CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The objective of this chapter is to present a literature review on tube hydroforming (THF) process studies. Initially, a number of analytical studies are summarized. A guideline is then proposed for employing finite element modelling (FEM) in the process analysis. Factors affecting the process output are addressed by a number of research studies which are categorized and reviewed in the present chapter. To study on different input parameters that will produce the desired hydroformed component are outlined. In conclusion, production of complex elliptical tubular junctions by means of the tube hydroforming process is found to need more investigation.

2.2 Analytical studies

Researchers started to study tube hydroforming theoretically in order that they could predict the hydroformed component shape using a certain combination of process parameters, or to identify the necessary process parameters that obtain the desired shape using mathematically developed equations, with experiments being carried out to validate the analytical results.

In one of his studies, Hashmi [17] presented an analysis of wall thickness distribution round the dome of T-branches formed by tube hydroforming. In this analysis the developed dome was assumed to be spherical. A comparison with experimental results indicates that the analysis over-estimated the thinning of the wall. In a separate work [18], the same author reported an analytical method to predict the bulge height and wall thickness distributions of both axisymmetric and asymmetric hydroformed parts. The analysis was based on the geometry of the forming bulge but did not take into account key parameters such as pressure, friction, die corner radius, etc. Later, experiments were conducted Hashmi and Crampton [19] to compare experimental results with the analytical ones and a fairly close agreement was discovered.

In a different approach, calculation of the internal pressure and the axial force values required to reach the yield limit in tube hydroforming process was achieved by Asnafi [20] taking into consideration sealing and frictional forces. The analysis was done using the formulas of thin-walled tubes subjected to internal pressure and axial loads with an assumption that the stress condition is bi-axial in nature. The predicted values were useful in the free-forming stage of the tube hydroforming process Figure. 2.1.

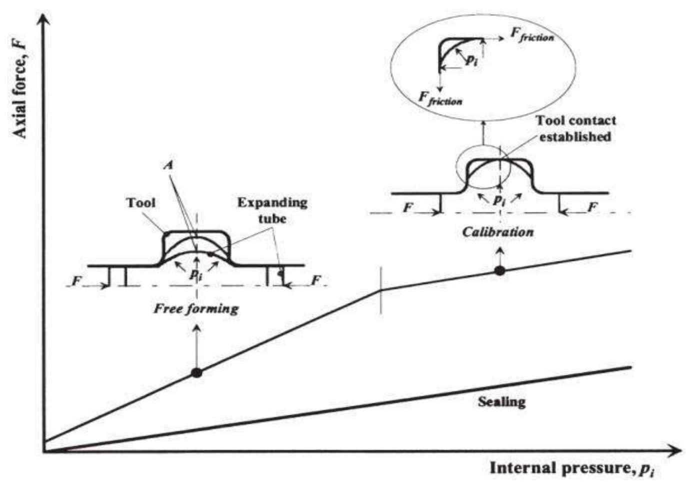


Figure 2.2.1: Stages of Tube Hydroforming [20]

The yield pressure (P_{iy}) and compressive force (F_y) required to yield the tube at the beginning of the bulging were described in equations 2.1- 2.2.

$$p_{iy} = \frac{R_{p0.2}}{(1 - \alpha + \alpha^2)^{1/2}} \cdot \frac{2t_0}{(d_0 - t_0)}$$ **Equation 2.2.1**

$$F_y = p_i \cdot \pi \cdot \frac{(d_0 - t_0)^2}{4} \cdot (1 - 2\alpha)$$ **Equation 2.2.2**

Where $R_{p0.2}$ is the yield strength, t_0 is the initial wall thickness, d_0 is the outer diameter of the tube while α represents the ratio of the axial stress to the tangential stress.

Ahmad and Hashmi [6] developed a theoretical estimation of the internal pressure, axial load, and clamping force for different materials and blank geometries. From the analytical study, it was evident that the axial punch has to deliver more force when stronger materials are used, higher friction is faced, or bigger tube diameters are utilized. Al-Qureshi [21] presented a theoretical study which predicts the limiting bead height, the total applied load and the total axial feed required to form circumferential cylindrical bead in a tube. A close agreement with experimental results was noticed using tubes made from different materials.

Instabilities and failures were studied by different researchers in attempting to theoretically determine the onset of instabilities. Saver et al [22] worked on the theory of failure of bulge formed tubes due to buckling and fracture. A numerical algorithm was developed based on different principles of solid mechanics to compute values of axial load and internal pressure from increments in the diameter of the bulge. Analytical solutions were presented by Mellor [23] to predict the strain at instability of a thin-walled tube subjected to internal pressure and independent axial load. In this study, it was assumed that the circumferential to axial stress ratio remains constant during the process. It was shown that the greatest ductility of a material can be gained when the ratio of the hoop stress to axial stress has the value of one half. In a subsequent work Jones and Mellor [24] did experiments to validate Mellor's model. A close correlation was found between the two sets of results.

Tensile instability of thin-walled cylinders of finite lengths was checked theoretically by Weil [25]. Results showed that burst pressure increase progressively as the length/diameter ratio of the cylinder is reduced. In another study, Koc and Altan [26] formulated analytical models to predict buckling, wrinkling, and bursting in the free bulge forming process using plasticity, membrane, and thin-thick-walled tube theories. The critical axial compressive stress for wrinkling was formulated as a function of the tube material properties and the tube geometry Equation. 2.3. Similarly, the critical strain at bursting was given as shown in Equation. 2.4.

$$\sigma_{cr}=\frac{1}{\sqrt{3(1-\nu^2)}}E\frac{t}{r}$$ **Equation 2.2.3**

$$\bar{\varepsilon}=\frac{2n\sqrt{1-\alpha+\alpha^2}}{(1+\alpha)}$$ **Equation 2.2.4**

Where E and ν are the tangent modulus and Poisson's ratio of the tube material, t is the wall thickness, r is the tube radius, n is the strain-hardening exponent of the material while α representing the stress ratio. Due to the complexity of tube hydroforming processes, theoretical studies have produced a limited understanding of the process. Therefore, it would seem important to employ numerical capabilities to provide valuable insight into the process and to increase the understanding of its parameters.

2.3 Finite element modeling

Through the last decades it has been discovered that it is expensive and time consuming to use trial and error for the investigation of tube hydroforming process, as well as the conventional metal forming process. The application of numerical simulation for the hydroforming process was found to help engineers to efficiently improve the process development avoiding the cost and limitations of compiling a database of real-world parts.

Finite element analysis permits arbitrary combinations of input parameters including design parameters and process conditions to be investigated at limited expense. The finite element method (FEM) is a numerical technique by which differential equations are solved approximately up to a selected degree of accuracy [27]. In FEM, the behaviour of a continuum, which is normally impossible to determine exactly, is approximated by idealization. For this purpose, the shape and behaviour of the continuum is redefined by a mesh which is composed of a finite collection of sub-domains called finite elements and nodal points where the values of the function (displacements) and its derivatives (velocity and acceleration) are specified.

The analysis and design of metal forming has increased considerably in recent years due to the advances in computer performance. FEM came of age in the early 1960's with the replacement of analogue with digital computers and the development of the first commercial finite element analysis code. At this early stage, the application was confined to the contained elastic–plastic deformation where the plastic strain is of the order of 0.1%. The extension to the large strain regime was achieved in the late 1970's when limited nonlinear solvers were developed and made available. With the continuous development of computers, the use of FEM for hydroforming process simulations has become a standard development tool after investigations and validations conducted by many researchers since the early 1990's [28] and the application of current commercial FEM software, such as LS-DYNA, PAM-STAMP, ABAQUS, MARC, AUTOFORM, and DEFORM into tube hydroforming process was performed and successfully presented.

The application of numerical methods to the analysis of hydroforming is not so straight forward as it may appear. The THF process is highly non-linear due to large displacements, material non-linearity, and non-linearity due to contact. In many cases, a three-dimensional analysis is required in order to properly represent hydroforming operations and to be able to identify defects such as wrinkling and buckling. Thus, in order to simulate the hydroforming process sufficiently, non-linear three-dimensional models with large contact surfaces are required. Formulation selection is a very important matter; usually static analyses are studied using the implicit method, whereas dynamic analyses are conducted by the explicit method. Furthermore, there are a few processes which are quasi-static in nature. These processes can be analyzed by either implicit or explicit methods. Considering the low strain rates during deformation of the typical tube hydroforming, the process can be categorized as a quasi-static deformation and different researchers [29, 30, 31, 32] have taken this advantage to simulate the process with a scaled down simulation time with respect to the actual experiment time as the process is time independent. However, it has been noticed that for more complex models, with more refined meshes, the explicit method is much more effective than the implicit method. Explicit finite element codes have much better capabilities to handle such kind of nonlinear behaviour exhibited by the metal forming process and provide a better understanding of the plastic deformation mechanism over implicit finite element analysis. On the other hand, the implicit method is reasonably effective and can be faster than the explicit method in simplified problems [33].

Ahmed and Hashmi [29] simulated the T-branch bulge forming process using the commercial explicit finite element code LS-DYNA. Taking the advantage of asymmetry, one fourth represents the numerical model which was built with brick elements to simulate both the die and the tube blank. The tube was assigned a piecewise linear plastic material model, while the die was considered as rigid. Finite element simulation of solid medium bulge forming of cross-joint components was performed by MacDonald and Hashmi [34]. By taking the advantage of symmetry it was possible to model one-eighth of the system. Both the die and the tube were modelled using eight-node solid elements. The interfaces between the die and the tube, and between the bulging medium and the tube, were modelled using the automatic surface-to-surface contact algorithm. The algorithm uses the material properties of both contacting surfaces to calculate the stiffness of the contact elements. The internal pressure was generated by applying a prescribed displacement to the nodes at the end of the filler material, while axial load is obtained by applying a prescribed displacement to the nodes at the edge of the tube end. In further work, finite element models for the X and T-branches tube hydroforming were constructed using ANSYS/LS- DYNA pre-processor by Ray [31]. The blank was modelled with four node 3D explicit thin shell elements with fully integrated advanced Belytschko Wong Chiang shell element formulation. Shell elements are treated as two dimensional, with a thickness for the element entered, but not shown on the model. However, thin shells theories are successfully adopted if the ratio of tube thickness to the diameter of tube is smaller than 0.1 [35]. The interfaces between the tube and the die, and the tube and the end plunger, were modelled with an advanced automatic surface-to-surface contact algorithm with an elastic coulomb friction law. Another contact parameter with single surface entity was defined for the tube shell that becomes effective in case of wrinkling or buckling. Bi-layered tube hydroforming was simulated using the ANSYS program by Islam et al [16]. Tubes were modelled with solid brick elements where the die was considered as a rigid surface. The pressure was applied on the inner surfaces of the internal tube and the axial displacement was applied at the end of both tubes.

As a result of the rapid IT revolution in recent years, there has been a significant increase in the processing power, and a considerable increase in the availability of commercial finite- element analysis (FEA) packages capable of simulating three-dimensional hydroforming processes. However, a successful application still requires the existence of a well-defined physical problem, for which a numerical analysis can provide a solution [27] and the accurate idealization of this problem (simplifications, assumptions, detection of governing physical phenomena). The significant spatial discretization of the idealized problem (type of elements, topology of the element mesh, and density of element mesh) is essential in the numerical analysis. Moreover, accurate boundary conditions (friction, machines, dies) and material laws and parameters (flow curve, anisotropy) need to be defined. Furthermore, proper numerical parameters (convergence limits, increment sizes, re-meshing criterion) should be selected. In addition, reasonable computational times and storage requirements are necessary to gain an economical finite element analysis. Nevertheless, because of the limitation of the experimental study and theoretical analysis, the application of finite elements numerical simulation became a very essential tool for the investigation of the factors affecting the process output.

2.4 Investigation of the factors affecting the process output

Tube hydroforming process output was found to be affected by the properties of the material used and the die and tube geometry, as well as to the applied process parameters and friction. Each of these components plays an important role in the success of the process and they have to be addressed during the stage of the development of the process.

2.4.1 Effect of material properties on the process output:

Material properties were found to fundamentally affect the tube hydroforming process output. Several tests are used in industry to determine material properties. As a consequence of its simple and easy implementation, the uniaxial tensile test is widely used to determine material parameters and stress–strain relationship. Due to the different stress state encountered in the tensile test (uniaxial stress state) and in tube hydroforming (bi-axial stress state), it is better to use the bi-axial test in order to understand reliable material parameters and stress–strain relationships [36].

Experimental research on the effect of the hydroformed material tensile strength was conducted by Fuchs from 1966 onwards [37], who performed tube hydroforming experiments on different materials and concluded that a small increase in tensile strength of the material would lead to a considerable increase in the process formability. Assuming that the tube materials obey the power law of strain hardening, the influence of strain hardening of the material (n) was investigated by Orban and Hu [38]. Increasing the strain-hardening exponent was found to lead to a better thickness distribution along the tube wall Figure. 2.2, which indicates a decrease in corner thinning during the expansion of a circular tube into a square die. The same conclusion was arrived at analytically and numerically by Kridli et al [39] and the two sets of results were in good agreement with each other.

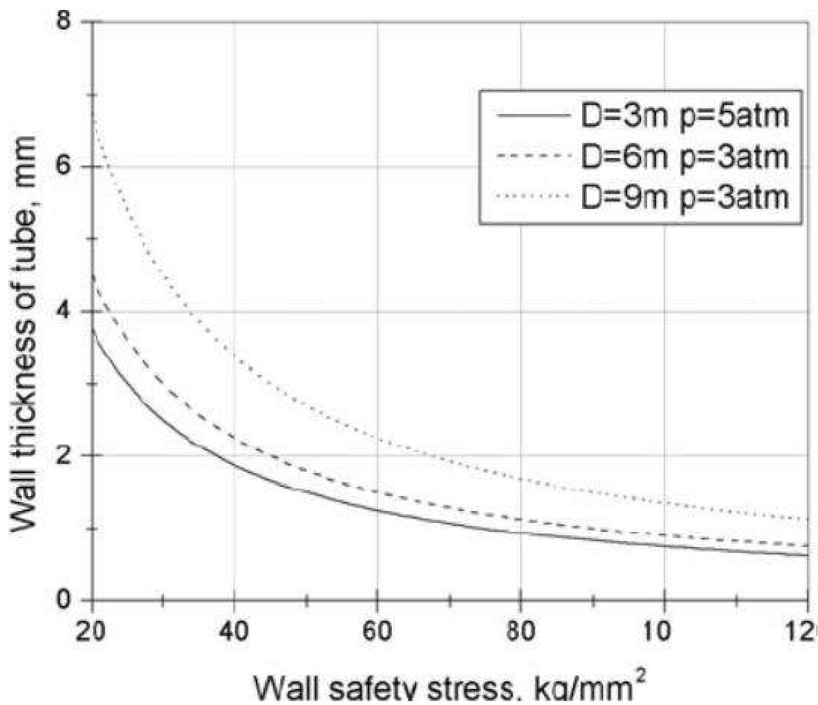


Figure 2.2: Effect of material properties on wall thickness distribution [38]

Bulge forming of finite-length thin-walled cylinders was studied by Fuchizawa [40] using the incremental plasticity theory, and the effect of strain-hardening exponent on the bulge height limits was covered. In a subsequent work, Fuchizawa [41] explored the influence of plastic anisotropy *r* on the deformation behavior of thin-walled tubes under internal pressure. Longitudinal anisotropy was reported to have a significant effect on the thinning ratio and the critical expansion limit while anisotropy in the hoop direction was found to affect the maximum internal pressure required. Carleer et al [42] investigated the influence of various parameters on the process formability. The parameters that were studied included the anisotropy parameter (*r*) and strain hardening coefficient (*n*). In their study they found that *r* and *n* have a large impact on the shape of the free expanded tube and on the strain distribution. Higher values for *r* and *n* result in more evenly distributed strain and will favor larger deformations.

Furthermore, a tube material with a higher strain hardening exponent can be formed to a smaller die corner radius than a material with a low strain hardening exponent since it can achieve a higher amount of strain at a given stress (pressure) level [39]. It was also found that with hydroforming materials with less *r* value, smaller axial displacement is required in order to obtain the same formed profile [43]. The influence of the material properties on bursting pressure was examined by Kim et al [44]. It can be seen from figure. 2.3, that bursting pressure can be increased either by decreasing of the hardening exponent *n*-value or by increasing the strength coefficient *K*-value.

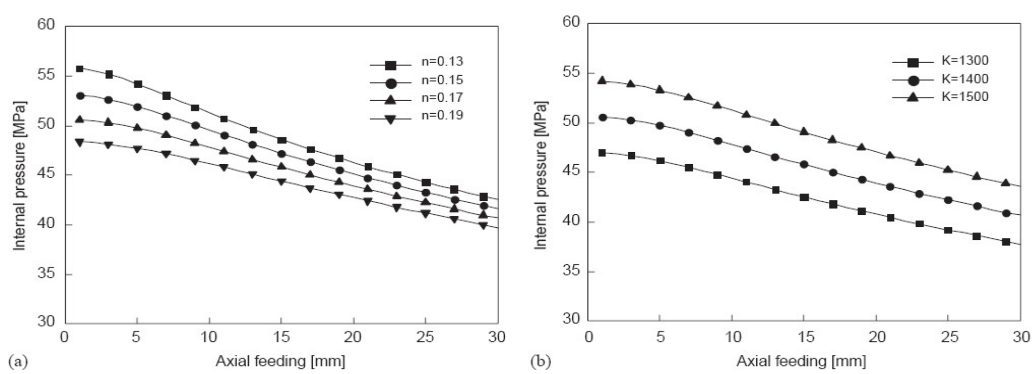
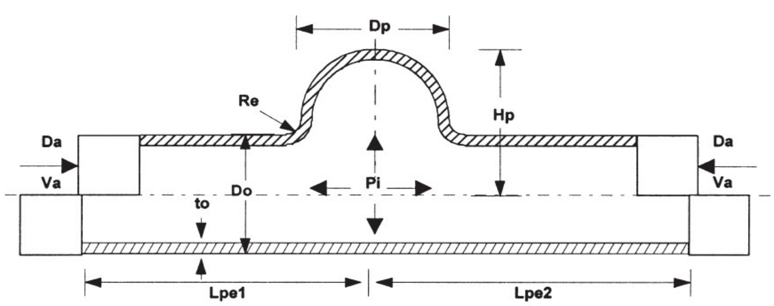


Figure 2.3: Effects of material properties on bursting pressure [44]

2.4.2 Effect of geometrical factors on the process output

The geometry of the tube and die was indicated by different researchers to have an important influence on THF process success. A series of experiments were carried out by Hutchinson [45] to explain the limits of the process. Tee pieces and cross joints were formed successfully from various dimensioned sizes of copper tubes. It was concluded that the ratio between the wall thickness and the outside diameter gives the extent of the forming range (the lower the ratio, the larger the forming range). The tube diameter effect on the process formability was investigated for a member with a complex section of a vehicle bumper rail by Kang et al [46]. In their study it was observed that a remarkable reduction to about one-third in thinning rate and more uniform thickness distribution were reported when bigger diameter tubes were used. Moreover, pre-pressure influence was found more effective when applied to bigger diameter tubes. Based on the finite element modelling of X-branch tube hydroforming [47], it was found that with the initial tube length increase, a smaller bulge height has resulted simultaneously with an increase of wall thinning at the branch top and a decrease of wall thinning at the X-junction.



Hp	Height of Feature
Lpe1	Distance between Feature and Edge
Lpe2	Distance between Feature and Edge
Do	Initial Outer Diameter of Tube
Dp	Outer Diameter of the Feature (i.e., protrusion)
Re	Fillet (Entry) Radius of Feature
to	Initial Tube Wall Thickness

Figure 2.4:Effect of geometrical factors on protrusion height [32]

An integration of finite element modelling and design of experiment was conducted by Koc et al [32] to study the influence of geometrical factors on the tube hydroforming process. Bulge height was modelled as a function of the geometrical parameters and plotted for the corresponding levels of the factors Figure. 2.4. Distances between the protrusion and the tube edges (L_{pe1} and L_{pe2}) were concluded as the most influential factors. Forming of shorter tubes yields higher protrusions than that of longer tubes with less thinning in the protrusions. The influences of the tube diameter and die corner radius were also determined. The effect of the die fillet radius on minimum wall thickness was examined by Kwan et al [48] in T-shape tube hydroforming. From their study, it was noticed that thinner protrusion tips resulted from increasing the die corner fillet radius. Similar results were found in [47] for the X-shape tube hydroforming. Hydroforming of a circular tube in a square die was investigated by Kömmelt et al [49]. It was concluded that the larger the perimeter of the initial tube, the more uniform was the wall thickness distribution of the hydroformed part. The hydroforming pressure requirements were found to be mainly affected by the initial tube wall thickness value, with the required die closing force for the thin tube being lower than that for the thick tube. The die closing force increases with decreasing die corner radius since a higher pressurization level is required to fill the die corner [39].

2.4.3 Effect of process parameters on the process output

The output of a tube hydroforming process was found in many research studies to be affected by the process parameters applied. A 1976 article described the experimental work carried out by Kandil [50] into the axis-symmetrical tube hydroforming of brass, aluminum, and copper tubes using internal pressure only. Later, Ogura and Ueda [51] found that axial feed has an important influence in order to obtain sound products. Influence of the axial feed was investigated by Kang et al [52] for metallic elbows hydroforming. Experiments were performed using different forming dies such as rectangular, circular, and triangular shaped inserts. In all investigated cases, it was found that the axial feed has a significant role in avoiding cracks during the forming process. In another investigation [53], better wall thickness uniformity was obtained in the hydroformed parts when applying a proper axial feed. However, with axial feed increasing, a rise of the maximum internal pressure would be needed to achieve the desired shape of the part. Manabe and Amino [43] studied the factors effecting tube wall thickness distribution analytically and numerically. Axial loading and better lubrication condition were found to improve the wall thickness uniformity for the hydroformed part. Application of axial feed was used, accompanied by either prescribing fluid pressure or specified volume flow rate. It was observed by Varma and Narasimhan [54] that the axial feeding with a specified flow rate resulted in a proportional strain path while the axial feeding with a prescribed pressure gave a non-proportional strain path.

The forming internal pressure required to produce a desired part using the tube hydroforming process was examined by Chen et al [55]. The relationship between the hydraulic pressure, outer corner radius of the deformed tube, tube thickness, and tube yield stress was established based on a proposed theoretical model. Calculated values were found to agree well with the values obtained from the numerical study. A finite element comparison of high- and low-pressure tube hydroforming was conducted [56]. Stress variation and wall thinning were more pronounced when high forming pressure was used. Furthermore, high pressure hydroforming was found more sensitive to friction than low pressure hydroforming.

However, a balance of the axial load and internal pressure was required to obtain sound products, hence a device was used to apply an axial compressive force proportional to the internal pressure in tube bulging by Thiruvarudchelvan and Lua [57]. Bulge forming of copper tubes was conducted using different ratios of the axial compressive force to the hydraulic pressure. The proper coordination of internal pressure and axial feeding during the process time is the key issue, as these process parameters have to be applied synchronously. Effect of loading path (internal pressure versus axial material feed) is discussed in a number of published articles. In one of these articles, axisymmetric bulge forming of tubes using two different loading patterns was numerically simulated by Ahmed and Hashmi [29]. A pressure predominant loading path and an axial predominant loading path were examined. It was concluded, that a pressure predominant path gives smoother deformation while a predominant axial load path may result in buckling or wrinkling. In other work, Limb et al [58] found that increasing the internal pressure as a step function of the axial feed is the most recommended method of forming thin-walled tubes using hydroforming. Finite element simulations of the THF process using rectangular dies were carried out by Hama et al [59], and various loading paths were tested as shown in Figure. 2.5. The so-called pressure advanced type (A), in which the hydraulic pressure was raised to a certain magnitude in advance of the axial pushing, gave the best formability. Application of internal pressure in advance of the axial feed was recommended for the X-shape tube hydroforming [47] as it results in high bulges and small protruded wrinkles. Big wall thinning in sensitive areas can lead to bursting. The application of the majority of axial feed after tube material yielding under internal pressure, was suggested by Imaninejad et al [60] in order to avoid wrinkling. In the same study, it has been observed that using multiple strokes for axial and vertical actuators would improve the formability of the process.

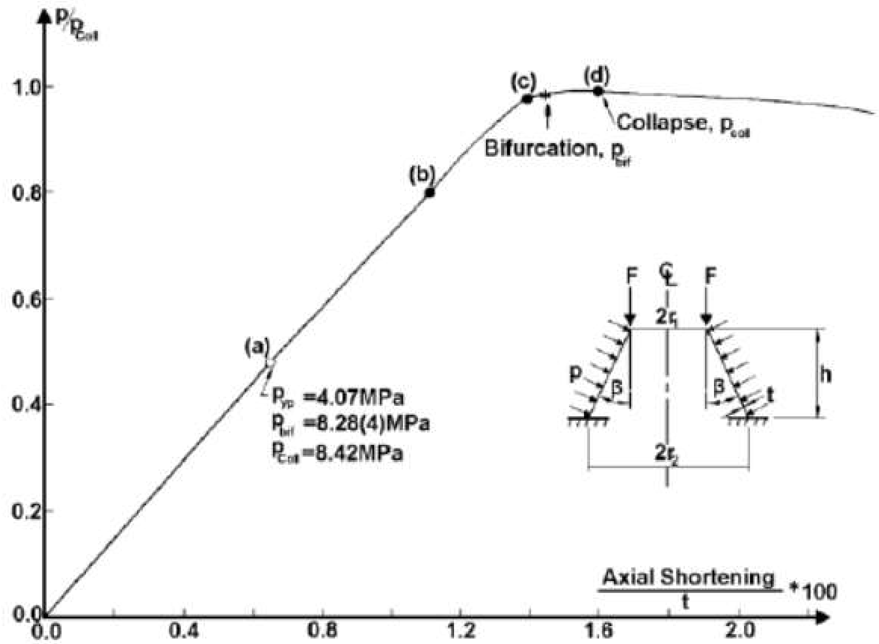


Figure 2.5: Loading paths types (a: Pressure advanced, b: Linear, c: Feed advanced) [59]

2.4.4 Effect of friction and lubricating on the process output

Due to the high contact pressures and large contact surfaces in the tube hydroforming process, high frictional forces between the tube and die are obtained. These forces affect not only the required process parameters for a specified hydroformed part but also affect its quality, such as its wall thickness distribution [61,62]. Knowing the coefficient of friction is indispensable in the tube hydroforming process analysis. A number of friction tests were developed to determine the coefficient of friction in tube hydroforming process. One of these tests is the "push-through" test, where a tube subjected to internal pressure is pushed through a die. The friction force is calculated as the difference between the forces measured at the both punches. A new analytical model to determine the friction coefficient in the forming zone of tube hydroforming was proposed by Plancak et al [61]. According to the developed model, the friction coefficient could be calculated from the deformed tube and material properties without force measurement. The main parameters affecting the friction in tube hydroforming are the lubricant, the tube material properties (yield strength), tube surface texture, die surface finish, die hardness, and die surface treatment.

Lubrication is important in successful hydroforming as good lubrication conditions allow a tube to reach its final desired expansion and shape in the die, whereas poor lubrication often results in premature failure, due to excessive local thinning. Using lubrication was found to decrease wall thickness differences [52] between bulged and non-bulged regions. The effect of lubrication on the bulge shape was reported in axisymmetric and asymmetric hydroforming by Limb et al [58]. It was observed that the bulged dome was more pronounced if there was no lubricant between the tube and the die, where as a flatter dome was achieved with lubricants in the interface.

From the friction attitude, the hydroformed component can be divided into three different zones: guided, transition, and expansion zones figure 2.6. Due to the difference in the material flow and the state of stress, the three zones are exposed to different tribological conditions [62,63]. In the guiding zone, due to the high values of the relative velocity at the die/tube interface, different types of lubrication can be efficiently used to lower the interface friction. Whilst in the transition and expansion zones, the relative velocity at the die/tube interface drops, and the interface friction increases, in addition high forming pressure causes the conventional lubricants to break down. Therefore, dry film lubrication is more appropriate for these zones, especially when protruding high bulges as it follows the surface expansion without breaking down [64,65].

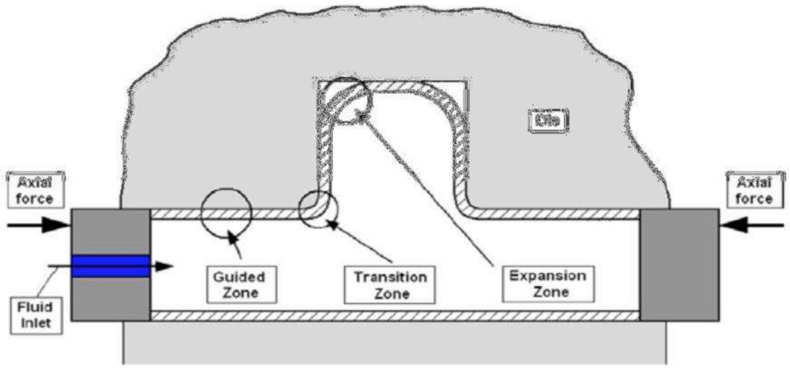


Figure 2.6: Friction zones in tube hydroforming for T-shape [61]

The relationship between the coefficient of friction and the lubricant viscosity as well as the surface roughness was investigated by Lee et al [66]. Test results in figure 2.7 showed that the friction coefficient was high when surface roughness is extremely low or high, while lubricant viscosity was found inversely proportional to the friction coefficient value. Different lubricants were tested in the tube hydroforming process by Hwang et al [67]. The effects of the internal pressure and the axial feeding velocity on the friction forces and coefficients of friction were discussed. A higher pressure was found to decrease the coefficient of friction while the effect of feeding velocity on the coefficient of friction value was found to be insignificant.

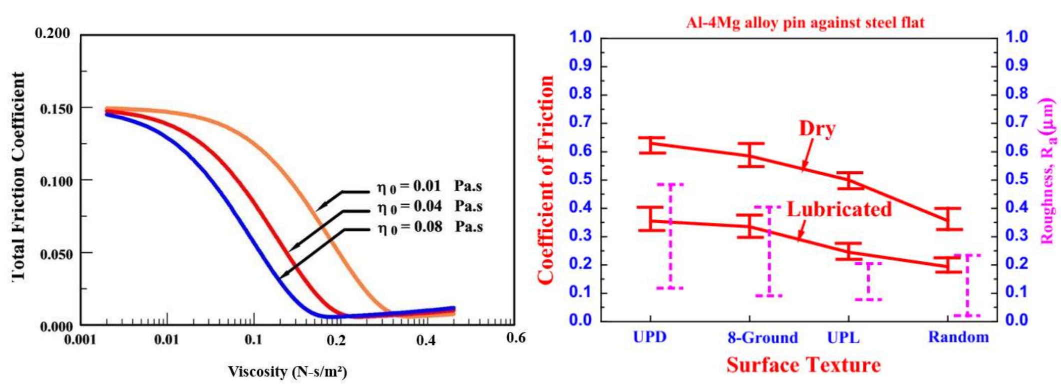


Figure 2.7:Friction coefficient changes with both lubrication viscosity and surface roughness [66]

With the aim of minimizing friction forces between the tube and die, a new sliding die system was invented by Dohmann and Klass [68] in which the die pushes the tube ends, giving an axial compressive forming load without friction between the die and tube. In a consequent work, Dohman and Hart [69] developed a flexible die system for tube bulging of both axisymmetric and asymmetric products. In this system, the die is divided into segments that can be driven separately during the process. Sliding type and fixed type dies were numerically investigated in hydroforming of an automobile rear axle housing by Lei et al [70] using finite element method. It was found that the sliding-type die can result in a better hydroformed part but it had the drawback of a possibility of buckling during the process. On the other hand, bursting failure could be caused when the fixed-type die is used.

2.5 Instabilities and failures

In the tube hydroforming process, the loads applied in the deformation zone are multidimensional, and the ratio of the loads in different directions may not be constant during the forming process. Therefore, the process is very prone to instability and defects. The common modes of failure in tube hydroforming are: bursting due to formation of a localized necking on the tube wall which leads to fracture, and wrinkling due to local buckling. The amount of axial feeding has to be coordinated with the internal pressure. If the internal pressure is applied rapidly and the axial feeding slowly, the process will fail and cracks will appear in the hydroformed part as the tube can't sustain any increased tensile loading. Splitting usually follows due to extreme deformations in the bursting area. Conversely, if the internal pressure is applied slowly and the axial feeding rapidly, there will be wrinkling or bulking on the tube as a surplus amount of material is pushed through the die which cannot be successfully formed by the applied pressure [71,72].

2.5.1 Instabilities overview

A summary of instability modes, in conjunction with an analytical model to predict the forming limits and parameters in tube hydroforming process, using the thin-walled tube theory, were presented by Koc and Altan in [26]. Even though these models apply only to simple geometries, they could provide helpful predictions in the early stages of design, or could be used as initial hypotheses in the finite element simulations. Numerically, each of the static implicit and dynamic explicit finite element codes were tried by Kim et al [73] to predict wrinkling in straight tube bulge forming. Superior predictions using the explicit method were reported compared to implicit calculations. The effect of the tube material properties on the tube wrinkling or buckling during the hydroforming process was determined by Chu and Xu [74]. Tubes with stronger work hardening coefficient and bigger plastic anisotropy were found to have higher resistance to either buckling or wrinkling during hydroforming. Furthermore, Yuan et al [75] differentiate between useful and dead wrinkles; useful wrinkles can be used as a pre-form as they can be flattened by applying high internal pressure in the calibrating stage, while dead wrinkles start to arise from the beginning of the process and the calibrating pressure would not be able to flatten them. The initial pressure was found to mainly affect forming of useful or dead wrinkles. However, hydroforming with useful wrinkles was found suitable for low formability metals, but the hydroformed part wall thickness would not be uniform along the axial direction. Minimum thickness can be found at the original top zone of the wrinkle wave, while the original bottom zone of wrinkle wave has the maximum thickness in the forming area [76]. In contrast with buckling and wrinkling, bursting is an irrecoverable failure in the hydroforming process. In order to predict the bursting failure in tube bulging test, Kim et al [77] evaluated the Oyane's ductile fracture criterion [78] from the histories of stress and strain, which are obtained from finite element analysis. The region of fracture initiation and the bursting pressures were predicted and compared with a series of experimental results. An analytical prediction of the bursting failure in the tube hydroforming process under combined internal pressure and independent axial feeding was carried out by Kim et. al. [44].

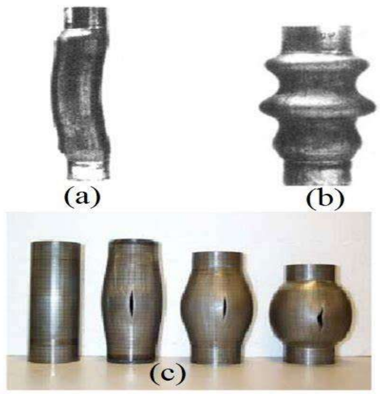


Figure 2.8: Tube Instability through (a) buckling (b) wrinkling and (c) bursting [44, 77]

The incremental theory of plasticity for an anisotropic material was adopted. From the analytical study, it was concluded that plastic instability is reduced with a decreasing strain hardening exponent, *n*, while it increases with a decrease of the plastic anisotropy parameter, *r*, and strength coefficient, *K*. In other work, Kim et al. [79] examined the finite element analysis for bursting failure prediction in the hydroforming process of a seamed tube. Through a series of finite element simulations with consideration of the weld line, it was shown that the initial fracture takes place in the heat affected zone near the weld line, which was found more realistic in view of the actual bulge forming operations.

2.5.2 Forming limit diagrams (FLD)

In order to obtain a defect free hydroformed part, a space is required in which plastic deformation can be assumed to be safe. Operating windows, which are created based on the proposed forming limits, were indicated by many researchers. Tube hydroforming experiments using different tube materials and different tube dimensions were conducted by Hutchinson [80] to establish formability zones for hydroforming of T and X-junctions. Based on a theoretical investigation, forming limits for tube hydroforming process were developed by Kim et al [81] for a different plastic anisotropy (*r*) and strain hardening exponents (*n*) as shown in Figure. 2.9. Analytical results were compared with Back's experimental study [82,83]. Wrinkling limit obtained from the theoretical study was in good agreement with the experimental results. However, the theoretical analysis produced an overestimate when compared to the experimental results for the occurrence of bursting.

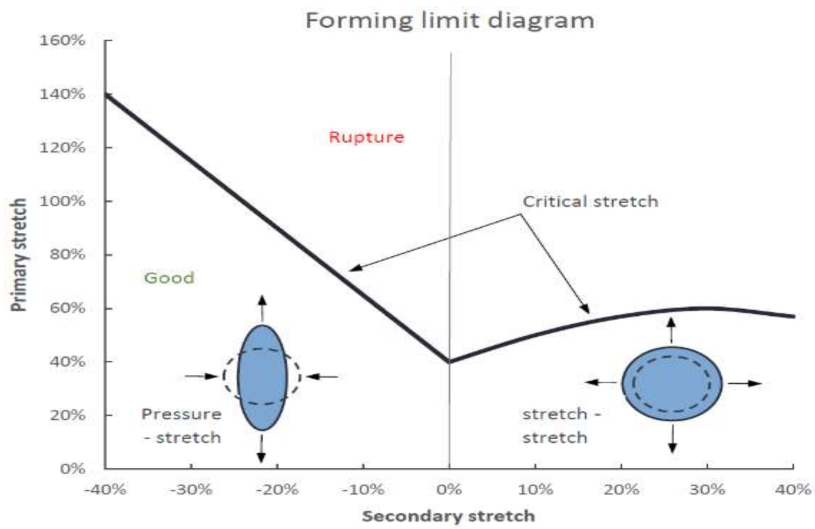


Figure 2.9: Forming limits for different anisotropic parameters [81]

The effect of material properties on the forming limits diagram was outlined in [84]. It was observed that both plastic anisotropy (*r*) and strain hardening exponent (*n*) have more effect on the bursting failure than on the wrinkling failure. However, the strain hardening was found to have a more significant influence on the forming limits. The effect of tube wall thickness on the forming limits was covered, and thicker tubes were reported to be more resistant to wrinkling and bursting failures. Based on a theoretical analysis, forming limits diagrams were drawn up by Xia [85] according to the internal pressure and axial

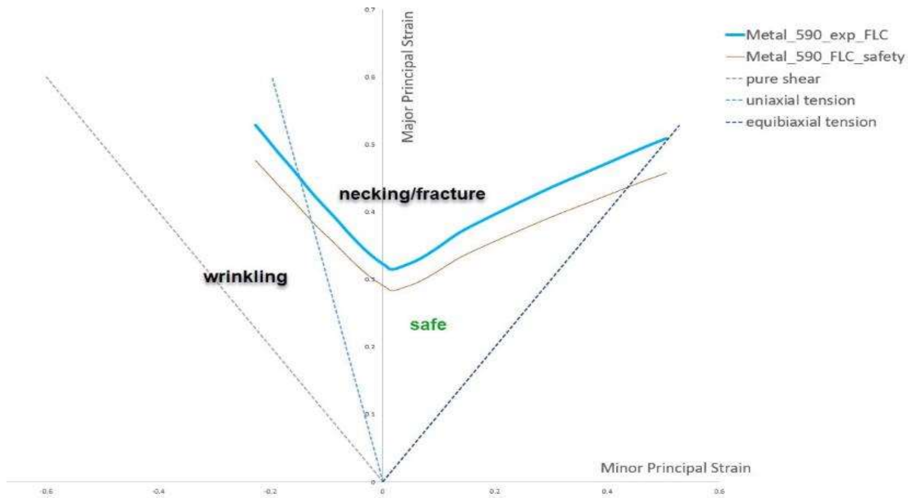


Figure 2.10: Operating windows for different metals [85]

feed values for different materials figure 2.10. From this theoretical study, it was concluded that the internal pressure that causes bursting failure was found to be proportional to the wall thickness/tube radius ratio.

2.5.3 Improvements resulting in delayed bursting

Since bursting is an irrecoverable failure, different techniques were developed by researchers to avoid over-thinning leading to fracture and bursting. The rationale to apply counter punch in hydroforming process comes from the fact that counter punch has been used effectively in many manufacturing processes to enhance the manufacturing capabilities. A counter punch can be used to control the branch height and avoid over-thickening or bursting in the protruded branch during tube hydroforming. A general-purpose hydroforming machine with internal pressure, two axial feeding punches, and a counter punch was designed as in figure. 2.11 by Hwang et al [86]. T-shape tube hydroforming experiments with and without a counter punch were carried out using this machine. Application of the counter punch was found to lead to 20% higher bulges protruded. In the counter punch application, the counter punch did not move in the first stage until sufficient contact is generated between the counter punch and the hydroformed material, at which moment the counter punch started to move backwards. In this way, the wall thickness reduction at the top of the branch can be halted until the end of the forming process. Different loading paths for the counter punch were investigated and a nonstop one was recommended in order to obtain the best results. Furthermore, application of the counter punch was found to be essential in the successful hydroforming of Y-shapes as it supports the protrusion while it is being formed figure 2.12. Thus, the protrusion can be formed with fine wall thickness distribution [87].

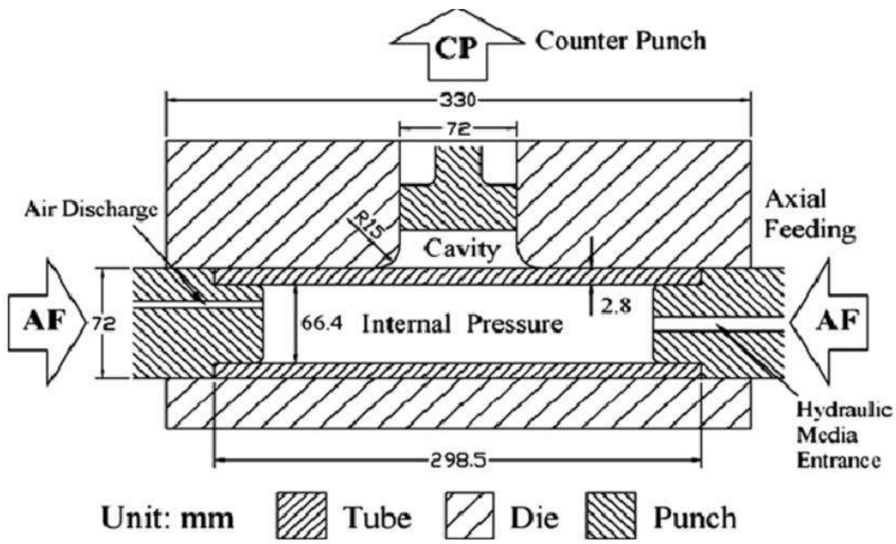


Figure 2.11: Die structure in tube hydroforming with counter punch [86]

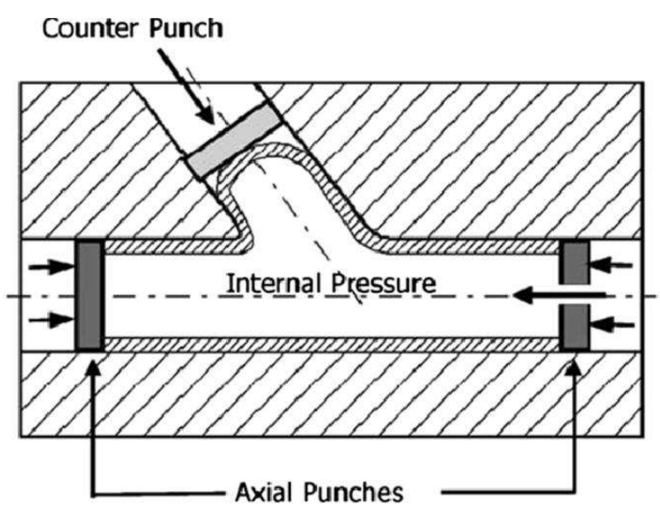


Figure 2.12: Hydroforming of Y- shapes [87]

However, in some cases like axisymmetric bulging, counter force cannot be applied due to inherent constraints. The part geometry precludes using a counter punch. Thus, the application of a dual pressure system as shown in figure 2.13 was suggested by [88] as a logical alternative.

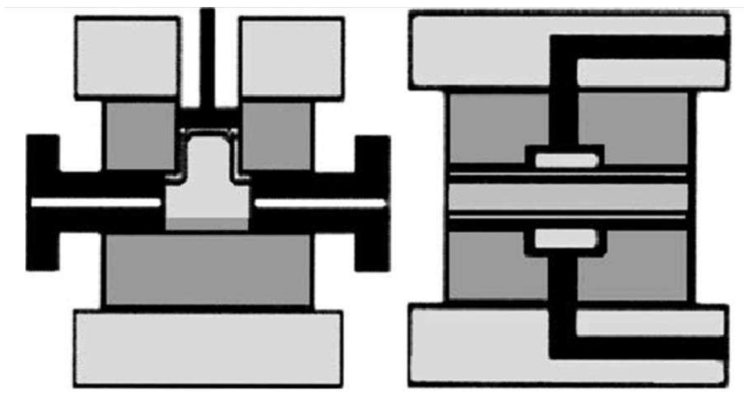


Figure 2.13: Application of a counter punch in asymmetric bulging, and application of a dual pressure system in axisymmetric bulging [88]

2.6 Summary

Amongst the unconventional metal forming processes, tube hydroforming proved to be one of the most promising. From the analytical studies summarized in the literature review, it was observed that the theoretical approach would indicate a limited understanding of the process. The application of the finite element method in the tube hydroforming process analysis was introduced, as it avoids the cost and limitations of compiling a database of real-world parts, while guidelines for the successful application of the finite element modelling were proposed. Based on a number of research studies, a detailed investigation of the factors affecting the tube hydroforming process output was revealed, in which the effects of the tube material properties, the tube and die geometries and the process parameter on the hydroformed part were examined.

However, in contrast to the large number of research studies conducted on the analysis and development of the tube hydroforming process, relatively no any investigations were found on experimental investigation of elliptical bulge Al6061 T4 Aluminium tube samples formed using tube hydroforming for the production of complex tubular parts. Elliptical aluminium tube samples can be of considerable practical advantage in complex working environments as it offers enhanced properties with lighter weight that other alloys structures cannot offer.