Prediction of Springback in CNC Tube Bending Process Based on Forming Parameters

Levent Sözen, Mehmet A. Guler, Recep M. Görgülüarslan, Engin M. Kaplan
Department of Mechanical Engineering
TOBB University of Economics and Technology
Ankara, TURKEY

Abstract

CNC tube bending machines are commonly used in several industries such as automotive, aerospace and shipping. Especially in automotive industry, usage of tube formed geometries is common because they provide weight reduction without loss of strength. Obtaining desired dimensions and geometries is a necessity for design engineers to achieve high quality end-products. One of the easiest ways of having high quality tube formed end-products without the need of welding operations is using CNC tube bending techniques. The most common problems encountered during tube bending operations are thickness reduction, ovalisation, wrinkling and springback. Especially; springback which is defined as the deviation from the predefined bend angle after the bending operation performed is an undesirable condition that causes some difficulties in the assembly process. It depends on various geometrical parameters such as thickness of the tube, bend angle and effect of mandrel type used. Occurrence of springback is also dependent on forming parameters such as friction coefficient between dies and tube, internal pressure that is applied to the tube and axial loading. In the design stage, determination of springback and various parameters affecting springback behavior by experimental methods is quite cumbersome and costly. Therefore, prediction of springback by virtual methods such as finite element method (FEM) would shorten the time and reduces the cost of the pre-determination of springback.

1. Introduction

CNC tube bending operation is a manufacturing process commonly used in various industries such as automotive, aerospace, shipping, agriculture, furniture, ornament, outdoor play systems, etc. Generally steel and aluminum tubes are bent plastically by utilizing CNC tube bending machines. Compression, draw, ram, roll and press tube bending methods are used frequently in order to bend tubes made of various materials to different angles and radii [1,2]. Rotary draw tube bending is the most common, useful and flexible bending method among the types of tube bending processes mentioned above. It provides low production cost because of low scrap rate and have variety of tooling options. High quality, accuracy, repeatability, high volume production and process automation are the most conspicuous advantages of rotary draw tube bending operations. Tight radii and thin wall bent tubes can be easily obtained by using CNC technology [1-3]. The tooling of this machine basically includes four components: a bend die, a pressure die, a clamp die and a wiper die [3] as shown in Figure 1 where a solid model of rotary draw tube bending components is demonstrated.

The fundamental steps of rotary draw tube bending operation are described by [2-4]:

- The bend die assistant, clamp die and pressure die are parallel to the feeding axes before the start of the bending operation.
- The clamp die presses the tube tightly against the bend die for the purpose of preventing the tube sliding between them during the bending process.

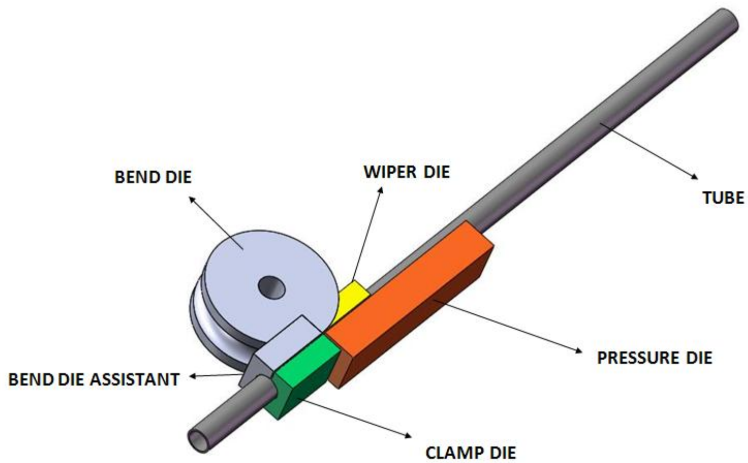


Figure 1. Components of rotary draw tube bending

• The bend die and clamp die then rotates together so that the bend die draws the tube along with it and against the pressure die, by the way this rotation provides plastic deformation at intrados and extrados sections of the tube.
• The pressure die pushes the tube at the outer surface of it to reduce the thinning of the tube and also assists to completing the bend by supplying additional torque during the bending operation.

In bending operations of tubes having large diameters or thin walls, the tooling can also be equipped with an internal mandrel, a wiper die and a booster [3]. The mandrel is used for preventing the cross-section of the tube from ovalising and collapsing during bending [4]. The mandrel usually remains stationary during the bend, but retracting mandrel near the end of the bending operation may be useful in order to reduce wrinkling and flattening [4]. The wiper die provides additional support to the tube just behind the tangent point of the bend and works in conjunction with the mandrel to prevent wrinkling at the intrados of the tube. The wiper die also minimizes frictional drag during bending operation [3,4]. Booster is a component that provides axial loading to the tube during bending operation [3].

There are many papers that include experimental, numerical and analytical studies about rotary draw tube bending operations in the literature. Pan and Stelson [5] introduced an analytical study on the relation between curvature of the tube and the cross sectional deformation. In their study, plastic deformation in the bent part of the tube and elastic deformation in the pressure die area were represented as the two main reasons of the springback occurrence. A comprehensive experimental study was carried out by Khodayari [6]. In his study, rotary draw tube bending machine was used for the experiments and the effect of different tube materials such as aluminum and steel on springback, cross-section, ovality, and wall thickness change were investigated. Shr [1] performed finite element rotary draw tube bending simulations both for forming and springback processes and compared his own results with the experimental data of Khodayari [6]. Wang and Agarwal [7] also preformed finite element studies and they applied axial load with internal pressure to their models in order to improve process quality. They achieved reducing wrinkling tendency and cross-sectional distortion. Gu et al [8] focused on springback occurrence for thin walled tubes at the end of the bending operation. The author performed bending simulations using the model which includes mandrel and classified the whole tube bending process into three steps that are bending tube, retracting mandrel and springback. Da-xin et al[9] investigated the effect of tube's geometrical parameters on the occurrence of springback by performing different bending simulations for various parameters. The effect of material properties on the springback occurrence were also analyzed and they realized the difference between mechanical properties obtained from standard bar tensile tests specimens and from specimens which were taken from metal tube.

Most of the studies in literature only analyze the forming processes; therefore they mostly consider the state of thickness variation and ovalisation problems. On the other hand, the studies investigating the springback behavior consider the effect of parameters such as material properties, wall thickness, tube diameter, bend angle and radius by using both experimental and finite element methods. In this study, in addition to parameters which are mentioned above, the effect of various parameters such as friction coefficient, mandrel type, axial loading and internal pressure on the springback was investigated and the investigation was expanded with the intention of determining dominant parameters that have a bearing on springback. The nonlinear explicit finite element code LS-DYNA® was used for the forming analysis. The results are validated by using the experimental results in literature.

2. Forming Simulation

Rotary draw tube bending operation was simulated by the using LS-DYNA. The results of the simulations were validated by the data obtained from Khodayari's experimental study[6]. The simulations were performed using the material data and the geometrical properties given in Table 1 which are used in Khodayari's experiments [6].

Table 1. Mechanical and geometrical properties [6]

Material	A573-81 65
Yield Strength (MPa)	270
Tangent Modulus (MPa)	900
Young Modulus (GPa)	219.4
Poisson's Ratio	0.3
Outside Diameter of The Tube(mm)	20
Thickness of The Tube (mm)	1.5
Bend Radius (mm)	50

Finite element mesh is generated for the four basic components (i.e. clamp die, bend die, pressure die and wiper die) of the tube bending machine in ANSA. The element size was set to 3 mm as shown in Figure 2. The dies were modeled as rigid and the tube was modeled as piecewise linear plastic using MAT-024 from the LS-DYNA material library.

In order to simulate the contact behavior between the tube and the dies, surface to surface contact type was used with the "CONTACT_ONE_WAY_SURFACE_TO_SURFACE" keyword in LS -DYNA. The friction coefficient values are given in Table 2.

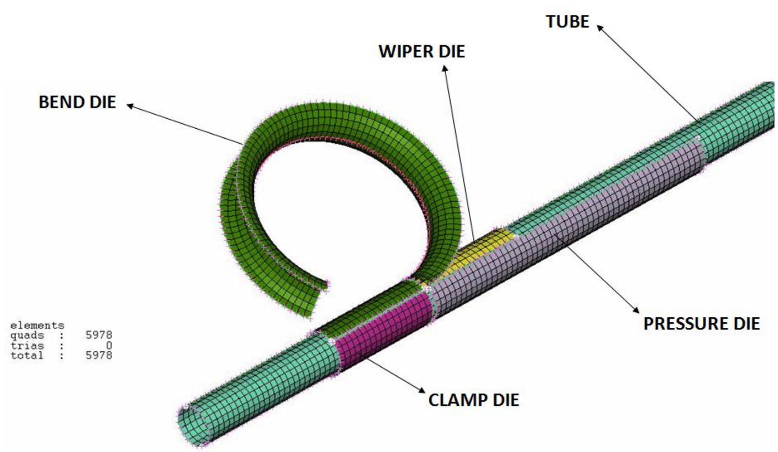


Figure 2. Finite element model

Table 2. Friction coefficients for forming simulation

Tube-Component	Friction Coefficient
Tube-Bend Die	0.1
Tube-Clamp Die	0.1
Tube-Wiper Die	0.1
Tube-Pressure Die	0.05

Bending operation starts with the rotation of bend die and camp die which grips the tube; by the way tube had a displacement towards axes between wiper die and pressure die. In order to create the necessary moment for the bending operation, pressure die applies 50 MPa pressure to the tube. It also reduces the thinning of the tube's outer surface. Bending simulation was terminated when bend radius reached 90^0. At the end of simulation, cross sectional distortion occurred and thinning took place in extrados of the tube whereas thickening occurred at the intrados.

In Figure 3, thickness reduction contour is plotted by using LS-PREPOST. Minimum and maximum thickness values were measured as 1.378 mm at an element on the extrados of the bent tube and 1.679 mm at an element on the intrados as expected. The elements, which the thickness data were obtained, are given in Figure 3. Thickness reduction graph is plotted in Figure 4 by using the thickness data which was obtained from a cross-section of the tube near the plane of having 45^0 of angle with the feeding axes. The simulation results are compared with the analytical results that obtained by Eq.A.10 given in Appendix from Kervicks's[10] and Shr's model [1], experimental data of Khodayari [6] and simulation results from Agarwal's study [2].

Effective plastic strain values were measured from the elements which were detected from the extrados and intrados segments of the bent tube by using LS-PREPOST. These data were compared with the analytical results obtained from the Eq.A.3 from the study of Shr[1]. Maximum effective strain value at the extrados segment was calculated to be 0.185 and it is considerably close to the maximum effective strain value 0.187 measured from the model which was bent to 90^0. Comparative plots are shown in Figure 5.

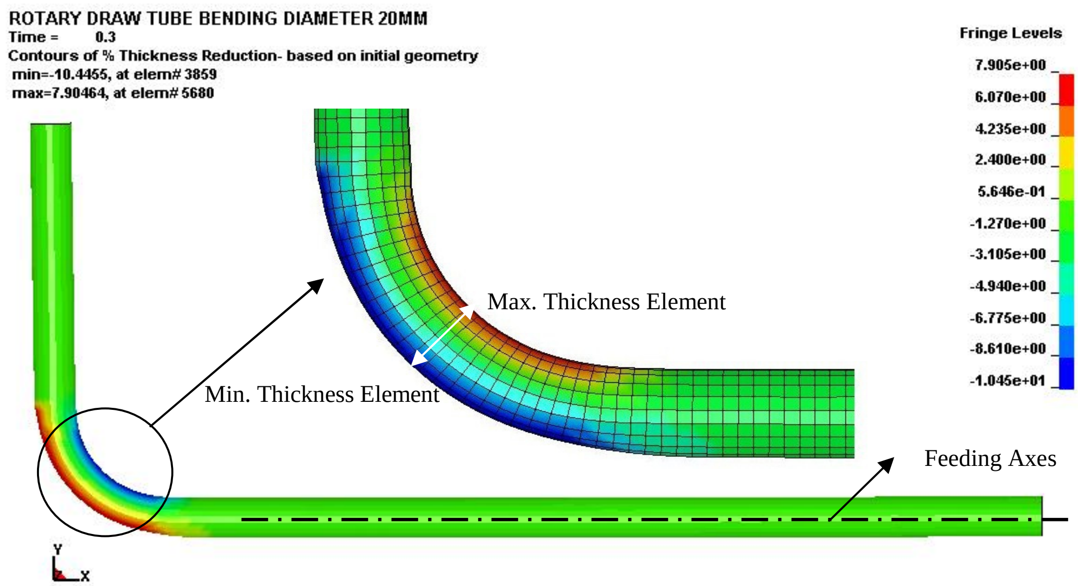


Figure 3. Thickness reduction contour

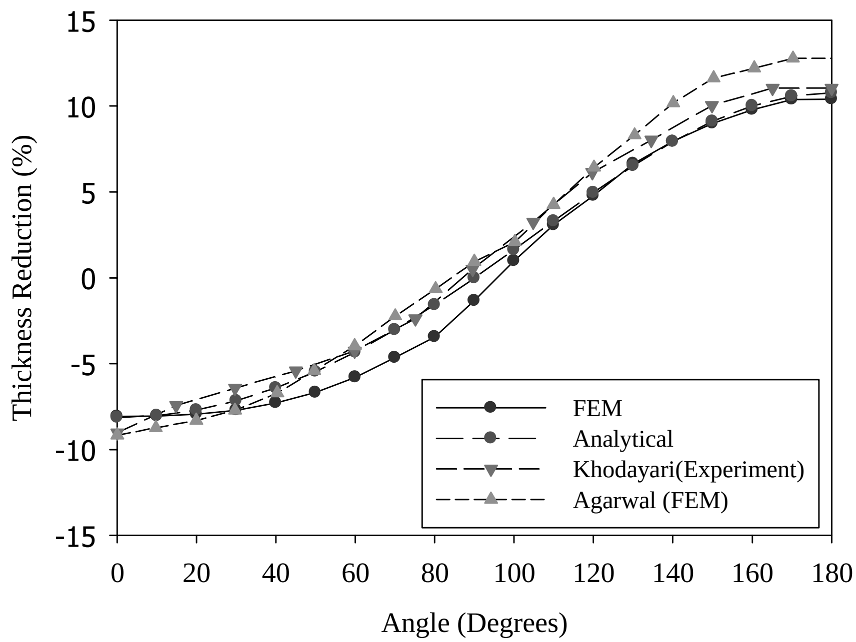


Figure 4. Thickness reduction

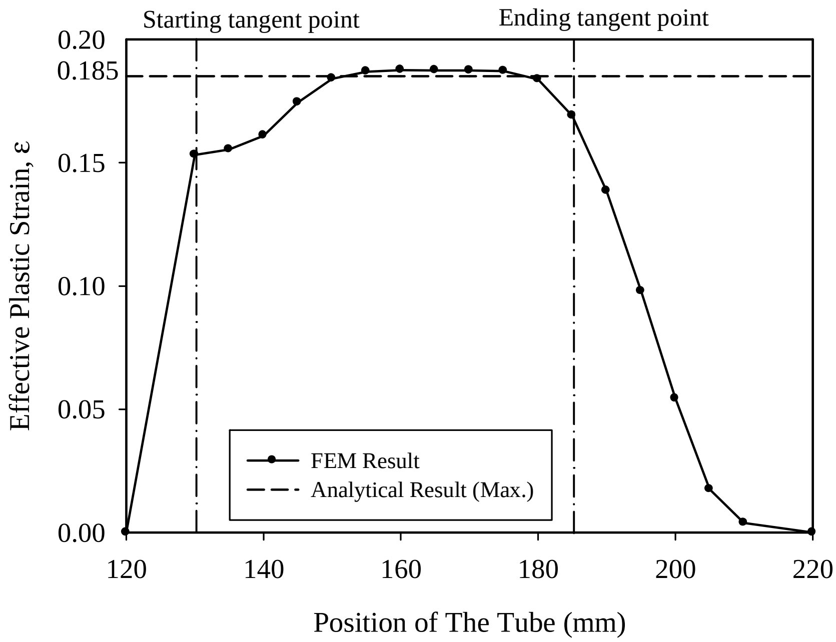


Figure 5. Effective plastic strain at the extrados

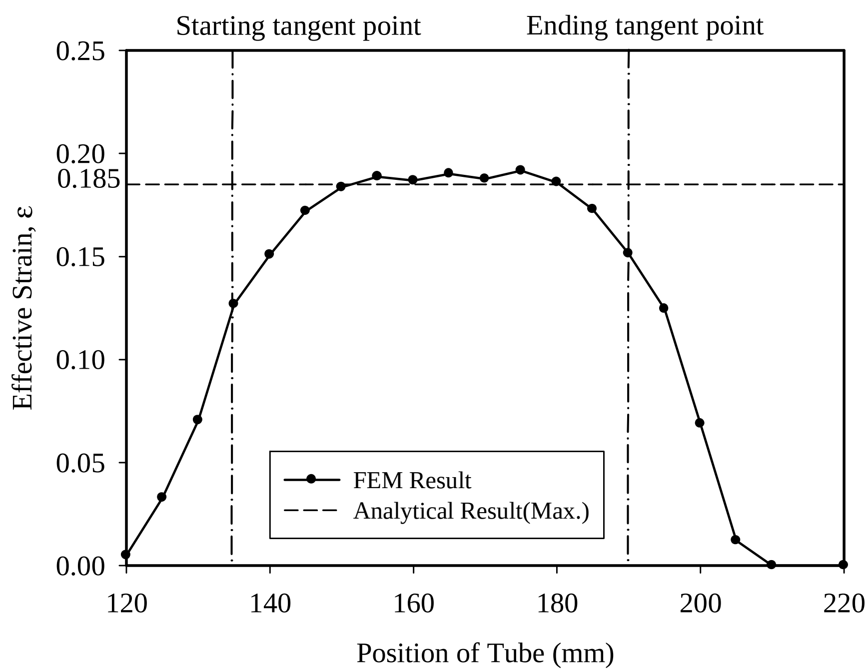


Figure 6. Effective plastic strain at the intrados

At the intrados segment of the tube, maximum effective plastic strain value was measured as 0.19 from the finite element model. Simulation results were also compared with the maximum effective strain calculated by analytical model and comparative plots are given in Figure 6.

3. Springback Simulation

Springback prediction by analytical methods may not give satisfactory results due to the several parameters involved such as geometrical, mechanical and forming parameters. It is therefore necessary to use the finite element method to predict the springback angle. In this section rotary draw bending simulations were performed for different geometrical parameters such as tube thickness, bend angle, internal mandrel type respectively. Moreover simulations were repeated for forming parameters such as coefficient of friction, internal pressure and axial pull. First of all, rotary bending simulation was achieved by LS-DYNA and dynain file was generated at the end of the simulation. By using dynain file, springback simulations were performed for the mechanical and geometrical properties which are given in Table 1. Springback values for different bend angles were compared with the experimental results of Khodayari's study as shown in Figure 7. In order to determine the effect of internal pressure and axial loading; 10 MPa internal pressure (P_i) and 7.2 kN axial loading (F_a) were applied to the model in separate simulations and the results are also compared in Figure 7.

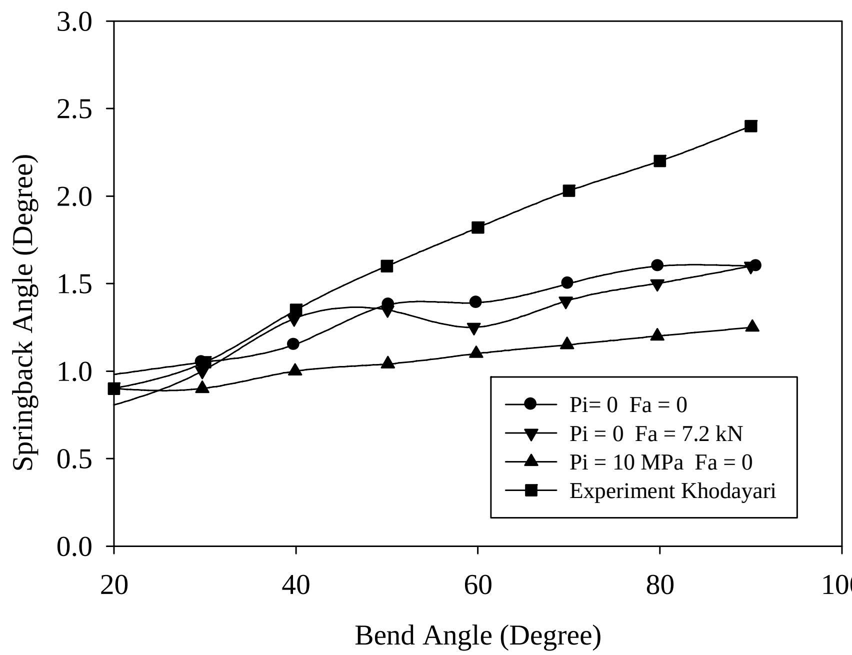


Figure 7. Springback values for different bend angles (D = 20 mm)

Thickness and friction coefficients are also the parameters that affect the occurrence of springback. Springback angles for various values of thickness and friction coefficients between tube and dies are given in Table 3 and Table 4 respectively. Springback angle were measured at the end of the 90^0 bending simulation.

Table 3. Springback values for different tube thickness

Thickness of the tube(mm)	Springback angle for 90^0 bend angle
1.0	1.9^0
1.5	1.3^0
2.0	1.3^0

Table 4. Springback values for different friction coefficients

Coefficient of friction between tube and dies	Springback angle for 90^0 bend angle
0.05	1.6^0
0.10	1.6^0
0.15	1.5^0
0.20	1.4^0

Springback behavior is also investigated for different geometrical and mechanical properties which are given in Table 5. This model was agreed with Shr's study[1] and springback was also calculated for different bend angles. Material model of the dies were rigid and the tube material was modeled as power law plasiticity using MAT-018 from the LS-DYNA material library. In Figure 8; variation of springback angles with respect to bend angles are shown for 10 MPa and no internal pressure. The data are also compared with the analytical results of Shr[1], which were obtained from Eq.A.16.

Table 5. Mechanical and geometrical properties [1]

Material	SS 304
Yield Strength (MPa)	215
Young Modulus (GPa)	210
Strain hardening coefficient (MPa)	1451
Strain hardening exponent	0.6
Poisson's Ratio	0.3
Outside Diameter of The Tube (mm)	57.15
Thickness of The Tube (mm)	2.858
Bend Radius (mm)	171.45

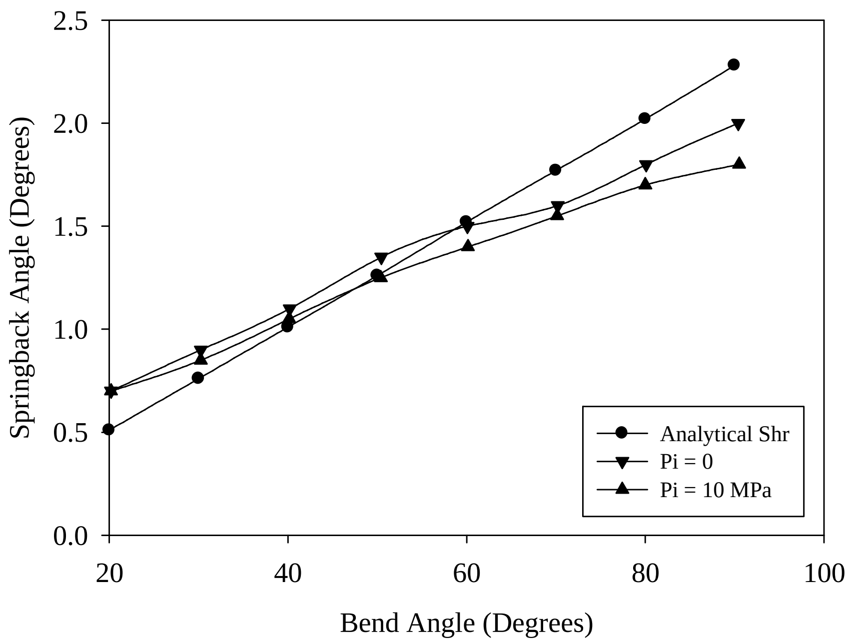


Figure 8. Springback values for different bend angles (D = 57.15 mm)

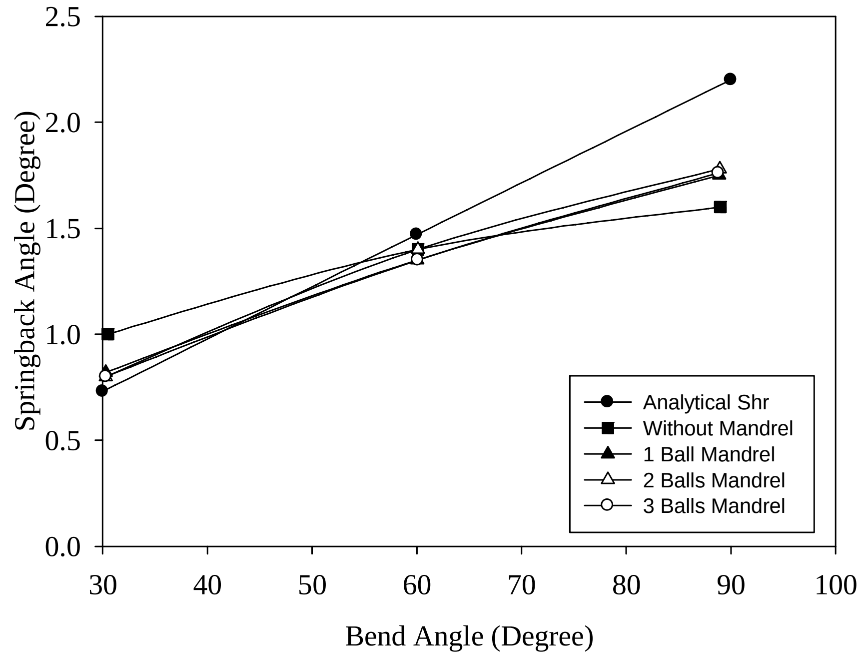
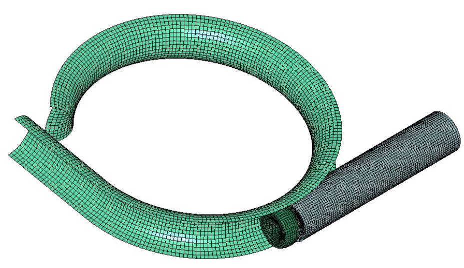
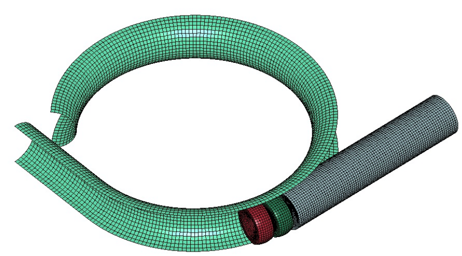


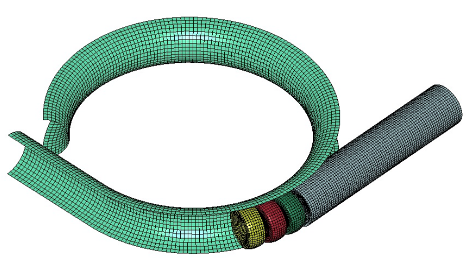
Figure 9. Springback values for different bend angles (D = 60 mm)



Mandrel with 1 ball



Mandrel with 2



Mandrel with 3

Figure 10. Mandrels with different ball numbers

Effect of mandrel type on the springback occurrence was also investigated in this study. Springback angles were measured for 30^0, 60^0 and 90^0 bending simulations for models having different number of mandrel balls in Figure 9. Finite Element model of the mandrels, which have different number of balls are given in Figure 10. For the models equipped with internal mandrels, mechanical and geometrical properties were the same as in Table 5, except outer diameter of the tube was taken to be 60 mm and clearance between mandrel and tube were 0.286 mm.

Springback results are given for the models which had 1 ball, 2 balls and 3 balls internal mandrel in Table 6 respectively.

Table 6. Springback angles for different mandrel model

Ball number for internal mandrel	Springback angle for 90^0 bend angle
1 ball	1.75^0
2 balls	1.78^0
3 balls	1.76^0

4. Results

In this study, both forming and springback simulations were performed for the rotary draw tube bending operations and the results were compared with the experimental, numerical and analytical studies in literature. The following conclusions can be drawn from this study:

- The thickness distribution obtained after the forming simulations were compared with the experimental, numerical and analytical studies in the literature and very good agreement was observed. The effective strain distribution at the intrados and extrados were compared with the analytical study in the literature and again good agreement was observed.
- Springback angles were obtained from simulations for various bend angles and it was observed that as the bend angles were increased the amount of springback was also increased.
- Axial pull and internal pressure were applied and their effect on the springback angles was determined. As the axial pull was applied, the springback angles decreased on most of the bend angles, the internal pressure were determined to lower the springback.
- As the thickness of the tube was enhanced the springback angle reduced.
- When the friction coefficient between the tube and the dies was increased, the springback angle decreased.
- To see the effect of the number of mandrel balls used, models having one, two and three balls have been prepared and the springback angles were measured. It was concluded that there was not much effect of number of mandrel balls used on the springback angle.

Acknowledgments

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Appendix

A.1. Normal Strain Distribution on the Cross-Section of the Bent Tube [1, 10]

The coordinate system of a bent tube is shown in Figure 11. Let R be the radius of curvature measured at the mid-plane of the tube and let h be the distance of an element from the mid-plane. Moreover, let L be the arc length at h and let L_0 be the arc length at the mid-plane.

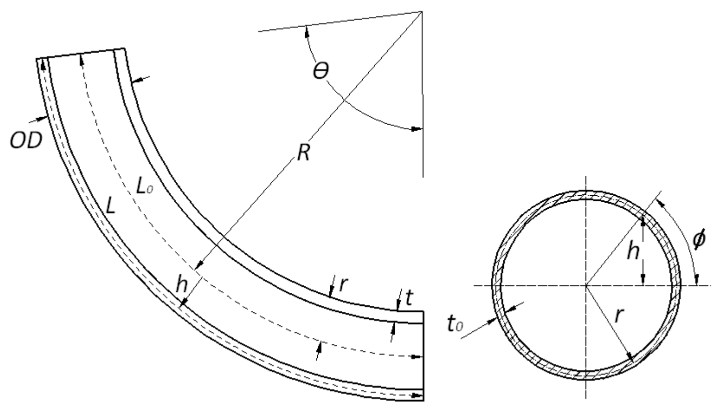

Figure 11. Coordinate system of a bent tube

L_0 is constant during bending operation and can be written as below.

$$L_0 = R \cdot \theta \tag{A.1}$$

At h, the arc length L can similarly written as below.

$$L = \theta \cdot (R + h) \tag{A.2}$$

In Eq.A.2, *h* can be expressed as $h = r \cdot \sin\phi$ where r is the radius of the tube and ϕ is the angle on the cross-section. By using these equations the nominal strain distribution in the axial direction is written as below.

$$\varepsilon_z = \frac{L - L_0}{L_0} = \frac{h}{R} = \frac{r \cdot \sin\phi}{R} \tag{A.3}$$

Also, the plastic strain value on the cross-section, ε_Z, can be written as:

$$\varepsilon_z = \ln\frac{L}{L_0} = \ln(1 + \frac{h}{R}) = \ln(1 + \frac{r \cdot \sin\phi}{R}) \tag{A.4}$$

The plastic strain in tube axial direction, ε_Z, is defined as negative inside of the neutral plane (compression) and positive outside of the plane (tension). The strain is linearly distributed with the distance from any point on the tube to the neutral plane.

A.2. Thickness Distribution on the Cross-section [1, 10]

Volume of the tube material is considered as constant and the material is considered as homogeneous; in order to obtain the thickness distribution on the cross-section easily. The length of the bent tube at any point on the cross-section is obtained with the following equation by using the geometrical parameters of the bent tube.

$$L = L_0 (1 + \frac{r \sin\phi}{R}) \tag{A.5}$$

The total strain in every direction at an infinitesimal element must be zero if the volume is assumed to be constant.

$$\varepsilon_z + \varepsilon_r + \varepsilon_\theta = 0 \tag{A.6}$$

It is assumed that pure bending moment subjects to the tube, so any fiber of the tube is subjected to normal stress only in axial direction. Therefore, the strain in the radial direction becomes as follows.

$$\varepsilon_r = \varepsilon_\theta = -\frac{1}{2}\varepsilon_z \tag{A.7}$$

If plastic strain (Eq. A.4) is substituted into Eq. A.7;

$$\ln\left(\frac{t}{t_0}\right) = -\frac{1}{2}\ln\left(\frac{L}{L_0}\right) \tag{A.8}$$

By substituting Eq. A.5 into Eq. A.8, the thickness distribution on the cross-section expressed as the following equation.

$$t = \frac{1}{\sqrt{1 + k\sin\phi}} t_0 \tag{A.9}$$

In this equation, $k=r/R$ is the ratio of the tube radius to the bending radius. Therefore, the thinning distribution on the cross-section becomes:

$$Thinning(\%) = \frac{t - t_0}{t_0} = (\frac{1}{\sqrt{1 + k\sin\phi}} - 1)\cdot 100\% \tag{A.10}$$

A.3 Springback Angle [1, 10]

While the machine load released from the bent tube, the total bend angle decreases and the radius of bent increases simultaneously due to the springback. In analytical calculations, it is assumed that the total bending length in the deformation zone remains the same at all time. Let θ_L and R_L be the bend angle and bend radius in loaded condition; let θ_U and R_U be the parameters for unloaded one. Total bending length L can be written as ;

$$L = \theta_L \cdot R_L = \theta_U \cdot R_U \tag{A.11}$$

The springback angle $\Delta\theta$ is defined as:

$$\Delta\theta = \theta_L - \theta_U \tag{A.12}$$

and the curvature *(K=1/R)* changes due to the radial growth is defined as:

$$\Delta K = K_L - K_U \tag{A.13}$$

the curvature changes due to the springback can be calculated in terms af bending moment M_L as follows.

$$\Delta K = \frac{M_L}{(dM / dK)} \tag{A.14}$$

where *dM/dK* is the slope of the moment-curvature relationship in the elastic region that is given by the following equation.

$$\frac{dM}{dK} = E \cdot I \tag{A.15}$$

and I is the moment of inertia of the tube ($I = \pi r^3 t_0$). By substituting Eq. A.13 and Eq.A.14 into Eq.A.15, the final bend angle θ_U after the occurrence of springback is calculated with the equation below.

$$\theta_U = \theta_L (1 - \frac{R_L M_L}{EI}) \tag{A.16}$$