FINITE ELEMENT SIMULATION OF THE TUBE BENDING PROCESS

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LIST OF SYMBOLS

\( d \) : Diameter of the Tube at the Beginning
\( d_s \) : Diameter After Bending
\( d_1 \) : Diameter Measurement in the XY Plane
\( d_2 \) : Diameter Measurement in the XZ Plane
\( E_n \) : Neutral Axis Deviation
\( k \) : Geometry Parameter of the Tube
\( K \) : Strength Coefficient
\( l \) : Length of Whole Bend
\( l_c \) : Length of the Constant Deviation Sector
\( l_t \) : Length of the Transitional Sector
\( m \) : Slope of a Line
\( M \) : Bending Moment
\( n \) : Strain-Hardening Exponent
\( r \) : Radius of the Tube
\( r_c \) : Minimum Corner Radius
\( P_i \) : Internal Pressure in the Hydroforming Operation
\( R \) : Bending Radius of the Tube
\( t \) : Wall Thickness
\( t_{im} \) : Largest Thickness Located at the Innermost Point
\( t_{om} \) : Smallest Thickness Located at the Outermost Point
\( t_0 \) : Original Thickness of the Tube
\( w \) : Angle of the Constant Deviation Sector
\( W \) : Section Modulus
\( x \) : X-Displacement of the Node
\( y \) : Y-Displacement of the Node
\( z \) : Z-Displacement of the Node
\( \alpha \) : Cross-Section Rotational Parameter
\( \beta \) : Angle of the Transitional Section
\( \varepsilon \) : Strain
\( \varepsilon_0 \) : Pre-Strain or Offset Strain Constant
\( \sigma \) : Stress
\( \sigma_c \) : Circumferential Stress
\( \sigma_f \) : Flow Stress of the Material
\( (\sigma_f)_0 \) : Initial Yield Stress
\( \sigma_r \) : Radial Stress
\( \sigma_x \) : Longitudinal Stress
ÖZET

Boru bükme, uçak-uzay, otomotiv ve inşaat sektörleri de dahil olmak üzere pek çok alanda kullanılan bir işledir. Bütün boru bükme yöntemleri arasında en çok kullanılan borunun dönene İlk kalıp etrafına sardırıldığı yöntemdir. Bu yöntemde en çok karşılaşılan problemler borunun kırıması, boru şeklinin ovalleştmesi ve boru yüzeyinde kırılma meydana gelmesidir. Bu problemler, kalıpların yağlanma durumlarına, yanlış malzeme seçimine, gerekrenden ince veya kalın cidar kalınıguna sahip bir borunun kullanılmasına veya çok düşük değerde bir bükme oranı seçiminden kaynaklanıyor olabilir. Bu çalışma, iş parçası olarak kamyonlarda kullanılan dört farklı yerden bükülmüş bir boru seçilmiştir. Çalışmanın amacı, tasarım mühendislerinin proses geliştirmeye aşamasında zaman kazanma amaçlı olarak da kullanabileceğini hızlı ve doğru sonuçlar veren bir sonlu elemanlar modeli geliştirmek ve istenmeyen durumları önceden değerlendirmektir.

Bunun için, üç boyutlu Belytschko-Wong-Chiang tipi kabuk eleman tipi kullanılarak bir sonlu eleman modeli geliştirilmiştir. Sac malzemesinden ve bükülmemiş borunun üzerinden kesilen deney parçalarına çekme testi uygulanarak malzeme akma eğrileri elde edilmiştir. Prosese ait bütün veriler aynen alınmış, malzeme modeli olarak da boruden alınan parçanın çekme testi sonuçlarından çıkarılan malzeme özellikleri kullanılmıştır. Değişik bükme açılarına sahip iki farklı simulasyon kuruluşu ve çözülmüştür. Bükülen boru örnekleri üzerinden bükülmüş bölgedeki et kalınlığı değerleri ve çap değerleri ölçülmüş, bu değerler doğrultusunda şekil değişimi hesaplanmıştır. İki bükme işleminde de simulasyon sonuçlarından elde edilen değerler, hesaplanan değerler ile uyum göstermektedir.
FINITE ELEMENT SIMULATION OF THE TUBE BENDING PROCESS

SUMMARY

Tube bending is a widely used process in the aerospace, automotive, construction and other industries. Rotary-draw bending is the type that is used the most among all types of the tube bending process. The main problems that can be faced during tube bending using rotary-draw die are; wrinkling, cross-section distortion and tube breakage. The problems can be due to lubrication conditions, incorrectly selected material type or wall thickness and too small bend ratio. In this investigation, a tube that is bent at four locations to be used as a part on a heavy commercial truck was selected as the work-piece of the case study. The objective of the study was to develop a simple, fast and accurate finite element model of the tube bending process and predict undesirable conditions that may occur during the process for design engineers to use, for saving time during the set up of the operation.

To simulate the draw die tube bending process, a dynamic explicit finite element model was developed using 3-D Belytschko-Wong-Chiang shell elements. The material flow curve was obtained from tensile tests performed on both flat sheet steels as well as coupons cut out of unbent tubes. The process variables are taken as they are, and the material model properties are taken from the unbent tube tensile test results. Two different simulations with different bending angles are built and solved.

To verify the simulation results, thicknesses and the diameters of tube samples’ bent regions are measured and strain values are calculated. Corresponding results with the experimental measurements are in good agreement with the finite element simulations of the bending process results of both bends.
1. INTRODUCTION

Tube bending is a widely used process in the aerospace, automotive, construction and other industries. It is sometimes used as a final operation while it is also used as a pre-forming operation before hydroforming operations. There are types of tube bending such as roll bending, laser assisted bending and push-method, but the most commonly used one particularly in the automotive industry is the rotary-draw bending process. Rotary draw bending is basically a bending operation where the tube is wrapped around a radius block to form the required bend with or without a mandrel depending on cross section requirements.

The main problems that can be faced during tube bending with rotary-draw bending are; wrinkling, cross-section distortion and tube breakage. The correct use of the process parameters would help to avoid or minimize these defects. The important process parameters of tube bending are bend ratio, lubrication, tube thickness and tube material.

In this thesis, a tube that is bent four times to be used as a part on heavy commercial trucks is the work-piece. The objective of the investigation is to develop a simple, fast and accurate computer model of the bending process for design engineers to use, and to save time during the set up of the operation. This is achieved when correspondence between the results of the analysis that represents the bending process and the experimental results are obtained.

The material properties are defined using tensile testing, and a curve is fit in the form $\sigma = K \varepsilon^n$ to the stress-strain curve obtained from the data. The mathematical model is formed according to the exact values of the rotary draw bending machine used for the process. This model is imported in the ANSYS program and using the material model, the geometrical model is meshed, the contacts are defined and the boundary conditions are applied to the model. The results are compared with the experimental results and it is approved that the simulation results mostly meet with the experimental results.
In the second chapter, brief information is given about tube hydroforming and the effects of tube bending on hydroforming since tube bending is the pre-forming operation of the hydroforming operations. The tube bending process is explained in detail, with the tooling, the process parameters and the defects that may occur. Plastic-deformation theory of Tang has found practical formulae for seven common tube-bending questions: Stresses in the bend, wall thickness change, shrinking rate at the tube section, and deviation of neutral axis, feed preparation length of the bend, bending moment, and flattening. These equations are given as a headline in this section.

In the third chapter, the process’ importance in the automotive industry is clarified and the previous uses of finite element method with tube bending examples are also given in detail. The work piece of the study is also introduced in this section.

In the fourth chapter, the performed simulations of the two bends with different bending angles which are 106 and 46 degrees are given in detail with the element type choice, real constants definitions, defining material models, meshing the model, defining components and parts, defining contacts between components and specifying loads. The strain values are read and from the deformed shapes node coordinates the diameter of the bent region is calculated. The strain values and the diameter values are compared with the experimental values.
2. TUBE BENDING

The principles of tube bending are similar to bar bending, except that since the tube is hollow, an internal support is normally needed. The internal support is provided by a mandrel inserted inside the tube prior to the bending operation. In practice, there exist several types of mandrels such as, rigid, flexible and articulated. The main purpose of the mandrel is to avoid wrinkling and collapse of the tube during the bending process. Generally, tube geometry and radius of the bend determine whether a mandrel is needed, and if so, the type necessary. In fact, as a general guideline, when the ratio of the center line radius to the outside diameter of the tube is less than 1.7, then collapse may take place for any ratio of outside diameter to wall thickness. The use of suitable lubricant is very essential; otherwise the friction force can be high enough to damage the surface.

It is generally accepted knowledge that residual stresses are purely elastic even if they result from plastic deformation. They may be sufficiently large to cause fracture of the material in a brittle manner. Residual stresses may, under certain conditions, cause failure of the structure at a lower applied load than that predicted. Therefore, it is extremely important to determine the residual stress distributions throughout the section of the material [1].

2.1 Tube Hydroforming

In the tube hydro-forming process the tubular blank is preformed by bending and inserted into an axially or radially split die. Then the die is closed crushing the tube and the tube is sealed at each end. Finally, hydraulic liquid fills the tube and hydraulic pressure is applied inside the tube while simultaneous axial loading is applied at the ends of the tube pushing it into the die. The tube wall is pressed and the internal contour of the die and part is formed (Figure 2.1). Thus the internal pressure and the axial loading are the two key parameters of the process. These two parameters have to be optimized for the successful operation of the process [2].
In comparison to traditional stamped and welded parts, tube hydro-forming offers several advantages such as: part consolidation (instead of welding two or more parts together, a single part can be made through hydro-forming); weight reduction through efficient section design; lower tooling and manufacturing costs due to a reduction in the number of parts; tight dimensional tolerances and minimal spring-back; and reduced scrap [3]. On the other hand, since the application of tube hydro-forming technology into mass production is relatively new compared to other metal forming processes such as stamping and forging; existing knowledge base, design rules, and experience for design of part, process and tooling are limited. As a result, this leads to high development cost, which decreases the competitiveness of tube hydro-forming process [4].

2.1.1 Failure modes
In tube hydro-forming, the ultimate goal is to form a blank tube (either straight or pre-formed) of usually uniform cross-section into a die cavity of complex shape with varying cross-sections without causing any kind of forming instability such as
bursting, necking, wrinkling or buckling. In order to achieve this goal, some measures and alterations need to be performed during the design procedure and trials. These measures can be in terms of:

- Altering the part design, i.e. smooth transitions, cross-sectional perimeter reductions, generous corner radii, etc.
- Changing initial parameters, i.e. tube diameter, thickness, length, material
- Changing the process design, i.e. use of internal pressure, end feeding and occasionally counter punches at the protrusion regions in a properly coordinated manner [5].

There are three types of failure modes of tube hydro-formed components:

(a) Buckling - This is caused due to excessive axial compressive deformation.
(b) Wrinkling - This is caused due to excessive axial compressive loading or insufficient internal pressure.
(c) Bursting - This is caused due to the thickness of the tube blank being smaller than needed to sustain the hoop stresses caused by internal pressure or due to the axial loading being insufficient (Figure 2.2).

![Fig. 2.2: Common Failure Modes That Limit the Tube Hydroforming Process. (a) Wrinkling; (b) Buckling; (c) Bursting [5]](image)

Buckling of tubes as a column is observed when a tube is long and has relatively thick walls. Wrinkling occurs when a tube is either short or long but with thin walls. However, there is no definite boundary between buckling and wrinkling conditions since they are both dependent on combination of many other factors such as material, edge conditions, geometry, imperfections and loading types.
Bursting as a result of localized thinning (necking) in sheet metal forming is a consequence of excessive tensile stresses. It is an instability situation that causes fracture eventually. When the sum of tangential (hoop) and longitudinal strains goes beyond the strain-hardening exponent \((n)\) of the material at any area on the tube at any time during forming, necking will begin at that local area.

### 2.1.2 Effect of internal pressure

Internal Pressure \((P_i)\) should be:

- High enough to prevent buckling due to excessive compressive axial force at the initial stages of hydro-forming. This value, \((P_i)_{\text{min}}\) is determined by the minimum \((P_i)\) required for preventing buckling or wrinkling at very beginning of the forming.

- High enough to start deformation of the tube walls at the initial stages of deformation. It is usually dictated by the yield strength of the tubular material.

- High enough to form the tubular material into intricate die cavities (such as corners). This limit, \((P_i)_{\text{max}}\), is dependent on the ultimate tensile strength, corner radius and thickness.

- High enough not to allow any wrinkling during the intermediate stages of the forming due to excessive compressive axial force.

- Low enough not to cause instability by necking (i.e. bursting pressure).

Maximum internal pressure, \((P_i)_{\text{max}}\), can be expressed as

\[
(P_i)_{\text{max}} = \frac{2}{\sqrt{3}} \sigma_f \left[ \ln \left( \frac{r_c}{r_c - t} \right) \right] \tag{2.1}
\]

where \(\sigma_f\) is for flow stress of the material (usually Ultimate Tensile Strength is used), \(r_c\) is for minimum corner radius and \(t\) is for wall thickness [5].

### 2.1.3 Effects of tube bending on hydroforming

All metals that are strained tend to become stronger. This phenomenon is often referred to as strain-hardening or work-hardening. Caution must be exercised while using this increased yield strength as a basis for stress analysis because the effect will be lost in the immediate vicinity of any welding, owing to local annealing.
During the bending process, the tube undergoes significant cold work. Often it is the bending process rather than the hydro-forming operation that establishes the minimum allowable material-formability properties [6].

Nearly all complex hydro-formed parts require a tube bending operation prior to hydro-forming. Tube bending often strains the material to a greater degree than the subsequent hydroforming operation; therefore much of the material's ductility is exhausted during tube bending. It is observed that larger bend radii in the bending process resulted in reduced material thinning and strain levels, which lead to improved formability during the subsequent hydro-forming operation. Positive boost during tube bending has been shown to decrease material thinning, thereby increasing the formability of pre-bent tubes during hydroforming [3].

2.2 Rotary-Draw Bending

This process is basically a metal drawing operation where the tube is wrapped around a radius block to form the required bend(s). The principles of the rotary-draw bending process and the tooling required are as follows.

2.2.1 Tooling

The bend die, clamp and pressure die are required in all rotary draw bending applications. Under certain conditions, depending on the tube diameter, wall thickness and bend radius, two additional tooling pieces may be required to provide additional support for the material during the bend, which are the mandrel and the wiper die (Figure 2.3).

![Fig. 2.3: Tooling of Rotary-Draw Bending [7]](image-url)
2.2.1.1 The bend die
The bend die (radius block) provides the radius about which the tube is formed. The outside radius of the die has the profile of half the tube cross-section, to contain the tube during bending. The radius block also includes a straight length, tangential to the radius, to provide an area in which the tube can be gripped for bending.

2.2.1.2 The clamp block
The clamp block mates with the straight clamping area on the bend die and hold the tube in position during bending. Both the bend die and the arm of the bender are mounted on another arm that rotates about the center of the bend die. It is this rotary action that pulls the tube to form the bend around the die.

2.2.1.3 The pressure die
The pressure die (also known as the reaction block and/or follower die) is located so as to provide the reaction force to the bending torque. When the bend die and clamp rotate with the tube clamped in place, the natural tendency of the tube is to remain straight and simply rotate with the die. The reaction block contains the trailing end of the tube and keeps it aligned with the bed of the machine thus forcing the tube to bend around the radius block. A second function of the pressure die is to provide forward boost to the tube during bending. This is typically accomplished using a hydraulic cylinder that pushes the die forward during bending thus helping to move material along the outer wall of the tube into the bend area.

2.2.1.4 The mandrel
During the bending process, the material along the outer wall is under a considerable tensile load that can lead to excessive flattening of the outer wall of the tube unless the material is supported from the inside. This internal support is provided by a mandrel that consists of a straight shank portion and one or more balls connected by flexible links or ball joints. This mandrel is slightly smaller than the inside diameter of the tube and prevents the tube from collapsing during bending [6].

Mandrels are usually made from the same materials as the wiper die, usually steel with hard chrome plating or aluminum bronze, depending on material being bent. For example, an aluminum-bronze mandrel should be used when bending stainless steel, Inconel and other exotic materials. A hard chrome plated steel mandrel should be used when bending aluminum, mild steel, copper, and titanium [7].
Sometimes the mandrel has balls which are the parts of the mandrel assembly that supports the arc of the bend from flattening along the outside radius after the tube has passed through the point of bend. Especially, bends with small diameters and thin-wall tubes require more support around the bend and these usually require ball links on the end of the mandrel [8]. There are basically five types of mandrel.

1) Plug mandrel is used for heavier walled tube or large bend die radius (Fig. 2.4).

![Fig. 2.4 : Plug Mandrel [7]](image)

2) Formed end plug mandrel is used for similar applications as plug mandrel but the formed end is machined to match the bend die radius of the bend to provide more support on inside of the tube (Fig 2.5).

![Fig. 2.5 : Formed End Plug Mandrel [7]](image)

3) Standard mandrel is the most widely used type of mandrel because it covers the widest range of bending applications. Standard mandrels are made with one ball or can be made with any amount of balls. The standard mandrel is the most durable of the three flexible mandrel configurations because it uses the largest size links possible (Fig 2.6).

![Fig. 2.6 : Standard Mandrel [7]](image)

4) Thin wall mandrel (sometimes referred to as close pitch mandrel) is used mostly for thin wall tubing. Thin wall style mandrels use the same style linkage as standard mandrels except the size of the link is the next size smaller than it would be on a standard mandrel. The ball segments are closer according to the standard mandrel
and more support is needed for thin walled tube bending. Strength is sacrificed for more support (Fig 2.7).

![Fig. 2.7 : Thin Wall Mandrel [7]](image)

5) Ultra thin wall mandrel is used with very thin wall tube. Ultra thin wall mandrels use the same style links as the standard and thin wall mandrel, but the size of the link is the next size smaller than the thin wall size link or 2 sizes smaller than the standard mandrel. The ball segments are closer according to the thin wall mandrel and even more support is needed for thin walled tube bending. Again, strength is sacrificed for more support (Fig 2.8) [7].

![Fig. 2.8 : Ultra Thin Wall Mandrel [7]](image)

2.2.1.5 The wiper die

While the outer wall is under tensile load, the material along the inside of the bend is subjected to high compressive forces. If the compressive force exceeds the column strength of the material, the inside wall tends to buckle leading to wrinkles along the inside of the bend. To prevent this, a wiper die is added that, in conjunction with the mandrel inside the tube, gives support to the inner wall [6]. The material the wiper die is made from is also important. Steel is preferred for bending aluminum, copper, or mild steel; Aluminum-bronze for bending stainless steel, Inconel and titanium. The steel wiper dies can also be hard chrome plated to help reduce friction [7].

2.3 Principles of Rotary-Draw Bending

The tube-bending sequence begins with the tube being advanced along its axis and rotated, to position it where the bend needs to be formed. Once in place, the clamp closes against the corresponding clamping area on the bend die so as to grasp the tube and the pressure die closes on the tube to keep the trailing end of the tube
aligned with the machine. If a mandrel is being used, the mandrel also advances to move the flexible ball section into the area of the tube being formed. With all the tooling in place, the bend die and clamp are rotated by the desired amount pulling the tube along with them. At the same time, the pressure die is boosted forward to help move material into the bend to reduce wall thinning.

When the bend is complete, the mandrel is retracted back out of the bend area. This motion reforms the material to some degree where the outer wall has collapsed slightly between the mandrel balls. When the mandrel is clear, the clamp and pressure die release the tube and it can be indexed into the position for the next bend. The bending process reduces the cross-sectional area of the tube in the bend area. This effect becomes more pronounced as the bend radius becomes tighter. This factor is also affected by the size of the mandrel relative to the inside diameter of the tube at the start, since the tube will collapse down to the size of the mandrel during bending. Finally, allowance must be made for spring back. This is usually greater for large bend radii and high-strength materials and must be compensated for by over-bending [6].

The procedure can be summarized as:

1. Mandrel in.
2. Clamp die in.
3. Pressure die in.
4. Arm swings forward.
5. Arm stops.
7. Clamp die and pressure die retract.
8. Arm returns to zero position [7].
2.4 Plastic-Deformation Analysis in Tube Bending

Tang developed an analytical model and practical closed form solutions for seven common tube-bending questions: Stresses in the bend, wall thickness change, shrinking rate at the tube section, and deviation of neutral axis, feed preparation length of the bend, bending moment, and flattening. An experimental sample was also tested to illustrate that the results of the formulae are very close to the experimental results.

In the outer semi-circle of the tube, the longitudinal stress $\sigma_x$ is tensile, and the circumferential stress $\sigma_c$ is compressive. Since the wall thickness is much smaller than the radius of the tube, the radial stress $\sigma_r$ can be neglected. By the maximum-shear-stress theory, the relation between the two stresses is given by

$$|\sigma_x| + |\sigma_c| = \sigma_f$$  \hspace{1cm} (2.2)

where $\sigma_f$ is the yield strength of the tube material.

Then the longitudinal and the circumferential stresses are, respectively, expressed by the following equations:

$$\sigma_x = \frac{\sigma_f}{2k+2 - \cos \alpha} \left(\frac{2k+1}{2k+2 - \cos \alpha}\right)$$  \hspace{1cm} (2.3)

$$\sigma_c = -\sigma_f \frac{1 - \cos \alpha}{2k+2 - \cos \alpha}$$  \hspace{1cm} (2.4)
where \( \alpha \) is the cross section rotational parameter; \( k \) is the geometry parameter of the tube which equals to \( R/2r \); \( R \) is the bending radius of the tube and \( r \) is the radius of the tube. The range of \( k \) in Tang’s paper is 1.4-30.

The smallest thickness is located at the outermost point and it is expressed as

\[
t_{\text{om}} = \left(1 - \frac{2k + 1}{2k(4k + 2)}\right)t_0
\]  

(2.5)

where \( t_0 \) is the original thickness of the tube wall.

The largest thickness is located at the innermost point and it is expressed as

\[
t_{\text{in}} = \left(1 + \frac{2k + 3}{3k^2}\right)t_0
\]  

(2.6)

The diameter shrinking \( d_s \) is expressed as

\[
d_s = \left(1 - \frac{0.16}{k + 0.8}\right)d
\]  

(2.7)

where \( d \) is the diameter at the beginning and \( d_s \) is the diameter after bending operation.

Since the longitudinal stress in the outer half is smaller than in the inner half and the outer wall is thinner than the inner wall for balance of the moment of the internal force, the neutral axis should move to its inner side as shown in Figure 2.10. The neutral axis deviation can be calculated by

\[
E_n = \frac{0.42}{k}r
\]  

(2.8)

The preparation length of the whole bend is

\[
l = l_c + l_t = Rw - E_n(w + B)
\]  

(2.9)

where \( l_c \) is the length of the constant deviation sector, \( l_t \) is the length of the transitional sector and \( \beta \) is the angle of the transitional section.
The bending moment on either side of the neutral axis is equal. The total internal bending moment can be expressed as

$$M = \sigma W \left( 1.41 + \frac{0.42}{k} \right)$$  \hspace{1cm} (2.10)$$

where \( W \) is the section modulus and is given by

$$W = 0.1 \left( \frac{D^4 - d^4}{D} \right)$$  \hspace{1cm} (2.11)$$

It is likely that for uniform load acting on a half-ring bridge, the worst-case of flattening is on the top part. Flattening or ovalization is mostly determined by technology and mold design. The critical point where flattening starts is when the ring bending reaches the elastic limit. When,

$$R \leq \frac{3.43r^2}{t_0}$$  \hspace{1cm} (2.12)$$

flattening should occur without any special control.
After the experiments, Tang found out that, even for such big strain and thinning at the extrados of the elbow which is the part of the tube that is exposed to the tensile forces; for internal high pressure testing, the failures occur in the straight portion and not at the elbow. This can be explained by some associated factors, such as extrados shape and strain hardening. In his experiment, pure bending method was used, i.e. non-mandrel and non-booster [9].

2.5 Process Variables During Bending

The process variables were observed to be sensitive to $R/d$ ratio, pressure die clamp load, lubrication conditions, tube thickness, and tube material [3]. Below, influence of each one is discussed, respectively.

2.5.1 $R/d$ bend ratio

The need for a mandrel depends on the tube and the bend ratios. The tube ratio is $d/t$ where $d$ is the outer diameter and $t$ is the wall thickness. The bend ratio is $R/d$ where $R$ is the radius of the bend measured to the centerline [2].

In order to quantify the level of plastic strain and work hardening after tube bending, strain measurements on steel and aluminum tubes after mandrel rotary draw bending are observed by researchers at three different $R/d$ ratios. All the researchers found that the axial strains in bent tubes increase with decreasing $R/d$ ratios. The hoop strains, however, were not observed to vary appreciably with changes in $R/d$ ratio. Thickness measurements were also performed and they observed that decreased $R/d$ ratio led to increased thinning on the outside of the bend and increased material thickening on the inside of the bend. Similar experiments are performed on stainless steel tubes after radial-draw bending and came to similar conclusions [3].

2.5.2 Lubrication

Lubrication is an important aspect to making good bends. Lubrication comes in several different forms such as oil, grease, and paste. The kind of lubrication used will depend on the material of the tube to be bent. A generous amount of lubrication may be applied to the mandrel and the inside of the tube; however, precautions should be taken to avoid getting any lubrication on the bend die and clamp die. The amount applied will determine whether or not a good bend is made [7].
Radial draw bending of stainless steel tubes are performed by a researcher using three different lubricants. It is observed that mandrel loads could be reduced by as much as 40% by changing the lubricant. The reported mandrel loads were over five times higher when lubrication was not used at all. Improving the lubrication conditions reduced the amount of tube wall thinning by almost 20%.

The wiper die is lubricated in order to further reduce friction, while the clamp die, pressure die and bend die are kept dry in order to maximize friction and minimize slip during bending. The inside surface of the tube is lubricated via holes in the mandrel in order to reduce friction with the mandrel during bending, which in turn reduces the torque required to complete the bend [3].

2.5.3 Tube thickness
The wall thickness of the tubing affects the distribution of tensile and compressive stresses in the bending. A thick wall tube will usually bend more easily to a smaller radius than a thin wall tube [2].

2.5.4 Tube material
Strain-hardening is a phenomenon exhibited by most metals and alloys in the soft condition whereby the strength or hardness of the material increases with plastic deformation.

Material in which the same properties are measured in any direction is termed isotropic, but most industrial sheet will show a difference in properties measured in test-pieces aligned, for example, with the rolling, transverse and 45° directions of the coil. This variation is known as planar anisotropy.
If the material is isotropic, the effective stress–strain curve is coincident with the uniaxial true stress–strain curve and a variety of mathematical relations may be fit to the true stress–strain data. Some of the more common empirical relations are shown in Figure 2.11 and in these diagrams elastic strains are neglected. In the diagrams shown, the experimental curve is represented by a light line and the fitted curve by a bold line.

A simple power law,

\[ \sigma = K\varepsilon^n \]  \hspace{1cm} (2.13)

will fit data well for some annealed sheet, except near the initial yield; this is shown in Figure 2.11 (a). The exponent, \( n \), is the strain-hardening coefficient. The only disadvantage of this law is that at zero strain, it predicts zero stress and an infinite slope to the curve. It does not indicate the actual initial yield stress.

Although it requires the determination of three constants, flow curve model

\[ \sigma = K(\varepsilon_0 + \varepsilon)^n \]  \hspace{1cm} (2.14)
is useful and will fit a material with a definite yield stress as shown in Figure 2.11 (b). The constant $\varepsilon_0$ has been termed a pre-strain or offset strain constant. If the material has been hardened in some prior process, this constant indicates a shift in the strain axis corresponding to this amount of strain as shown in Figure 2.11 (b). In materials which are very nearly fully annealed and for which $\varepsilon_0$ is small, this relation can be obtained by first fitting equation 2.13 and then, using the same values of $K$ and $n$, to determine the value of $\varepsilon_0$ by fitting the curve to the experimentally determined initial yield stress using the following equation [10].

$$ (\sigma_f)_0 = K\varepsilon^n $$

(2.15)

For this study, the tube material used for bending is a type of cold-rolled steel with a chemical composition of 0.07-0.1 % C, 0.020-0.035 % S, 0.015-0.0035 % P and 0.35-0.45 % Mn.

In order to designate the material behaviour of the tube sample, nine tensile tests have been done according to the standard TS 138 EN 10002-1 [11]. These samples are three test-pieces with the rolling direction, two pieces of 45° direction, and two pieces with the transverse direction of rolling. Besides these sheet pieces, two tests have been done to the two pieces that have been cut out from the tube. Figure 2.12 (a) shows the samples used in the tests. The tube samples are prepared for the machine by crushing the grasping ends as suggested in the standard. (Figure 2.12 (b))

The width and the thickness are measured for each sample at five different lengths, and their average is taken to be used in the cross-sectional area calculations. These values are shown in Table 2.1.
These average values are entered in the tensile test machine and the strain-stress data is given by the program. Besides the data values to draw the engineering stress-strain curves, the true values with the changing area values are calculated and true stress-strain curves are drawn.

The graphs that are drawn according to the tube sample data are fitted into a power-law model with the values between the metal flowing part and the necking part of the graph. The true stress-true strain curve fit for the first tube sample is shown in Figure 2.13 while the true stress-true strain curve fit for the second tube sample is shown in Figure 2.14.
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Table 2.1: Measurements of the Samples After Tensile Testing
The tube sample has higher stress values than the sheet samples as shown in Figure 2.15, and this is due to strain-hardening of the material when roll-forming of the tube.

**Fig. 2.13:** The True Stress-True Strain Curve for the Tube Sample 1, the Equation Stands for $\sigma=541\varepsilon^{0.14}$, $K=541$ and $n=0.14$

**Fig. 2.14:** The True Stress-True Strain Curve for the Tube Sample 2, the Equation Stands for $\sigma=571\varepsilon^{0.15}$, $K=571$ and $n=0.15$
2.6 Tube Bending Defects

Normally, the bending of tubes, while at first glance of a simple nature, involves several problems, the chief of which is the tendency of the material to wrinkle and buckle, cross-section distortion and fracture. The bendability of a tube depends on geometrical factors such as the bend radius, the diameter and the thickness of the tube.

2.6.1 Wrinkling

If wrinkling occurs in a compressive area of the tube during the bending process, a mandrel and wiper die are used to suppress the wrinkling [12]. For this reason, the bending operations are sometimes performed by inserting the articulated-linked ball mandrel inside the tube [1]. Evidently, the mandrel was used mainly to prevent collapse of the tube or uncontrolled flattening in the bend.
Fig. 2.16: Wrinkles After Bending [8]

Tube wrinkling may be caused by the following:

1. Tube slippage in clamp die.
2. Mandrel is not far enough forward.
3. Wiper die is not far enough forward.
4. Wiper die is worn or not fitting properly.
5. Too much clearance between mandrel and tube.
6. Not enough pressure on the pressure die.
7. Excessive lubrication being used [7].

The prediction of wrinkling in tube bending processes has been a challenging topic. The analysis of a curved tube can be characterized as buckling of a sheet with double curvatures. The analytical model for the onset of the wrinkling of an elastic-plastic doubly-curved sheet is developed in Wang and Cao’s paper using the energy method and the effective compressive area, which is the actual area under compression in the tube obtained from stress analysis either analytically or numerically.

They found that the minimum bending radius increases with an increase in tube radius and a decrease in tube thickness. For materials, aluminum and stainless steel, the normalized critical die radius tends to increase with tube radius. When the normalized tube radius $2r/t$ is small, i.e., close to 10, there is no distinguishable difference between two materials. However, with increased $2r/t$, the steel shows lower critical die radius
than aluminum, i.e., has better formability in tube bending. When the strain hardening exponent $n$ is in the range between 0.05–0.25, which are typical values for most carbon steel and aluminum materials, critical die radius changes little with $n$. When $n$ increases beyond 0.25, the critical die radius decreases dramatically. The change of critical die radius with material strength coefficient $K$ is relatively unnoticeable for material with a higher strength, i.e., when $K$ is greater than around 600 MPa. Only when $K$ is lower than around 600 MPa, it can be seen that a higher $K$ yields a higher critical die radius. It appears that the effect of strength coefficient $K$ on critical die radius is relatively insignificant for most high strength materials [13].

### 2.6.2 Cross-section distortion

The material along the outer wall is under a considerable tensile load that can lead to excessive flattening of the outer wall of the tube (Figure 2.17). The stress can be reduced by using a larger bend centerline radius. It is important to support the tube with a mandrel, unless the material is supported from the inside. A mandrel wears with use, and as it wears, the tube may show signs of excessive flattening in the bend area. Small radius of bends and thin-wall tubes require more support around the bend. These usually require ball links on the end of the mandrel. The cross-sectional shape can also be supported by increasing the wall thickness [8].

![Excessive Flattening After Bending](image)

**Fig. 2.17** : Excessive Flattening After Bending [8]
2.6.3 Tube breakage

Tube breakage can be caused by several things; it can be a ductile or a brittle failure. A ductile failure is indicated if there is considerable stretching and thinning of the material on each side of the break and the edges of the break are ragged in appearance. A brittle failure is very abrupt, with no stretching of the material, and the edges of the break appear almost clean and shiny-looking. Figure 2.18 shows an example of a brittle fracture. Materials with high tensile strength and hardness tend to exhibit brittle failure, whereas materials such as mild steel tend to have ductile failure [8].

![Fig. 2.18: Tube Breakage After Bending [8]](image)

Tube breakage may be caused by the following:

1. Material does not have the proper ductility and elongation properties.
2. Tube slippage in the clamp die.
3. Too much pressure on the pressure die causing excess drag.
4. Material is wrinkling and becoming locked between the mandrel balls
5. Not enough lubrication is being applied, or the wrong type of lubrication is being used.
6. Mandrel is advanced too far forward past tangent [7].
2.7 Other Types of Tube Bending

It is observed that rotary draw bending was the best method for pre-bending tubes prior to hydroforming. The use of a wiper die and a mandrel is also an important manner in this type of bending; even the choice of a mandrel plays an important role on the hydroforming operation. Through the use of finite element simulations of the bending and hydroforming processes, a researcher found a substantial improvement in the hydroformability of pre-bent tubes when using a four-ball mandrel as opposed to a cylindrical mandrel (a standard mandrel) [3].

The method selected for a particular application depends on the equipment available, the number of parts required, the size and wall thickness of the tubing, the work metal, the bend radius and the number of bends in the work-piece [2].

2.7.1 Push method of tube bending

Zhang and Redekop simulated the push bending process for the forming of curved tubes using the finite element method in their paper. In their model, a tube in a die is pushed from back with an axial load, and the tube takes the shape of the die as shown in Figure 2.19.

![Symbolic Representation Before and After Forming](image)

Fig. 2.19 : Symbolic Representation Before and After Forming [14]
As the bend radius decreases, the thickness at the extrados (tensile part) decreases and the thickness at the intrados (compressed part) increases. Furthermore, the maximum Von Misses stress increases as the bend radius is decreased. It is clear that there is a difficulty in bending of a very small radius tube. For a low value of wall thickness there are obvious problems: there is easier breakage and erosion, and even the potential for buckling. Furthermore, the stress is important in the process; in the tensile part if the stress exceeds the ultimate stress of the material the tube will fail. The wrinkling of course is a problem at the intrados in the compressed part. To control the wrinkling problem a higher internal pressure could be applied, or a longer forming time used. A higher internal pressure would imply a stiffer mandrel, with a larger Young’s modulus.

A number of parameters affect the forming results, including bend radius, internal pressure, material, friction coefficient, and process time. The bend radius is an essential parameter; as it is decreased difficulties arise. Inner pressure is important in maintaining the shape of the tube, and specifically to reduce wrinkling. Material properties are also important parameters for the forming. The friction coefficient is less important, but when it is larger than 0.2, an undesirable shape containing wrinkles is generated. Limiting the coefficient to 0.15 is required for good lubrication. A final method of controlling wrinkling is to vary the forming time [14].

Zeng and Li introduced a tube push-bending process combining axial forces and internal pressure in their paper. The outside forces applied to the tube and the effects of the internal pressure, friction condition and push distance on the tube deformation are analyzed with mechanical analysis and experiments. Aluminum alloy tube components with a bend radius that is equal to the tube diameter were manufactured in the process.

The following conclusions are reached:

1. Wrinkles and cross-section ovality will take place at the inside of the bend zone when the internal pressure is very small. With the increasing of the internal pressure, the ovality and wrinkles can be eliminated.

2. Too-bad and too-good a friction condition are detrimental to tube bending. A perfect tubular part is able to be manufactured under a suitable friction condition.
3. It is the limitation for the push-bending process that only short bent components can be manufactured, due to the fracture occurring at the head of the tube.

4. It is proven by experiment that tubular parts with a bend radius that is equal to the tube diameter can be formed with the push-bending process [15].

2.7.2 Laser Bending

Laser bending is a laser process with potential for use in line bending or spatial forming of metal components. The process is achieved by introducing thermal stresses into a work-piece by controlled irradiation with a focused laser beam. Unlike mechanical forming, there is no spring-back effect.

Laser bending of tubes has the following advantages over mechanical bending of tubes. Neither a hard bending tool nor external forces are required, and thus the cost of tube bending is greatly reduced for small-batch production and prototyping. Wall thickness reduction seems to be avoided and lesser ovalization results. With the flexibility of the laser beam delivery and numerical control systems, it is easier to automate the process. Tube laser bending has the potential to deal with materials whose bending normally requires repeated annealing when conventional mechanical means are used.

The mechanisms of laser bending of tubes are combinations of thickening of the laser-scanned region due to thermally induced axial compressive stress, and a slightly outward displacement of the region caused by a component of the thermally induced circumferential compressive stress. As a result, bending is primarily achieved through the thickening of the scanned region instead of the thinning of the unscanned region, and the scanned region assumes a slightly protruded shape. The absence of appreciable wall thinning is one of the major advantages of laser bent tubes. Cross-section ovalization of the laser-bent tubes is also much smaller than that observed in comparable mechanical bent tubes due to lack of bending die and appreciable tensile stress/strain in the extrados. The bending radius is governed by the laser beam diameter, not by tensile failure at the extrados. The curvature radii of the bent tube increase with the beam diameter and the ratio of the tube outer diameter to the wall thickness. The bending efficiency increases with the maximum scanning angle up to a critical value. Asymmetry of the bending
process can be reduced by varying the scanning speed or employing a two-segment scanning scheme [16].

2.8 An experiment on tubes with square cross-section

A tube may not always have a circular cross-section. Utsumi and Sakaki studied the positive effects of additional axial tension and the presence of a center rib of a tube that has a square cross section using the finite element method. According to the simulations they have done, it is seen that when adding axial tension to the working conditions, although the wrinkling disappears, a flattening distortion arises due to the lack of a mandrel. When using a tube with ribs without axial tension, it is observed that there is only a slight flattening distortion.

Under working conditions for the tube that does not have a rib with additional axial tension without a mandrel, wrinkling does not occur, but the concave distortion is large due to the axial tension. In the case of tube that has a rib, these distortions are minimal due to the lack of axial tension and the presence of a center rib in the tube.

Considering the case of a maximum bend degree, for example, using a tube that does not have a rib, the bend degree can reach 0.42 without any defects. Using a tube that has a center rib, the bend degree can reach 0.57 without any defects [17].
3. THE TUBE BENDING TECHNOLOGY OF HYDRO-FORMING PROCESS FOR AN AUTOMOTIVE PART

Automotive parts made of steel sheet, steel bar, or forged steel have often been substituted with hollow parts made of steel tube in recent years, as an effective way of simultaneously reducing the car body weight to improve fuel consumption and of strengthening the car body for occupant protection. The steel tubes for these parts are requested to have higher performance than ever, including the ability to withstand extremely severe plastic working, even though they are high strength steel tubes and high carbon steel tubes [18].

3.1 Process in the Automotive Industry

The motivation towards vehicle weight reduction within the automotive sector has created a need for the replacement of mild steels with thinner gauge high strength steels and lightweight aluminum alloys. The impetus for weight reduction is to boost vehicle performance, and most importantly, to increase fuel economy and lower greenhouse gases; it has been reported that a 15% reduction of the weight of all vehicles in North America and Europe is equivalent to a savings of 800 million liters of fuel annually. A substitution towards thinner gauge high strength steels presents several challenges. The first challenge involves structural stiffness; since the modulus of elasticity is essentially a constant, provision is necessary to ensure adequate structural stiffness of the components made from thinner gauge materials. The formability and weldability of these new materials are additional challenges that must also be addressed. The final challenge is to ensure that the crashworthiness of automobiles is not degraded as a result of the substitution. In order to overcome the latter obstacle, extensive research into the manufacturing processes involved in fabricating crush structures and their effects on the crashworthiness of the structures is imperative.
Due to the complex shapes of automotive structural components such as s-rails, pre-forming operations, particularly tube bending are often needed. Mandrel rotary-draw tube bending is the most commonly used of all pre-forming bending processes due to its accuracy and repeatability [3].

![Fig. 3.1: (a) S-Rails in Automotive Frames; (b) Idealized S-Rail Structure [2]](image)

When a high strength tube is bent to a small bending radius, the fracture caused by the wall-thickness reduction (especially, local necking) at the extrados (the outer side of the bend) must be prevented. Accordingly, it is important to assure ductility of the mother tube and to suppress wall-thickness reduction by optimizing the bending conditions.

To investigate the influence of mechanical properties and working conditions on the maximum wall-thickness reduction rate during rotary draw bending, the experimental results of the rotary draw bending for steel tubes were applied to the statistical analysis. Consequently, for smaller bending radius, it becomes increasingly important to improve the mechanical properties in order to suppress the wall-thickness reduction. When applying the tube hydroforming process to the forming of three-dimensional parts with complex cross-sectional shapes, the bending technology in the preliminary forming stage is particularly important [18].

Yang worked on simulation of pre-bending and hydro-forming processes that are used to form an automotive part, which is a tie bar. Two types of pre-bending simulations, by a rotary draw bending machine and a bend die, are carried out to obtain the shape change of the cross-section and the thinning of the tube. A parametric study is carried out to obtain the effect of the forming parameters such as bend radius and tube thickness.
The pre-bending model using a bend die is composed of a tubular blank and an upper and lower die. The rotary draw-bending model is composed of a tubular blank, a bend die, a clamp die, a pressure die and a wiper die to prevent wrinkling. The models are shown in Figure 3.2.

![Diagram of Die Models](image)

**Fig. 3.2**: (a) Bend Die Model; (b) Rotary-Draw Bending Model [12]

In case of bending with the mandrel, the section shape remains close to circular, but the thickness reduction is the largest. When the bend radius is small, the deformation of the section is increased and the thickness is reduced. In the case of bending with the bend die, the shape of the section is similar to that of draw bending, but the thickness reduction is the smallest. In order to find the effect of the tube wall thickness, finite element method simulations were performed with three different thicknesses 1, 2 and 3
mm. The thickness strains of the bending with various initial tube thicknesses are similar to each other [12].

3.2 Bent Steel Tube for Heavy Commercial Trucks

The tube that the simulations performed on is a tube which has a length of 2 m, an outer diameter of 40 mm and a thickness of 2 mm. It is bent at four locations, and the part is a symmetric part which means that the first two of the bends are the same as the last two bends. These two bends have the bending angles of 106° and 46° respectively. The bending operation is shown in Figure 3.3.

The part is used in different types of trucks, and its function is holding the part which is connecting the tire to the truck, in all types.

Fig. 3.3 : The Part’s Location on the Trucks
Fig. 3.4: The Bending Operation of the Part; Starts with the Clamping and Continues with the First, Second, Third and the Fourth Bending
3.3 Finite Element Method

Previously, finite element simulations of tube bending operations are done by some researchers, two of the important research papers are prepared by Grantab and by Mahanty and Balan; following are the detailed explanations they made to describe how they built the simulations.

3.3.1 Material characterization for tube forming simulations

In order to simulate the tube bending and hydro-forming processes using FEM, accurate tube material properties are required. The most common method of determining material properties is by performing tensile tests on flat specimens cut from sheet metal before it is rolled into a tube; however, the material properties change due to work hardening during the tube rolling process. Consequently, it is imperative that the material properties used in tube bending and hydro-forming simulations are derived from the tube itself, and not from the sheet that was used to fabricate the tube. This problem can be solved by performing tensile tests on specimens cut from the longitudinal direction of the tubes used in the bending and hydroforming experiments [3].

3.3.2 Tube bending simulations

In Grantab’s work [3], the tube bending analysis sequence involved two explicit dynamic bending simulations, and two implicit spring-back simulations. After each analysis, a file was written that included all nodal positions and element connectivity, as well as the effective plastic strain, stress tensor, and thickness for each of the elements comprising the tube. After the first bend, the file containing the forming history was used as the input for an implicit calculation to account for elastic spring-back after bending. The forming history file written after the first spring-back calculation was used as the input for the second bend, which was followed by the second spring-back calculation. In this manner, forming effects were carried over from one analysis to another. Mahanty and Balan’s work [19] involves only one explicit simulation.

3.3.2.1 Finite element mesh

For Grantab’s [3] tube bending and hydroforming simulations, the tube was modeled using fully integrated quadrilateral shell elements with seven integration points through
the thickness. All tooling components were modeled as rigid bodies. Despite their computational cost, fully-integrated elements were required for discretization of the tube since reduced-integration elements were incapable of modeling elastic spring-back. The finite element mesh and setup for the first and second bends is shown in Figure 3.5. Upon completion of the first bend, the tooling was translated in the negative z direction by the distance corresponding to the appropriate length for each \( R/d \) ratio, the tooling was also rotated 180° about the z-axis in order to create the second bend in the opposite direction, as shown in Figure 3.5 (b).

![Fig. 3.5: Finite Element Mesh of, (a) The First Bend; (b) The Second Bend [2]](image)

The tube was meshed using 2.5 mm elements, based on a mesh convergence study. The pressure die, clamp die, bend die, and wiper die were meshed with an element size of 5 mm, while the mandrel was meshed with 2.5 mm elements. The tube bending models were comprised of 57720 total elements, 31980 of which belonged to the tube. A
detailed view of the mandrel is shown in Figure 3.6. In order to accurately capture the kinematics of the mandrel, rigid beam elements were created to depict the links between the balls. Each link was fixed to a mandrel ball at one end, and attached to a spherical kinematical joint at the other end to model the ball joints of the actual mandrel. All tooling dimensions were based on measurements taken of the actual tools used in the experiments. The wiper die rake angle was also measured for each of the experiments and positioned accordingly in the numerical models [3].

![Fig. 3.6: Detailed View of Mandrel [2]](image)

The coordinate system adopted for Mahanty and Balan’s simulation has its origin located on the symmetry of the plane of the bend and along the axis of rotation of the bend die. The model used in the simulation is shown in Figure 3.7. For their study, the tube is modeled using 4-noded fully integrated Hughes-Liu shell elements located at the tube mid-surface. A minimum of five integration points across the thickness are used for the elements comprising the tube. Various material models are available for the tube, including the transversely anisotropic elastic plastic material model as well as the commonly used power law plasticity model.
Fig. 3.7: Schematic of FEM Model in Mahanty and Balan’s work [19]

All the external (bend die and clamp, pressure die and wiper die) and internal (mandrel) tooling is modeled using 3- or 4-noded shell elements located at the contacting surface. The default Belytschko-Tsay element formulation is used for this purpose. The bend die is modeled over 180 degrees, thereby limiting the maximum bend angle for the simulation to 180 degrees. Further, the minimum bend centerline radius is constrained to be equal to the outer diameter of the tube. The clamp is modeled along with the bend die. The bend die and clamp, pressure die and wiper die are modeled assuming a uniform clearance between the tube and the external tooling. All tooling is modeled as rigid.

In order to validate the finite element model for rotary draw bending, simulation results were obtained for rotary draw bending of a circular tube through an angle of 90 degrees. A three-ball universal flexing mandrel was used for this purpose. The tube material was Al 6061-T4, and the tube had an outer diameter of 69.85 mm. The tube thickness was 3 mm, and the tube was bent through a bend centerline radius of $2d$, where $d$ is tube outer diameter. A power law plasticity material model was used for the tube. A default clamp
length of twice the tube outer diameter was used, along with pressure die and wiper die lengths equal to the tube bend length [19].

3.3.2.2 Contact and friction
In Grantab’s work, the interaction between the tube and rigid tooling was modeled using a penalty-stiffness based surface-to-surface contact algorithm in LS-Dyna. Since friction is known to be an important parameter in tube bending, friction coefficients were used in the numerical models based on twist-compression experiments performed; these values are summarized in Table 3.1 for contact between the tube and each of the tools. In order to determine the friction coefficient for this contact scenario, a parametric study was performed numerically by varying the friction coefficient and measuring the degree of slip between the pressure die and tube [3].

<table>
<thead>
<tr>
<th>Tool</th>
<th>Material</th>
<th>Lubricant</th>
<th>Static and Dynamic coefficient of friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bend die</td>
<td>Nitrided 4130 tool steel</td>
<td>Dry</td>
<td>0.15</td>
</tr>
<tr>
<td>Pressure die</td>
<td>Nitrided 4130 tool steel</td>
<td>Pine tar powder</td>
<td>0.25</td>
</tr>
<tr>
<td>Clamp die</td>
<td>Nitrided 4130 tool steel</td>
<td>Dry</td>
<td>0.15</td>
</tr>
<tr>
<td>Wiper die</td>
<td>4130 tool steel</td>
<td>Hydrodraw 615</td>
<td>0.06</td>
</tr>
<tr>
<td>Mandrel</td>
<td>Nitrided and chromed 8620 tool steel</td>
<td>Hydrodraw 616</td>
<td>0.08</td>
</tr>
</tbody>
</table>

In Mahanty and Balan’s work, contact is defined between various pairs of surfaces: tube-bend die, tube-pressure die, tube-wiper die, tube-mandrel shank and tube mandrel balls using the *CONTACT_SURFACE_TO_SURFACE contact option, which allows for sliding between these surfaces with a Coulomb friction model. Different static and dynamic friction coefficients can be prescribed for different contact interfaces. Contact between the tube and the clamp is modeled using the *CONSTRAINED_EXTRA_ODE_SET option which allows for the nodes in the tube clamped region to be added to the clamp nodes, thereby constituting an ideal clamp [19].

3.3.2.3 Constraints, prescribed motions and loads
Constraints were assigned to the tools in the numerical tube bending models to match the constraints on the tools during Grantab’s experiments. The degrees of freedom for
each of the tools in the simulations are summarized in Table 3.2 (Refer to Figure 3.5 for orientation of the axes). The tube did not have any constraints or boundary conditions applied to it in the bending models, aside from the contact definitions discussed above.

<table>
<thead>
<tr>
<th>Tool</th>
<th>DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bend die</td>
<td>Y-rotation</td>
</tr>
<tr>
<td>Pressure die</td>
<td>X, Z-translation</td>
</tr>
<tr>
<td>Clamp die</td>
<td>X-translation</td>
</tr>
<tr>
<td>Wiper die</td>
<td>None (fully fixed)</td>
</tr>
<tr>
<td>Mandrel</td>
<td>All DOFs free</td>
</tr>
</tbody>
</table>

The tube bending process was simulated over a 30 millisecond span, even though the actual tube bending experiments lasted 4 seconds. This is a consequence of the fact that a real-time simulation of the tube bending process would surely require months of computation time. The 30 millisecond simulation time was determined before, to be the shortest time-span that did not inflict deleterious dynamic effects unto the results. The sequencing of the loads and displacements prescribed to the tooling is shown in Figure 3.8. The clamp die was closed under displacement control in the x-direction in the first millisecond of the simulation; once fully closed, the clamp die was rigidly connected to the bend die, which allowed for simple extraction of bending torque during post-processing of the numerical models. The pressure die clamp load was applied in the x-direction during the first six milliseconds of the simulation, and held constant for the remainder of the simulation. The bend die rotation about the y-axis and pressure die translation along the z-axis commenced upon full application of the pressure die clamp load at 6 milliseconds. The bend was completed during the final 24 milliseconds of the simulation using the same rotation and displacement ramping curves as the ones used in the experiments (the time axes of the curves were scaled accordingly). The mandrel was retracted 55 mm in the z direction at 26.9 milliseconds, the simulation time corresponding to a bend angle of 42°. All the prescribed values of final displacement, rotation angle, and load were identical to those used in experiments. It should be noted that for the second bend, the displacement of the clamp die, the pressure die load in the x
direction and the bend die rotation angle are negatives of the values displayed in Figure 3.8 since the tooling was rotated in the numerical models [3].

In Mahanty and Balan’s work, the bend die is constrained to rotate about the global z-axis, while the pressure die is constrained to translate along the global x-axis. The wiper die and the mandrel shank are constrained along all degrees of freedom, while translation along the z-direction and rotation about the x and y directions are constrained for the mandrel balls.

A trapezoidal profile is used to define the angular velocity of the bend die and clamp during the process of rotary draw bending as shown in Figure 3.9. This ensures a smooth angular rotation profile for the bend die-clamp-tube combination. In a similar manner, a trapezoidal profile is used to define the motion of the pressure die, with due care taken to ensure that the pressure and bend die do not collide during the process of rotary draw bending. The rotation of the bend die was adjusted so as to obtain a maximum linear velocity of 2 mm/ms on the bend die, while the pressure die was not allowed to move [19].

![Fig. 3.8: Tooling Motion and Loading History [2]](image-url)
Fig. 3.9: Linear Velocity Time History of Bend Die in Mahanty and Balan’s Work [19]
4. MODELLING AND ANALYSIS

The tube and the dies are modeled using the Solid Works program. The geometry that is created is then imported to the ANSYS Ls-Dyna program; the material properties, meshing and loading are applied with this program. The results are compared with the results that are obtained from the experimental measurements.

4.1 Experimental measurements

The tube samples of 106° and 46° bends are cut from the middle in order to measure the final thickness of the tube walls. Three samples per each angle of bend is marked by a turning operation that slightly cuts the tube to create the grids of 3 mm, for the measurements will be taken. The thickness measurements are taken by a micrometer that has conical tips which makes the measurements that are taken more accurate, because it can get more close to the cylindrical surface with the help of its conical tips rather than an ordinary tip. The measurements taken in the direction of the axis of the tube are measured by a digital caliper.

![Fig. 4.1: The Micrometer with Sharp Conical Tip Used for the Measurements](image)
The tube samples are cut from the middle and the thickness is measured along the bend (Fig. 4.2). From the measurements of the final wall thicknesses and final grids, the true strain is calculated using the formulae:

\[
\varepsilon_1 = \int_{t_0}^t \frac{dt}{t} = \ln \frac{t}{t_0} \quad (4.1)
\]

\[
\varepsilon_2 = \int_{l_0}^l \frac{dl}{l} = \ln \frac{l}{l_0} \quad (4.2)
\]

where \(t_0\) is the initial tube wall thickness which is 2 mm in this case. For the grids, \(l_0\) is the initial tube grid which is 3 mm in this case. For the calculated strain values, the negative sign in the strain indicate that there is thinning at the extrados (outer side of the bend), while there is thickening at the intrados (inner side of the bend).

In order to calculate the effective strain acting on the tube, the Von Mises equation is used as;
\[ \varepsilon_{\text{eff}} = \left[ \frac{2}{3} \left( \varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 \right) \right]^{1/2} \]  

(4.3)

\( \varepsilon_3 \) is calculated from the volume constancy during plastic deformation [20].

\[ \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \]  

(4.4)

The diameters are also measured vertically and horizontally in order to designate the ovalization occurred in the process. There is a slight increase as expected with the dimensions that are taken horizontally, and a slight decrease with the dimensions that are taken vertically. The initial diameter dimension is 40 mm.

4.2 Mathematical model

The tube is modeled with a diameter of 38 mm. All the tooling around (bend die, clamp die, pressure die and wiper die) and the tooling inside (mandrel) the tube are modeled so that the space between the tube surface and the tooling is 2 mm. The bend die and clamp die are modeled together as one piece. The model is shown in Figure 4.2; the mandrel is not seen in the figure, it is inside the tube.

![Fig. 4.3 : Geometrical Model Created in Solid Works, With Different Colored Components](image)

The dimensions of the tooling are taken from the tube bending machine that is used in the process. The bend die radius is 90 mm, which is a very important process parameter. The bend ratio happens to be 2.25 in this case. The origin is set to the bend die
centerline, for the reason that the loading can be done in this coordinate system later. This file is saved as an .IGES file and is imported in the ANSYS program.

The mandrel’s position needs to be tangent to the bend die, and it is modeled such that its end is a few millimeters before the tangency point. In real, the mandrel’s end is filleted but in the simulation the mandrel is made up of shell elements and it is not possible to fillet. For this reason, the mandrel’s position is withdrawn back a little.

4.3 Simulation

After the geometry is imported in the ANSYS LS-Dyna program, these steps are followed:

- Element type choice and real constants definitions
- Defining material models
- Meshing the model
- Defining components and parts
- Defining contacts between components
- Specifying loads

Shell elements are used in the entire model. Belytschko-Tsay (default) type of SHELL163 elements are used for the tooling, which have the following properties:

- Very fast and is recommended for most applications
- Uses reduced integration (one point)
- Should not be used when elements experience excessive warping

For the tube Belytschko-Wong-Chiang type of SHELL163 elements are used because this element type is recommended for the spring-back analysis. The properties for this element type are as follows:

- 25% slower than Belytschko-Tsay
- Uses reduced integration (one point)
• Generally gives correct results for warping [21].

The tube has a shell thickness of 2 mm which is the thickness of the tube wall and the number of integration points through the thickness used for the tube shell elements is 5.

Power-law plasticity model is used for the tube. Since the material is 6113 steel, the density is given as 7850 kg/m$^3$, the elastic modulus is given as 200 GPa and the Poisson’s ratio is given as 0.29. The values of $K$ and $n$ constants in the equation $\sigma = K \cdot \varepsilon^n$, are taken from the tensile experiment results of the two tube samples (Fig. 2.13 and Fig. 2.14) and are given as $K=556$ and $n=0.14$ on an average based on the tensile testing results of the two tube samples. The values are obtained from fitting a power rule for the true strain-stress curve of the samples.

The dies are modeled with rigid material properties for steel [21]. The bend die is constrained to rotate around to z axis, the pressure die is free to move along the x-axis and the wiper die and the mandrel are fixed with all degrees of freedom.

Since the tube is the contact part it has to be meshed finer than the tooling, and it is meshed with elements that have a length of 5 mm in the deformation area, meshed with elements that have a length of 1 cm in the remaining areas to reduce the computational time with less number of nodes in the model. The target parts which are the tooling parts are meshed with elements that have a length of 1 cm except the wiper die. The wiper die is meshed with elements of size 5 mm because during bending, the tube material tends to wrinkle in the area it contacts the wiper die. In order to prevent this, there is less clearance modeled between the tube and the wiper die than the other tooling.

After the elements and nodes are defined, the components are defined from the nodes that belong to that component. There are five components in the model. Their names and the number of nodes they contain are shown in Table 4.1.

The contact types between components are AUTOMATIC_SURFACE_TO_SURFACE contacts. Table 4.2 shows the contacts between the tube and the tooling and the friction coefficients used.
Table 4.1: The Number of Nodes Used for Each Component

<table>
<thead>
<tr>
<th>component</th>
<th>no. of nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>tube</td>
<td>2304</td>
</tr>
<tr>
<td>bend die</td>
<td>430</td>
</tr>
<tr>
<td>pressure die</td>
<td>232</td>
</tr>
<tr>
<td>wiper die</td>
<td>300</td>
</tr>
<tr>
<td>mandrel</td>
<td>252</td>
</tr>
</tbody>
</table>

Table 4.2: Contacts and Friction Coefficients Between Components

<table>
<thead>
<tr>
<th>contact no.</th>
<th>contact</th>
<th>target</th>
<th>Static friction coefficient</th>
<th>Dynamic friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>tube</td>
<td>bend die</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>tube</td>
<td>pressure die</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>3</td>
<td>tube</td>
<td>wiper die</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>4</td>
<td>tube</td>
<td>mandrel</td>
<td>0.06</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The friction coefficient between the tube and the bend die is a very high value to present the sticking friction condition because during bending there must not be any sliding between the tube and the bend die.

All the setting is the same for the 106° bend and the 46° bend except the loading. For the 106° bend, the process lasts for 3.5 seconds and the final bending angle is 106°. The bend die is given an angular velocity of 0.58 radians per second as shown in Figure 4.3.

For the 46° bend, the process lasts for 2 seconds, and the angular velocity is given as 0.45 radians per second accordingly. The time versus angular velocity diagram is shown in Figure 5.4.
4.3.1 Results for the 106° bend

The maximum Von Mises effective stress that forms the tube appears at the extrados of the tube with a value of 431 MPa. The maximum Von Mises effective strain value is 0.26 at both the intrados and the extrados. The strain at the intrados has a negative strain value resulting from thinning while the strain at the extrados has a positive value resulting from thickening. The high strained area of the intrados is higher than the high strained area of the extrados. The strain distribution on the tube can be seen in Figure 4.5.
When the experimental results are compared with the analysis results, it is seen that there is a slight difference between the measurements (Figure 4.6 and Figure 4.7). This difference can be caused by several reasons. For example, all parts in the model have cylindrical surfaces, and these surfaces are modeled with these elements, so the cavity between the components can not be constant. The wiper die is meshed with smaller elements to eliminate the effect on the simulation, however, still the model can not be exactly the same as the sample. For the experimental measurements, in order to calculate the effective strain, the thickness strain and the longitudinal strain are measured and the circumferential one is calculated from volume constancy. The longitude strain measurements are not as accurate as the thickness strain because of the measurement system. The small amount of differences in grids is measured by calipers which are not very accurate devices for this type of measurement readings. The error in the longitude strain readings, also effect the circumferential strain calculations, so the effective strain calculations. The grids are cut into the material, which also affect the plastic behavior of the tube material during bending. The grids at the ankle of the tube are more open than the ones that are far from the ankle. The reasons for the difference between experimental and analysis results include the reading errors and the error caused by the grid. Besides these, material’s anisotropy can not be emphasized with the power law plasticity model; so the behavior observed, is the behavior of an isotropic material.
Besides these, the strain at the intrados is distributed in a larger area in the analysis, the data points at the higher values of the node axis are decreasing for the experimental measurements while the analysis results for strain decrease a few nodes after. The deformed area is less in the experimental measurements. The distance between nodes are 3 mm in the experimental measurements, while it is 5 mm in the simulation results since the element sizes are 5 mm. That is why there are more data points with the experimental measurements.

![Comparison of the Strain Results at the Intrados of the 106° Bended Tube Between Experimental and Simulation Results](image)

There are compressive forces acting on the intrados of the tube that leads to thickening and tensile forces acting on the extrados of the tube results with thinning. The thickening is a positive strain while thinning is a negative strain.

The strain at the extrados is shifted when the analysis and experimental results are compared. The deformed area is not very different among them, however if the analysis curve is shifted to the right, or the experimental curves are shifted to the left, the curves will be more similar.
In order to study the ovalization occurred on the tube, the diameter measures are calculated vertically and horizontally (XY plane and XZ plane). The nodes’ displacements are read from the post-processing menu of the ANSYS program. Because the midplane of element is set on the node in the element formulations, the half of the thickness after strain is added to the nodes’ coordinate value to find the exact coordinate. The distance between the opposite two nodes give the diameter measure.

While calculating the diameter ($d_i$) in the XY plane (vertical), the following equation is used:

$$
d_i = \sqrt{((-0.019+y_j)-(0.019+y_i))^2+(x_j-x_i)^2+(z_j-z_i)^2+0.00(1+\varepsilon_c)+0.00(1-\varepsilon_A)} \quad (4.5)
$$

Figure 4.8 shows the cross-section of the tube and the node coordinates on the tube; $x$, $y$ and $z$ stand for the displacements at the last substep, not the coordinates of the node. In the root, the distance between the two points is calculated, and half of the shell thicknesses after the strain are added. $\varepsilon_c$ has a positive sign while $\varepsilon_A$ has a negative sign because there is thickening at node C while there is thinning at node A.
While calculating $d_2$, only the displacements on the $z$ axis are considered because node B and node D have the same displacements on the $x$ axis and the $y$ axis. The equation for calculating $d_2$ is as follows;

$$d_2 = \sqrt{((0.019 + z_2) - (-0.019 + z_4)) + 0.001(1 + \varepsilon_B) + 0.001(1 + \varepsilon_D)}$$ (4.6)

Figure 4.9 and 4.10 compare the vertical and horizontal diameter values measured at the bend area of the tube from the experimental results and the simulation results.

---

**Fig. 4.9**: Cross Section of the Tube

**Fig. 4.10**: The Change in the Vertical Diameter Dimension of the 106° Bended Tube After Bending
There is not much difference between the values of the experimental and simulation results, because the volume of the tube stays constant before and after the deformation; this means that when there is thinning somewhere on the tube there must be thickening somewhere on the tube also.

4.3.2 Results for the 46° bend

Results of the 46° bent tube are very similar to the results of the 106° bent tube. There is less number of sample points taken on the tube since the bent area is less due to the smaller bending angle.

The highest strain value on the tube is 0.26. The strain contour is plotted in Figure 4.11. The red plotted areas are on both the extrados and the intrados. The strain values at the red areas are in the range 0.23-0.26.
The comparison of the experimental and the analytical results can be viewed from Figure 4.12 and Figure 4.13 at the intrados and at the extrados, respectively.

The difference between the results of the experimental measurements and simulation can be explained by the same reasons with the 106° bend. For the 46° bend, it is seen that the
distribution of data points is better between the analysis and experimental results than the 106° bend. The deformed area is almost the same according to the plots. If a curve is to be fitted through the experimental measurements, it is clear that the curve would be very similar to the analytic curve.

For the extrados strain distribution, it is seen that the deformed area of the experimental measurement plots is narrower than the deformed area of the analytical results, with a slightly higher strain maximum.

While comparing the diameter dimensions, same as the 106° bend, $d_1$ represents the vertical diameter and $d_2$ represents the horizontal diameter. The comparisons are shown in Figure 4.14 and Figure 4.15.
Diameter 1 is the decreased diameter and diameter 2 is the increased diameter according to the ovalization of tube during bending.

The maximum strain values of the bends are very close to each other. The contour plots of the extrados and the intrados are shown in Figure 4.16. It can be clearly seen that the deformed area of the 106° bend is nearly two times the deformed area of the 46° bend. It is important to add that the scale is the same for both bends, which means that the colors
represent the same strain values. It is seen that the contour (b) and (d) is not as straight as the contour (a) and (c), if the red areas are observed. This is due to wrinkling in the intrados, but it is not very significant in the strain results. There is wrinkling also seen in the samples of the bends and the wrinkling is not significant on them either.

Fig. 4.17: Deformed Areas of (a) The Extrados of the 106° Bend; (b) The Intrados of the 106° Bend; (c) The Extrados of the 46° Bend; (d) The Intrados of the 46° Bend

The following figures are the comparisons of the experimental thickness measurements for both angles of bend and for both extrados and intrados of tubes. These figures show that the measurements taken from the thicknesses and the strains calculated from the thicknesses are consistent with each other, proving that the measurements do not show a significant error. As discussed before, the errors may result from the longitude grid measurements, since the measuring device is not very accurate.
The longitudinal strains are also measured with a measuring device that has a magnifying glass and a ruler on the glass, however the measurements could be taken to the tenths of a millimeter which shows a lower resolution than the digital caliper that measures to the hundredths of a millimeter.
Fig. 4.20 : The Experimental Results of the Thickness Strain for the 46° Bend at the Intrados

Fig. 4.21 : The Experimental Results of the Thickness Strain for the 46° Bend at the Extrados
5. CONCLUSIONS AND FUTURE WORK

The finite element simulation of the tube bending process can be helpful to observe the critical values of stress, strain and “damage” in order to prevent the tube from failure. There can be many different assumptions while simplifying and idealizing the process. In this investigation, a relatively simple finite element model was used with one crucial input that is the angular velocity.

After the simulations of two tube bending operations for two different bending angles, the strain values are compared to observe the effective strain change; and the diameter measurements are compared in two planes (vertically and horizontally) for the cross-section distortion. For the simulation, the strain values are read directly from the nodes, but for the diameter values, a calculation is required. This calculation is performed by adding the strained (final) shell thicknesses to the distance between the two nodes (the start and end points of the diameter).

The conclusions can be summarized as follows:

- The results agree well with the expectations except for the slight difference between strain values. The main cause of this difference can be the reading errors of the longitude measurements.

- For the experimental measurements, in order to calculate the effective strain, the thickness strain and the longitude strain is measured and the circumferential is calculated from volume constancy. The longitude strain measurements are not as accurate as the thickness strain because of the measurement system. The small amounts of differences in grids are measured by calipers which are not very accurate devices for this type of measurement readings.

- The error in the longitudinal strain readings, also effect the circumferential strain calculations, so the effective strain calculations.
• The grids are cut into the material, which also affect the plastic behavior of the tube material during bending. The grids at the ankle of the tube are more open than the ones that are far from the ankle.

• The deformed areas of the experimental results and the simulation results are not exactly the same in the plots. The deformed area is higher in the 106° bend intrados according to the simulation results, while the others are not significantly different than the experimental measurements.

• The maximum strain results of the 46° bend and the 106° bend have almost the same value, meaning that the bending angle does not change the maximum strain value that will occur on the tube, but the strained area.

• There is wrinkling in the intrados of bends on both experimental samples and the deformed simulation model, the wrinkling is not significant and does not affect the strain distribution.

• There are many assumptions made for the simulation to represent the process in a simple way. All parts in the model have cylindrical surfaces, and these surfaces are modeled with these elements, so the cavity between the components can not be constant. The wiper die is meshed with smaller elements than other tooling to eliminate the effect on the simulation; however the model can never be exactly the same as the sample. The elements and nodes increase in number leading to extra computational solving time when the element sizes are decreased. The element sizes used are optimum values that neither affects the solution in a considerable manner nor cost a lot of computational time.

• The material model is created from the material properties of the coupons cut out of unbent tubes instead of the flat sheet steels, since there is a great change on the stress values of nearly 100 MPa. The power law model represents the tube material properties except for the anisotropy; the behavior observed, is the behavior of an isotropic material

• Despite these assumptions, the results mostly meet well with the results discovered according to the measurements taken from the tube. Even though, the spring-back
effects are not taken into consideration because of their minor effects, the simulation results light the way for the process design in the early design stage.

The simulation is conducted after under a number of assumptions to create a simple, effective and fast model. A more complicated process model, with finer mesh and more detailed loading may reach more accurate results. Also, during the original process the work-piece is bent four times one after another, however for the simulation the bends are observed independently. The future work can include the bending of the tube simultaneous to study the effect of the straining of one bend on the other.

In order to compare the results of the experimental measurements with the simulation results, more accurate measurements need to be made to get good correlation between results. The grids need to be created by markers and for better measurement readings and measurement machines need to be used instead of calipers.
REFERENCES


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