranged from 1.97 (D=1.0 in, t=0.065 in, $\mu = 0.05$) at 18.8% thinning to 4.24 (D=2.0 in, t=0.035 in, $\mu = 0.15$) at 20% thinning.

For each die geometry simulated using the aluminum tubes, the smaller diameter tubes formed to a smaller R/t ratio. The tubes with the thicker walls also formed to a smaller R/t ratio. The coefficient of friction had minimal impact on the final corner radii. In most cases, the lower coefficient of friction resulted in smaller R/t ratios. The effect of the friction coefficients could not easily be determined because of non-optimized forming curves.

3.4.2 Forming Characteristic of Steel 1008 Tubing

The results from the Steel 1008 simulations were analyzed in a similar fashion to those of the Aluminum. Thirty-six simulations were completed using the Steel 1008; these results were grouped into 12 sets directly comparing the three die geometries. The first example is shown in Figure 3-10.

Figure 3-10: R/t and Percent Thinning for Steel Tubing

Because the initial forming pressure was limited to 20,000 psi, not all of the simulations using the Steel reached the forming limit of 20% thinning. In these cases the result was taken at the final time step. For the plot shown in Figure 3-12 (D=1.0 in, t=0.035 in, $\mu=0.05$) the R/t ratio for the Square die geometry was estimated to be 4.78 at 20.0% thinning, for the Pentagon die geometry was estimated to be 3.74 at 15.7% thinning, and for the Trapezoid die geometry was estimated to be 5.83 at 20.2% thinning. Although not all of the simulations were completed to the 20% thinning point, the trends between the die geometries could still easily be seen by comparing the forming curves. The R/t curves were very

similar, but the percent thinning curves differed greatly among the three die geometries.

The thinning in both the square and the trapezoid dies occurred at much lower pressures than in the pentagon tooling. The trapezoid tooling was again limited by the 85° corner. Because many of the simulations using the Steel 1008 did not reach the 20% thinning mark, a range of R/t ratios for the three die geometries could not be predicted. The same trends in tube diameter, and tube thickness appeared in the Steel simulations as appeared in the aluminum simulations. The smaller diameter tubes formed to a smaller R/t ratio, while the tube with the thicker walls formed to a smaller R/t ratio. The coefficient of friction did impact the R/t ratios, but once again the severity of the impact could not be determined because of non-optimized forming curves.

3.4.3 Forming Characteristics of Stainless Steel (SS304) Tubing

The results from the Stainless Steel SS304 were analyzed in the same manner as the Aluminum and the Steel. Thirty-six simulations were completed. The simulations were again grouped into 12 sets to make a direct comparison among the same tube geometries, and friction coefficients in the different die geometries. An example plot for the Stainless Steel SS304 is shown in Figure 3-11.

Figure 3-11: R/t and Percent Thinning for Stainless Steel Tubing

The forming did not reach the 20% thinning mark for all of the simulations performed using the Stainless Steel, at the maximum pressure of 20,000 psi in the linear pressure forming profile. In these cases, the last time step was used to report the R/t ratio. The results for the simulations seen above in Figure 3-11 (D=2.0 in, t=0.065 in, $\mu = 0.15$), the R/t ratio for the Square tooling was 5.56 at 19.7% thinning, for the Pentagon tooling was 5.32 at 12.1% thinning, and for the Trapezoid tooling was 7.22 at 20% thinning.

The trends among the three geometries were most obvious in the simulations involving the Stainless Steel SS304. The trapezoid tooling was once again limited

by the 85° corner. The pentagon tooling significantly outperformed both the square and the trapezoid tooling. The smaller tube diameters and larger wall thicknesses once again produced the smaller R/t ratios. The coefficient of friction had a more noticeable effect on the forming in the Stainless Steel SS304 results, but due to incomplete forming the amount, of the effect cannot be quantified.

3.5 *Influence of Friction on Thinning and R/t Ratio*

The next variable to be considered was the coefficient of friction. For these simulations, interface friction between the tube and the die is a limiting factor in the forming. The friction restricts the tube from redistributing around the circumference of the tube. Previous lubrication experiments conducted by Ngaile, Jaeger and Altan and the ERC/NSM utilized a “pear” shaped die to perform lubrication experiments [20,21]. These experiments consisted of a circular cross section die with a single corner to study formability resulting from the ability of the tube to “bulge” into the corner without suffering failure from excessive thinning. In the pear shaped testing at the ERC/NSM, the higher the friction, the shorter the bulge height that formed. Thinning occurs sooner due to the lack of new material to feed into the corner cavity. For this study three frictions coefficients of $\mu = 0.05, 0.15, \text{ and } 0.25$ were used. The friction factor did impact the amount of forming which occurred at the macro scale. This is shown in Figure 3-12.

Figure 3-12: R/t and Percent Thinning for Stainless Steel Tubing in a Square Die

From this Figure it is seen that at 20% thinning, the R/t ratio at $\mu = 0.05$ was approximately 8.59, at $\mu = 0.10$ was approximately 10.35, and at $\mu = 0.25$ was approximately 10.86. The effect of friction appeared to be consistent throughout the study. These results correspond to the finding by Hwang [19] in his analysis on the effect of friction on THF. As the coefficient of friction increases, formability is restricted. With respect to scalability, the impact of the friction coefficient is beyond the scope of this investigation; therefore a constant coefficient of friction of $\mu = 0.15$ was chosen for the next set of simulations.

3.6 Influence of Tube Materials on Thinning and R/t Ratio

The simulation results presented in section 3-4 were re-grouped to plot the forming results for the same tube geometries and the pentagon tooling for the three materials. An example of these plots is shown in Figure 3-13.

Figure 3-13: R/t and Percent Thinning for Stainless Steel Tubing in a Pentagon Die

From these plots it was determined that the stainless steel showed the most favorable thinning behavior. Because of this, more complete forming could occur resulting in a lower R/t ratio. For this reason, Stainless Steel SS304 was chosen to continue for the scalability simulations.

3.7 Influence of Tube Geometry on Thinning and R/t Ratio

The final determination for the scalability study was the geometry of the tubes. The tube geometries for the initial simulations were selected because they were available as standard sizes. The wall thickness of the tube has an important role in the amount of forming that can occur. A thicker tube has more material available for forming which reduces the severity of the thinning. A side effect of a thicker tube is that a higher forming pressure is necessary to complete forming. The effect of wall thickness on formability is shown in Figure 3-14.

Figure 3-14: R/t and Percent Thinning for Stainless Steel Tubing in a Square Die

The plot above demonstrates that the thicker-walled tube experiences less thinning and therefore reaches a smaller R/t ratio. This was an expected result and was consistent for all tube and die geometries.

To better establish the trends between the tube diameter and thickness on corner radius, additional simulations need to be completed with additional diameters and thicknesses. To better investigate the scalability of the THF process, outside tube diameters were chosen based on readily available tube sizes. The tube wall thicknesses were chosen based on a fixed tube wall thickness to outer diameter percentage (t_d). The material, friction coefficient, and relative die geometry were held constant for each simulation. The die geometry was scaled for each tube outer wall diameter. The detailed parameter selection for the scalability simulations are explained in greater detail in the next chapter.

3.8 Conclusions

After complete analysis of the results from the original simulation matrix in Table 3-1, the parameters for the scalability study were determined. Analyzing the results from these initial studies, indicate that the pentagon tooling resulted in more complete forming with respect to R/t ratio. This was seen for all three materials analyzed: Aluminum 6061, Steel 1008, and Stainless Steel SS304. This was a result of the greater corner angle of the pentagon die geometry compared to the square and trapezoid dies. Of the three materials studied, the Stainless Steel SS304 had the best forming characteristics followed by the Steel 1008 and Aluminum 6061. This

was expected because the strain hardening exponent for the Stainless Steel SS304 is significantly higher than those of the other two materials. The coefficient of friction affected the tube formability with the lower coefficient resulting in better forming. The variation in forming due to friction was determined to be insignificant for this study, so $\mu = 0.15$ was selected for future simulations. The original tube geometries were chosen because they were readily available for purchase. After analyzing the results, it was determined that additional simulations are required to define a trend for tube scalability.

CHAPTER 4

INFLUENCE OF TUBE GEOMETRY, MATERIAL PROPERTIES, AND PROCESS PARAMETERS ON TUBE HYDROFORMING SCALABILITY

4.1 Introduction

Using the results from the initial simulations, discussed in Chapter 3, parameters for the scalability simulations were determined. The results from the scalability study will be used to establish trends in THF forming parameters as the scale of the tube is reduced.

4.2 FEA Simulation Parameters

4.2.1 Tube Geometries

The tube outer diameters chosen for the simulations were 2.250 in, 2.000 in, 1.000 in., 0.625 in, and 0.250 in. These five diameters are commonly available tube sizes and are expected to provide enough information to predict a trend for miniaturization. The four larger diameters are considered macro scale, while the smallest is considered meso scale. The purpose of simulating the four large diameters when the goal of the study is on meso scale is to prepare for future experimentation on the macro level for validation of the FEA findings. The tube wall thickness to diameter ratios chosen for the study were 1.25%, 2.50%, 3.75% and 5.00%, which represent a selection of thin-walled tubing. With the chosen tube diameters and t_d ratios, the simulation matrix shown in Table 4-1 was created.

Table 4-1: Simulation Matrix

Stainless Steel 304			
Name	D (in)	t/D	t (in)
SS01	2.250	5.00%	0.113
SS02	2.250	3.75%	0.084
SS03	2.250	2.50%	0.056
SS04	2.250	1.25%	0.028
SS05	2.000	5.00%	0.100
SS06	2.000	3.75%	0.075
SS07	2.000	2.50%	0.050
SS08	2.000	1.25%	0.025
SS09	1.000	5.00%	0.050
SS10	1.000	3.75%	0.038
SS11	1.000	2.50%	0.025
SS12	1.000	1.25%	0.013
SS13	0.625	5.00%	0.031
SS14	0.625	3.75%	0.023
SS15	0.625	2.50%	0.016
SS16	0.625	1.25%	0.008
SS17	0.250	5.00%	0.013
SS18	0.250	3.75%	0.009
SS19	0.250	2.50%	0.006
SS20	0.250	1.25%	0.003

These simulations are expected to allow the trends in formability to be established. By scaling the tube wall thickness to a ratio of tube diameter, the pressures should remain constant to accomplish the same amount of forming. This is predicted as a result of the hoop stress theory for thin walled tubes. Hoop stress is defined in a thin walled cylindrical pressure vessel as:

$$\sigma = \frac{pr}{t} \quad \text{substituting } t_d \% \text{ leaves } \sigma = \frac{p}{2t_d} = \frac{1}{2t_d} p = \alpha \cdot p \quad \text{- Equation 4-1}$$

where, σ is the hoop stress, p is pressure, r is the cylinder radius, and t is the cylinder wall thickness.

The constant t_d percentage, along with similar process stress levels, create unvarying forming pressures for each $t_d\%$. The thicker the tube walls, the higher the pressure necessary to form the cross-section. Scaling the dimensions evenly changes the volume to surface ratio along the inside of the tube potentially creating trends which are not completely intuitive.

4.2.2 Material Properties Determination

Because of the better forming characteristics, the pentagon die geometry was chosen. Stainless steel 304 was chosen for the material due to its superior forming characteristics. As discussed in Chapter 3, the strain hardening coefficient has a large influence on formability. It was also noted that the strain hardening coefficient, n , of Stainless Steel SS304 is 0.46. It should be noted that the flow stress of a material can also be represented as:

$$\sigma = c \cdot \dot{\epsilon}^m \cdot \bar{\epsilon}^n \text{ - Equation 4-2}$$

where c is the strength coefficient, $\dot{\epsilon}$ is the effective strain rate, m is the strain rate hardening index, $\bar{\epsilon}$ is the effective strain, and n is the strain rate hardening index. The strain rate hardening index is normally small for cold forming. However, if the strain rate is very high, the effect of strain hardening index can be significant on the flow characteristics of the material.

4.2.3 Process Parameter Determination

The pressure forming curve for each simulation was optimized to ensure that all of the tubes were able to form past the 20% thinning limit. The pressurization profile for these simulations must be chosen carefully as unrealistic pressurization profiles can easily be simulated. The pressure profile remained linear for the scalability simulations. The deformation of the tube in the experimental THF process requires additional fluid to fill the larger volume. As a result, the flow rate of the THF equipment restricts the speed at which the pressurization occurs. Initial simulations demonstrated that it was possible to reach strain rates which severely alter the results. Using the previous simulation results, the pressure profiles were modified to ensure that the maximum forming pressures simulated were sufficient for complete forming, but not in excess of those required to produce 20% thinning.

4.3 FEA Simulation Results

4.3.1 Thickness to diameter ratio of 5.00%.

After completion of the simulation matrix shown in Table 4-1, results were extracted for each simulation according to the simulation procedures developed in Chapter 3. For each t_d percentage, the R/t ratios and percent thinning were plotted versus the pressure for each diameter tube. In Figure 4-1, the plots for $t_d = 5.0\%$ are shown.

Figure 4-1: R/t and Percent Thinning vs. Pressure for $t_d = 5.0\%$

From these plots, it can be seen that the scaling process does not significantly affect the formability of the tube. For the five different tube diameters with a tube wall thickness to diameter ratio of 5.0%, the curves produced are effectively identical. For these five tubes, the forming is completed at 20% thinning at a pressure of approximately 81,000 psi resulting in an R/t ratio of approximately 2.76. The material begins to yield at a forming pressure of approximately 8,000 psi. Calculating the hoop stress results in a yield strength of approximately 80 ksi for this tube.

4.3.2 Thickness to diameter ratio of 3.75%.

In Figure 4-2, the R/t ratio and percent thinning values were plotted versus the forming pressure for the tubes with a t_d value of 3.75%.

Figure 4-2: R/t and Percent Thinning vs. Pressure for $t_d = 3.75\%$

The curves for the $t_d = 3.75\%$ are also nearly identical for each of the five different tube diameters. For these five tubes, the forming is completed at 20% thinning at a pressure of approximately 68,000 psi resulting in an R/t ratio of approximately 3.13. The tube begins to yield at a forming pressure of approximately 6,000 psi. Calculating the hoop stress results in a yield strength of approximately 80 ksi for this tube.

4.3.3 Thickness to diameter ratio of 2.50%.

In Figure 4-3, the R/t ratio and percent thinning values were plotted versus the forming pressure for the tubes with a t_d value of 2.50%.

Figure 4-3: R/t and Percent Thinning vs. Pressure for $t_d = 2.5\%$

The curves for the $t_d = 2.5\%$ are also nearly identical for each of the five different tube diameters. For these five tubes, the forming is completed at 20% thinning at a pressure of approximately 40,000 psi resulting in an R/t ratio of approximately 3.46. The tube begins to yield at a forming pressure of approximately 4,000 psi. Calculating the hoop stress results in a yield strength of approximately 80 ksi for this tube

4.3.4 Thickness to diameter ratio of 1.25%.

In Figure 4-4, the R/t ratio and percent thinning values were plotted versus the forming pressure for the tubes with a t_d value of 1.25%.

Figure 4-4: R/t and Percent Thinning vs. Pressure for $t_d = 2.5\%$

The curves for the $t_d = 1.25\%$ are also nearly identical for each of the five different tube diameters. For these five tubes, the forming is completed at 20% thinning at a pressure of approximately 17,000 psi resulting in an R/t ratio of approximately 6.63. The tube begins to yield at a pressure of approximately 2,000 psi. Calculating the hoop stress results in a yield strength of approximately 80 ksi for this tube.

4.4 Influence of t_d on Wall Thinning and Forming Pressure

The results for all the simulations are shown in Table 4-2. The values for pressure and R/t ratio were interpolated to normalize all the values around a wall thinning percentage of 20.0%.

Table 4-2: Simulation Results at 20.0% Thinning

Stainless Steel 304						
Name	D (in)	t_d (%)	t (in)	% Thinning	Pressure (Psi)	R/t
S01	2.250	5.00	0.113	20.0%	80098	2.78
S02	2.250	3.75	0.084	20.0%	68228	3.14
S03	2.250	2.50	0.056	20.0%	39248	3.54
S04	2.250	1.25	0.028	20.0%	16941	6.71
S05	2.000	5.00	0.100	20.0%	80505	2.78
S06	2.000	3.75	0.075	20.0%	68504	3.13
S07	2.000	2.50	0.050	20.0%	39727	3.47
S08	2.000	1.25	0.025	20.0%	16869	6.74
S09	1.000	5.00	0.050	20.0%	81793	2.73
S10	1.000	3.75	0.038	20.0%	68917	3.12
S11	1.000	2.50	0.025	20.0%	39566	3.50
S12	1.000	1.25	0.013	20.0%	17409	6.53
S13	0.625	5.00	0.031	20.0%	81379	2.75
S14	0.625	3.75	0.023	20.0%	66119	3.15
S15	0.625	2.50	0.016	20.0%	41191	3.43
S16	0.625	1.25	0.008	20.0%	16859	6.73
S17	0.250	5.00	0.013	20.0%	81249	2.76
S18	0.250	3.75	0.009	20.0%	67599	3.09
S19	0.250	2.50	0.006	20.0%	42131	3.37
S20	0.250	1.25	0.003	20.0%	17620	6.43

When the R/t ratios and percent thinning values versus pressure for each t_d percentage are plotted on the same graph, it is seen that R/t ratios are nearly identical once forming has progressed past the initial yield point. In Figure 4-5, this is seen where the R/t ratios overlay, while the thinning percentages increase at a significantly different rate.

Figure 4-5: R/t and Percent Thinning vs. Pressure for all t_d percentages

The thicker tubes thin at a slower rate than the thinner tubes, indicating better formability. This was consistent with the initial simulations. To better understand the effect of the variables on the simulation results, the R/t and pressure data points at the time of 20% thinning are extracted and plotted to investigate other trends. As predicted by the hoop equation, as the t_d percentage increase the forming pressures increase. In Figure 4-6, the forming pressures for the 5 different tube outer diameters at each t_d percentage are plotted.

Figure 4-6: Forming Pressure vs. Diameter for Each t_d Percentage

From the values plotted in Figure 4-6, it is shown that forming pressure necessary to form a stainless steel 304 tube to 20% thinning are approximately equal for a tubes with a constant t_d percentage. As expected the thicker-walled tubes require significantly more pressure to completely form than the thinner tubes. This is shown in Figure 4-7.

t_d Percentage versus Forming Pressure for Stainless Steel 304 in Pentagon Die Geometry

Figure 4-7: t_d Percentage versus Forming Pressure for Constant Diameter

From these results it is predicted that thicker-walled tubes would require significantly higher forming pressures. Assuming a linear correlation, this trend can be predicted as:

$$P = 16,547 \cdot t_d - \text{Equation 4-3}$$

This equation has a R^2 correlation of 97.39% with the plotted values. Without performing additional simulations of other wall thicknesses, it is impossible to truly predict the pressures necessary to form tubes of other wall thicknesses, but this

equation can be used to estimate potential forming pressures with the range simulated.

Increasing the t_d percentages greatly improves the formability of the tube. The thicker tube walls result in better formability, i.e. smaller R/t ratios. This is seen in Figure 4-8.

Figure 4-8: R/t versus Tube Thickness for each Diameter

These results suggest that thicker tube walls will continue to approach lower forming limits before reaching significant thinning. There appears to be little effect of the diameter on the formability of the tubes. The five curves are nearly identical to each other. There are not enough data points to attempt to make a prediction of a trend

line relating the R/t ratio to the t_d percentage for all the tube thicknesses. The three thicker tubes appear to have a linear correlation. Additional results are needed between the t_d percentages of 1.25% and 2.50% to fit a trend to this data. At some point, the t_d percentage increases where the forming of the tube is no longer limited by thinning. This point has not been investigated in the study and is considered outside the scope of this research.

Figure 4-9 re-enforces the conclusion that the tube outer diameter has minimal impact on the formability of the tube.

Figure 4-9: R/t versus Diameter for Each t_d Percentage

As the tube diameter varies for each t_d percentage, the R/t value remains approximately constant. These results indicate promise for THF on the micro and meso level. Regardless of the scale, the forming pressures remained approximately constant as the scale of the tubes were reduced to meso scale. The key factor in forming the parts is the ratio between the tube wall thickness and the tube outer diameter. As long as the parts can be scaled at a constant ratio keeping the wall thickness at a minimum THF should be achievable on the micro and meso level. If the trends simulated hold consistent on scaled parts, the tubes will need similar forming pressures to the larger parts while forming to similar levels at 20% thinning.

The maximum effective strain in the formed tube is illustrated in Figure 4-10. This illustrates that the location of the maximum effective strain occurs at the start and end of the formed corner.

Figure 4-10: Effective Strain along the Tube Diameter

Figure 4-11 illustrates, the tube thinning along diameter of the tube. The even node numbers from Figure 4-10 are plotted in this figure. The tube thinning corresponds with the effective strain seen in the previous figure. The location of maximum thinning is equal to the location of maximum effective strain.

Figure 4-11: Percent Thinning Along Tube Diameter

4.5 Conclusions

The results from these simulations indicate that there is potential for THF on the micro and meso scale. The simulations indicate the key factor in the formability of the tubes is the ratio between the tube outer diameter and the tube wall thickness. This t_d ratio was held constant for multiple tube outer diameters and produced consistent forming results. The higher t_d ratios resulted in better formability for all tube diameters. This is a result of the additional material available for the forming process. While the higher t_d ratios resulted in better formability, higher pressures were also necessary to induce the forming. As the t_d ratio increased, the forming pressure increased linearly. This was expected based upon the hoop stress predictions. Experimental results are obviously necessary to verify the simulation results. These are discussed in Chapter 5.

CHAPTER 5

DESIGN AND DEVELOPMENT OF A TUBE HYDROFORMING TEST RIG

5.1 *Introduction*

The goal of the design of the tube hydroforming press and tooling was to secure a press capable of handling forming pressures up to 20,000 psi (138 MPa), in an 8 in (200 mm) long tube with a maximum tube diameter of 2.25 in (57 mm). From these boundary conditions, the press and axial cylinders were sized and selected to ensure that they could withstand the required forces. The tooling was required to be applicable to multiple forming and testing geometries. The following sections discuss the design requirement and process for the tube hydroforming press and the tooling.

5.2 *Tube Hydroforming Press Design*

5.2.1 Press Functional Requirements

In order to form a tube using internal pressure, a method is necessary to hold the upper and lower dies together without allowing deflections or separations in the tooling. This is typically accomplished using a hydraulic press. The primary functions of a THF press are to open and close the dies (Figure 5-1), provide sufficient clamping force to keep the die closed during the forming process (Figure 5-2), to provide axial force at the tube ends to seal and/or feed the tube during the forming process (Figures 5-3 and 5-4), and to pump high pressure fluid for the internal forming operation (Figure 5-4).

Figure 5-1: Open and Closing of the Die [22]

Figure 5-2: Clamping the Die [22]

Figure 5-3: Provide Axial Force to Seal Tube Ends [22]

Figure 5-4: Provide Internal Pressure for Forming and Axial Force to Feed Tube Ends [22]

5.2.2 Tube Hydroforming Test Rig Design and Operation

When designing a press for experimental testing, the size of the tube and the forming pressures used are needed to calculate the clamping force required. For this experiment, the maximum forming pressure was selected to be 20,000 psi, the maximum tube diameter 2.25 inches, and the maximum tube length 8 inches. The clamping force required is calculated using the following equation:

$$F = 2prl - \text{Equation 5-1}$$

where F is the clamping force, p is the internal pressure, l is the tube length, and r is the tube radius. Given the parameters established for this experiment, the maximum clamping force is calculated to 180 tons. The press purchased for the hydroforming has a maximum clamping capacity of 150 tons. Maximum forming pressures will be used for the 2.0 in tube.

5.2.3 Axial Cylinder Design and Operation

In the THF process, the axial cylinders serve two purposes. The first is to seal the ends of the tube, and the second is to provide pressure to feed the tube ends to force additional material into forming zones. Sizing the axial cylinders requires a calculation of force based on internal pressure and the area of the cylinder face using the following equation:

$$F = p \cdot A - \text{Equation 5-2}$$

where F is the force on the cylinder face, p is the forming pressure, and A is the surface area of the cylinder face.

For this experimental setup a maximum pressure of 20,000 psi and a maximum tube diameter of 2.25 inch were used. Based on these parameters, the maximum force from the forming pressure applied to the axial cylinders is 39.8 tons. Using this calculation a pair of 50 ton double acting Enerpac hydraulic cylinders were selected.

Figure 5-5: Enerpac 50 Ton Double Acting Cylinder

The critical factors in the axial cylinder design are related to mounting the cylinders and the design of the sealing system. The mounting method for the THF test rig is shown in Figure 5-6.

Figure 5-6: THF Press Model

This mounting method distributes the forces axially along the threaded rods connecting the two cylinders. This limits deflection which could create misalignment during the sealing or feeding process. To correctly size the mounting system, Finite element simulations were performed. The mounting system was modeled using Pro Engineer and the FEA was completed using ANSYS. The meshed mounting assembly is shown in Figure 5-7.

Figure 5-7: Meshed Axial Cylinder Mounting

For this analysis, symmetry of the model was used to reduce computational time. In this model the displacement at the ends of the two connecting rods was set to zero. A 50 ton load was then applied to the face of the axial cylinder.

Figure 5-8: Axial Cylinder Mounting Deformed Shape

The deformation results from the FEA model are shown in Figure 5-8. The maximum deflection is 0.082 in (2.1 mm).

Figure 5-9: Axial Cylinder Mounting von Mises Stress

The von Mises stress results for the FEA simulation of the cylinder assembly are shown in Figure 5-9. The maximum stress is 208ksi (1434 MPa). This maximum stress is located as a point load in the model. This is corrected in the actual construction through the use of radii in the machined parts. This was not included in the FEA model to reduce computational time. The majority of the model is well under the failure criteria for the material of 125 ksi (862 MPa)

Sealing of the tube ends is dependent on whether or not the tubes ends are being fed during the forming process. For expansion only forming, the seal must withstand the forces of the internal fluid pressure. For tubing being fed, the seal must

withstand both the forces from the fluid pressure, and the forces required to feed the tube. Figures 5-10 to 5-13 illustrate examples of metallic sealing systems. More complex elastomer sealing systems have also been developed [23].

Figure 5-10: Face Sealing System (adopted from [23])

Figure 5-11: Stepped Sealing System (adopted from [23])

Figure 5-12: Cone Sealing System (adopted from [23])

Figure 5-13: Wedge Sealing System (adopted from [23])

No single sealing system is ideal for all applications. For the experimental testing performed for the scalability study, the wedge sealing design was selected. This method of sealing plastically deforms the tube end against a tapered insert.

Expansion only forming was used for this experiment, so axial feeding of the tube is not required.

5.3 Tube Hydroforming Tooling Design

5.3.1 Modular Die Design

The goal for the tooling design for the THF press was to create a modular design that would allow multiple shapes to be formed using the same basic tooling. The tooling was also required to accommodate material and friction testing. To accomplish the goal of creating versatile tooling capable of forming many unique shapes while limit material costs, a modular tooling design consisting of a die base plate and a series of die inserts was selected. This modular design allowed for a wide array of tube sizes and shapes to be formed using the same press and tooling setup. This was important for the scalability study to ensure multiple sizes of tubing could be formed without requiring time consuming changeover of the tooling. The die base plate as shown in Figure 5-14 has outer dimensions of 8 in x 10 in x 3 in. The cutout for the die inserts is 5 in x 8 in x 2 in. This was designed for forming tubes 8 in long with a maximum OD of 2.25 in.

Figure 5-14: Die Base Plate Model

The base plate design was configured to allow axial compressive forces to be applied from four directions for forming of pre-bent tubes. The models and drawings for the tooling were created using Pro Engineer and Alibre Design.

5.3.2 Die Insert Design

The die base plate was designed to allow for inserts of various shapes to be used for the forming dies. A few examples of insert designs are shown in Figure 5-15.

Figure 5-15: THF Tooling Insert Examples

For the scalability study a series of die inserts were designed for experimental testing. Five tube outer diameters were selected: 0.75 in, 1.125 in, 1.375 in, 2.00 in, and 2.25 in. Each tube diameter required the design of 4 unique die inserts. The first pair of inserts was the pentagon die insert. A top and a bottom insert were required for the pentagon shape, Figure 5-16.

Figure 5-16: Pentagon Die Inserts

The critical factors in the design of the pentagon inserts were to ensure that the tube center would be aligned with the axial cylinders, and that the top and bottom of the pentagon dies were split in a location where no tube contact would occur. Two additional inserts were required for the scalability tooling, Figure 5-17. The outer insert shown in green is tapered to allow the punch tip on the axial cylinder to plastically deform the tube during the sealing process. The inner insert, shown in blue, is simply to support the tube outside of the forming region. For future experiments in which the tube is fed during forming, this will be used as the guiding zone. For this study, axial force will only be required to seal the tube ends.

Figure 5-17: Bottom half of Assembled Tooling Inserts for Pentagon THF

5.3.3 Manufactured Tooling

Using the created drawing, the tooling was manufactured, heat treated and ground.

Photographs of the completed tooling are shown in Figures 5-18 to 5-21.

Figure 5-18: Pentagon Tooling Inserts

In Figure 5-18 the completed pentagon inserts are shown for the 5 tube sizes. Figure 5-19 shows the outer inserts to support the tube and to seal the tube ends.

Figure 5-19: Outer Inserts

Figure 5-20 is the assembled die base plate and inserts. A second assembly is used for the top half of the die. These assembled components are then assembled into the press for forming.

Figure 5-20: Assembled Inserts

Figure 5-21 shows the sealing punches. The punch on the right was designed to be used with the large tubes, while the punch on the left and the adapter in the center were designed for the small tubes.

Figure 5-21: Sealing Punches

Figure 5-22 shows the complete press assembly. Both die assemblies have been assembled to the press, and the axial cylinder assembly with the punch tips are shown.

Figure 5-22: THF Press Assembly

5.4 Control Unit

The internal pressurization for the THF rig is accomplished through the use of the control unit shown in Figure 5-23.

Figure 5-23: THF Test Rig Control Unit

The internal pressurization is controlled by a series of PLC controllers. The pump operates on shop air, and uses a pressure intensifier to provide hydraulic fluid to a

maximum pressure of 20,000 psi. The programmed pressurization rate can be sinusoidal, stepped, linear or non-linear.

The axial cylinder control is performed by the rear control units, Figure 5-24. Each axial cylinder is controlled independently. The programmed feed rates can be sinusoidal, stepped, linear or non-linear.

Figure 5-24: Axial Cylinder Control Unit

CHAPTER 6

EXPERIMENTAL VALIDATION OF MACRO/MESO TUBE HYDROFORMING SCALABILITY

6.1 Introduction

To validate the FEA simulation results, experimental testing was conducted. Simulation results indicate that forming pressures ranging from ~17,000 psi (1.25% t_d tube) to ~80,000 psi (5.00% t_d tube) are required for completed forming in stainless steel tubing. The THF test rig is capable of a maximum forming pressure of 20,000 psi. To verify simulation results, an alternate material was required to ensure results were possible throughout the entire range of forming pressures. Copper tubing was selected for these experiments because of its similar strain hardening exponent but lower strength coefficient as compared to the stainless steel. The strain hardening exponent for the copper tubing was estimated to be 0.46 which is identical to the stainless steel used in the previous simulations. The strength coefficient was 87.0 ksi compared to 185 ksi for the stainless steel. This lower strength coefficient allows more complete forming at lower pressures.

Figure 6-1: Flow Stress Plot for Copper and Stainless Steel

6.2 Experimental Procedures

A total of 5 unique tube geometries were selected were selected for experimental testing. Prior to the experimental testing, a series of FEA simulations were performed using copper tubes. Using these results the tube geometries and forming pressures were selected to use for experimental testing. For each tube geometry, 4 forming pressures were chosen. The experimental testing matrix is shown in Table 6-1.

Table 6-1: Experimental Test Matrix

Tube	OD (in)	ID (in)	t (in)	Test Pressure (psi)	Test Pressure (bar)	Tube Number
T1	0.750	0.686	0.032	3,800	262	1
				5,600	386	2
				8,400	579	3
				10,000	689	4
T2	0.750	0.620	0.065	4,000	276	5
				5,400	372	6
				7,600	524	7
				10,000	689	8
T3	1.375	1.311	0.032	2,800	193	9
				4,000	276	10
				5,800	400	11
				9,000	621	12
T4	1.375	1.245	0.065	4,200	290	13
				6,200	427	14
				8,800	607	15
				10,000	689	16
T5	2.000	1.936	0.032	2,400	165	17
				3,400	234	18
				6,000	414	19

Prior to forming each tube was cut to a length of 10” and annealed. Each tube was then placed into the appropriated sized tooling insert. The ends were sealed using the axial cylinders. The tube was then pressurized to the pre-selected forming pressure over approximately a 1 minute interval. This pressure was held for a duration of 30 seconds. The pressure was then released from the tube and the formed tube was removed from the tooling.

6.3 Experimental Results and Discussion

Figures 6-2 to 6-6 show photographs of the formed tubes, along with a tube blank. A total of 19 tubes were formed. The 2.0 inch tube experienced failure due to bursting at a pressure of 6,000 psi. This burst occurred between the pentagon tooling insert and the support insert.

Figure 6-2: Copper Tubes Formed at Selected Pressures ($D = 0.75$ in, $t = 0.032$ in)

10,000 psi 7,600 psi 5,400 psi 4,000 psi

Figure 6-3: Copper Tubes Formed at Selected Pressure (D = 0.75 in, t = 0.065 in)

9,000 psi 5,800 psi 4,000 psi 2,800 psi

Figure 6-4: Copper Tubes Formed at Selected Pressures (D = 1.375 in, t = 0.032 in)

10,000 psi

8,800 psi

6,200 psi

4,200 psi

Figure 6-5: Copper Tubes Formed at Selected Pressures ($D = 1.375$ in, $t = 0.065$ in)

5,000 psi

3,400 psi

2,400 psi

Figure 6-6: Copper Tubes Formed at Selected Pressures ($D = 2.0$ in, $t = 0.032$ in)

After completion of the forming experiment, the corner radius for each tube was measured. This was completed using a radius gauge, Figure 6-7. Each tube was measured and the values recorded to the nearest 1/64 of an inch.

Figure 6-7: Radius Measurement

Bar charts comparing the radius measurements from the simulations and the experimental results are shown in Figure 6-8 to 6-12. The bar charts are organized by tube geometry. The trends in the corner radii for increasing pressures are correlated well between the simulation and experimental results. There is an offset between the values with the experimental results having a smaller corner radius in every case. The offset is most likely attributed to inaccurate flow stress obtained from the literature.

Figure 6-8: Simulated and Experimental Corner Radius ($D = 0.75$ in, $t = 0.032$)

In figure 6-8, the corner radius measurements for the experimental and simulation results for the $D = 0.75$ in, $t = 0.032$ in tubes are shown. The percent difference between the results at 3,800 psi is 20.5%. The percent difference between the results at 5,600 psi is 16.8%. The percent difference between the results at 8,400 psi is 11.0%. The percent difference between the results at 10,000 psi is 14.3%. The percentage error between the simulation and the experimental corner radius trends downwards as the pressure is increased. This is likely a result of using the power law for the flow stress of the material. The potential for error in the flow stress is greater at the lower initial strain.

Figure 6-9: Simulated and Experimental Corner Radius ($D = 0.75$ in, $t = 0.065$)

In figure 6-9, the corner radius measurements for the experimental and simulation results for the $D = 0.75$ in, $t = 0.065$ in tubes are shown. The percent difference between the results at 4,000 psi is 12.8%. The percent difference between the results at 5,400 psi is 9.4%. The percent difference between the results at 7,800 psi is 9.9%. The percent difference between the results at 10,000 psi is 7.0%. The percentage error between the simulation and the experimental corner radius trends downwards as the pressure is increased. As previously mentioned this is likely a result of using the power law for the flow stress.

Figure 6-10: Simulated and Experimental Corner Radius (D = 1.375 in, t = 0.032)

In figure 6-10, the corner radius measurements for the experimental and simulation results for the D = 1.375 in, t = 0.032 in tubes are shown. The percent difference between the results at 2,800 psi is 26.4%. The percent difference between the results at 4,000 psi is 27.7%. The percent difference between the results at 5,800 psi is 9.0%. The percent difference between the results at 9,000 psi is 3.4%. The percentage error between the simulation and the experimental corner radius trends downwards as the pressure is increased. As previously mentioned this is likely a result of using the power law for the flow stress.

Figure 6-11: Simulated and Experimental Corner Radius (D = 1.375 in, t = 0.065)

In figure 6-11, the corner radius measurements for the experimental and simulation results for the D = 1.375 in, t = 0.065 in tubes are shown. The percent difference between the results at 4,200 psi is 13.5%. The percent difference between the results at 6,200 psi is 22.5%. The percent difference between the results at 8,800 psi is 20.4%. The percent difference between the results at 10,000 psi is 21.5%. For this tube geometry, the error percentages between the simulation and experimental results increase. The reason for this increase is unknown and should be verified with additional experimental testing.

Figure 6-12: Simulated and Experimental Corner Radius (D = 2.00 in, t = 0.032)

In figure 6-12, the corner radius measurements for the experimental and simulation results for the D = 2.000 in, t = 0.032 in tubes are shown. The percent difference between the results at 2,400 psi is 15.9%. The percent difference between the results at 3,400 psi is 12.2%. The percent difference between the results at 5,000 psi is 12.9%. The percentage error between the simulation and the experimental corner radius trends downwards as the pressure is increased. As previously mentioned this is likely a result of using the power law for the flow stress.

Once the corner radius measurements were completed, the tubes were sectioned, mounted in epoxy, and polished in order to take images using an optical microscope. A photograph of a mounted sample is shown in Figure 6-13. The optical microscope used is shown in Figure 6-14.

Figure 6-13: Mounted Sample

Figure 6-14: Optical Microscope (Nikon Eclipse)

Images of each sample were taken with the optical microscope, and ImageJ® was used to take measurements of the tube thickness along the tube diameter. Multiple measurements were taken at each imaged location and these values were averaged. The values were then plotted and compared to the simulation results.

The tube thickness distribution for the $D = 0.75$ in, $t = 0.032$ in tube is shown in Figure 6-15. The node numbering begins at node 79 which is the location where the tube wall initially contacts the forming die, node 145 is the center of the formed corner. Node 79 is shown as P1 and node 145 is shown as P2 in the image. As the forming pressure increases, the amount of tube thinning increases. The location of maximum tube thinning is shifted closer to the tube corner as the forming pressure is increased.

Figure 6-15: Tube Thickness Distribution for Copper Tube Simulations

Measurements were taken for the tube formed at 10,000 psi. Thickness measurements were taken at 5 locations along the tube outer diameter. The experimental results were then plotted and compared to the simulation results. These results are shown in Figure 6-16. The experimental results appear to follow a similar trend as the simulation data. The measured values are offset from the simulated values at each node location. This offset is likely a result of manufacturing tolerances in the tube geometry. The tube was simulated using the nominal dimensions. In the case shown below, the initial tube thickness was likely greater than 0.032 in. The experimental tube experiences a greater amount of thinning between points P1 and P4 than does the simulated tube. This is likely a result of inaccurate material properties.

Figure 6-16: Thickness Distribution (D = 0.75 in, t = 0.032 in) Copper Tubing

The R/t and percent thinning results for the $D = 0.75$ in, $t = 0.032$ in copper tube are shown in Figure 6-17. The measured experimental R/t values for the four pressures are plotted along with the simulation results. These experimental values exhibit a similar trend to the simulation values as the pressure increases. The measured values are offset from the simulated values. There is a similar offset between simulation and experimental data for each of the five tube geometries used for experimental testing.

Figure 6-17: R/t and Percent Thinning for Copper Tubing (D = 0.75 in, t = 0.032 in)

A comparison of tube thickness between the experimental results and the simulations results was made at two locations along the tube. A sample of these results is shown in Figure 6-18. The two points selected are shown in the image in Figure 6-18. P1 is the location of initial contact of the tube wall and die surface, and P2 is the center of the formed corner. The measured thickness values at these two locations for each of the 5 tube geometries are within 18% of the simulated value.

Figure 6-18: Tube Thinning vs. Pressure for Copper Tubing (D = 0.75 in, t = 0.032 in)

6.3.1 Grain Analysis

The objective of the grain analysis was to investigate the effect of the grain deformation as the scale of the tube was reduced. The experimental study only included tubes of macro scale. In order to perform a grain analysis on the mounted samples, each sample was polished to remove scratches and the polished samples were then etched. Images were then acquired using the optical microscope. Figure 6-19 is an image of an un-deformed tube. Figure 6-20 is a tube of the same geometry formed at a pressure of 2,800 psi, and Figure 6-21 is a tube of the same geometry formed at a pressure of 9,000 psi. Deformation of the grains is observed as the forming pressure increases.

Figure 6-19: Grain Image for Un-Deformed Copper Tube (D = 1.375 in, t = 0.032 in)

Figure 6-20: Grain Image for Copper Tube formed at 2,800 psi (D = 1.375 in, t = 0.032 in)

Figure 6-21: Grain Image for Copper Tube formed at 9,000 psi (D = 1.375 in, t = 0.032 in)

Figure 6-22: Grain Image Locations

Micrographs were also acquired for a single sample along the outer diameter of the sample in the locations marked in Figure 6-22. The acquired images are shown in Figures 6-24 to 6-28. Figure 6-23 is an image of the un-deformed tube for comparison. Deformation in the grain is observed as the amount of deformation in the tube increases. The elongation of the grain would likely be more significant at a greater forming pressure.

Figure 6-23: Grain Image for Un-Deformed Copper Tube (D = 1.375 in, t = 0.032 in)

Figure 6-24: Grain Image for Copper Tube P1 (D = 0.75 in, t = 0.032 in, P = 3,800 psi)

Figure 6-25: Grain Image for Copper Tube P2 (D = 0.75 in, t = 0.032 in, P = 3,800 psi)

Figure 6-26: Grain Image for Copper Tube P3 (D = 0.75 in, t = 0.032 in, P = 3,800 psi)

Figure 6-27: Grain Image for Copper Tube P4 (D = 0.75 in, t = 0.032 in, P = 3,800 psi)

Figure 6-28: Grain Image for Copper Tube P5 (D = 0.75 in, t = 0.032 in, P = 3,800 psi)

**Figure 6-29: Grain Image for Copper Tube
(D=1.375 in, t = 0.032 in, P = 2,800 psi)**

**Figure 6-30: Grain Image for Copper Tube
(D=0.75 in, t = 0.032 in, P = 3,800 psi)**

A comparison in the grain size as the tube diameter is scaled down was completed. The selected tubes experience approximately the same amount of thinning during the forming process. Micrographs for tubes of the same thickness with different outer diameters were compared these are shown in Figures 6-29 and 6-30. The acquired images indicate that the larger tube experienced more grain deformation during the forming process than the smaller tube. This was most prevalent in the tube corner where the maximum deformation occurred.

Figure 6-31: Grain Image for Copper Tube
(D=1.375 in, t = 0.065 in, P = 10,000 psi)

Figure 6-32: Grain Image for Copper Tube
(D=1.375 in, t = 0.032 in, P = 2,800 psi)

A comparison in the grain size as the tube wall thickness was decreased was completed. The selected tubes experience approximately the same amount of thinning during the forming process. Micrographs for tubes with the same outer diameter, but different wall thicknesses are shown in Figures 6-31 and 6-32. These images indicate that more grain deformation occurs in the tube with the smaller wall thickness.

6.4 Conclusions

Experimental testing and analysis was performed for a total of 19 experiments. Five unique tube geometries were selected with four maximum forming pressures chosen for each tube. Upon completion of these experiments, the results were measured, plotted and compared with simulation results. The corner radius measurements for the experimental tubes were smaller than the simulations predicted for each of the experiments. This difference was as small as 3.4% ($D = 1.375$, $t = 0.032$, $P = 9,000$ psi) and as large as 27.7% ($D = 1.375$, $t = 0.032$, $P = 4,000$ psi). While there was variation between the simulated results and the experimental results, the trends in corner radius were consistent for each of the experiments. In all cases, the corner radius decreased as the pressure was increased. The variations between simulation and experimental results are likely attributed to inaccurate flow stress obtained from literature.

Tube thinning was also measured upon completion of the experiments. For each of the tubes, the wall thickness was measured at the peak of the formed corner, and along the middle of the side, Figure 6-15. The measured values for wall thickness had lower variation than the corner radius data. The difference in measured vs. predicted values was as small as 0.3% ($D = 1.375$, $t = 0.065$, $P = 8,800$ psi) and as large as 17.6% ($D = 2.000$, $t = 0.032$, $P = 3,400$ psi).

The results from the experimental testing indicate that the 2D FEM is an accurate method for predicting the THF process. There is variation between the corner radius

from the simulation values and the experimental values. In all cases, the experimental tubes had a smaller corner radius than the simulated tubes. These experimental results followed a trend similar to the simulation values. This is likely the result of inaccurate material properties taken from the literature. The variation in the tube thinning results between the simulations and the experimental results is much more random. The offsets most likely result from variation in manufacturing tolerances. The thickness tolerances for purchased tubes were ± 0.003 in for the 0.032 in tube and ± 0.002 in for the 0.065 in tube. Much of the variation in tube thinning falls within the range of this tolerance. Inaccurate material properties will also result in variation between the simulation and experimental results. To accurately predict forming results using FEM, the material properties for the annealed tubes should be determined experimentally prior to testing.

Additional analysis of the tube microstructure must be completed to make conclusions on the effect to tube scale. The analysis completed indicates that greater grain deformation occurs as the amount of deformation in the tube increases. For tubes of the same thickness, the tubes with the greater diameter demonstrated greater grain deformation. For tubes with the same diameter, the thinner walled tubes demonstrated greater grain deformation. The microstructure analysis for this study was completed using tubes of the macro scale. Investigations of tubes of the meso and micro scale must be completed to determine the actual microstructure of the smaller scale tubes.

CHAPTER 7

CONCLUDING REMARKS

7.1 *Conclusions*

This simulations and experiments performed in this study indicate that the scaling of the THF process from the macro to the meso/micro is theoretically feasible. The objective of this study was to investigate the scalability of tube hydroforming and determine the potential for hydroforming at the micro and meso scales. This was accomplished by establishing trends in the formability of tubes in the macros scale and using these results to predict the formability at the meso and micro scales. To establish these trends the effect of material properties, tube geometries, die geometries, forming pressures and friction coefficients on the formability of tubes was first investigated. The results from this initial study were used to refine the simulation matrix to better focus on the objective of the scalability study. A single die geometry, friction coefficient and tube material were selected for further study. Because of the larger corner angle the pentagon die geometry outperformed the square and the trapezoid dies with respect to tube thinning and corner radius. This was selected as the die geometry for the scalability study and for experimental testing. As expected, because of the high strain hardening coefficient the stainless steel outperformed both the aluminum and the carbon steel with respect to tube thinning and corner radius. Stainless steel was selected as the material for the scalability study.

To begin the scalability study, five tube diameters (2.250 in, 2.000 in, 1.000 in, 0.625 in, and 0.250 in) were selected. The tubes thicknesses were scaled as a percentage of the tube diameter (5.00%, 3.75%, 2.50% and 1.25%). FEM simulations were performed for each of the 20 tube geometries using the pentagon die geometry. Results for tube thinning and corner radius at 20% thinning were calculated and the results analyzed. The results from these simulations indicate there are trends tube formability as the scale of the tube is changed. The forming pressures increased linearly as the tube wall thickness was increased. The R/t ratios remained nearly constant for tubes with the same t_d percentage. The tube diameter did not affect the R/t ratio or the forming pressure. The R/t ratio was affected most by the wall thickness. The three largest wall thickness ratios correlated nearly linearly with respect to the R/t ratio. This indicates that increasing the wall thickness will continue to improve the R/t ratio until the point at which the forming of the tube is no longer limited by thinning.

Experimental testing was used to verify results from the theoretical FEM study. Because of the high forming pressures required for stainless steel, copper tubing was selected for the experimental testing. Both materials have an identical strain hardening coefficient of 0.46, but copper has a much lower strength coefficient resulting in lower forming pressures. The experimental results indicate that FEM can be used to predict the THF process. The tube thickness profiles measured align very consistently with the expected results from the simulations. The measured R/t ratios consistently follow the same trend as the simulated results. There is variation

between the measured and simulated results. This is most likely a result of inaccurate material properties taken from the literature.

While THF on the micro and meso scale are theoretically practical, there are issues in the manufacturing process which must be addressed. There are tubes manufactured at this scale, but the wall thickness of these tubes must be scaled appropriately to limit forming pressures to those achievable with the manufacturing equipment. The simulations in this study indicate that the t_d ratio is directly related to the forming pressure required. New sealing techniques will need to be developed to seal the axial cylinders to the end of the smaller tubes. Alignment with the axial cylinders will also become increasingly significant as the scales of the parts are decreased. High pressures are likely required as tubes on the micro scale will have greater t_d ratios. While the current need for hydroforming to achieve more intricate structural parts at this scale is currently unknown, the results from this study indicate that the process should be achievable.

7.2 Future Work

Tube hydroforming on the meso and micro level are theoretically feasible. Manufacturing issues are currently being addressed to begin experimental testing of tubes first on the meso level, and then on the micro level. Material properties and tribology conditions will be evaluated on an experimental condition to increase accuracy in the FEM simulations. Additional research and development are required

to create pressurization and feed profiles which are applicable for tubes on the meso and micro level. Additional research on the effect of the microstructure on the forming is also required. As the tubes are scaled down, the ratio of surface to volume grains will increase. This will change material properties, and the effect of friction on the forming process. Microstructure analysis must be completed on tubes of micro and meso scale to investigate this effect.

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