EFFECTS OF MANDREL SHANK POSITIONS AND THE GAP VALUES BETWEEN THE MANDREL BALLS AND THE TUBE ON THE THINNING AND THE OVALITY IN ROTARY DRAW BENDING

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Abstract

Tube and tube systems are very critical components to fulfill the design requirement of applications. Especially the bending radius is most important factor in a tube bending process. Therefore, as the bend ratio (bending radius/outer diameter of tube) and the wall thickness of the tube material decrease, the risk of encountering defects such as wrinkles, ovality, wall thinning, and crack increases. Rotary draw bending process is generally preferred for bending tubes with a small bend ratio and thin wall thickness. In this process, tools such as bend die, clamp die, clamp insert, pressure die, wiper die, and mandrel are used. For the minimum bending radius value can be accomplished considering the processes parameters such as material properties and geometry of tube, die geometries, position and geometry of mandrel, wiper die angle, pressure value of pressure die and bending speed. Bending of different tube materials by trial and error method results manufacturing cost and time increases. In this study, effects of mandrel shank positions and the gap values between the mandrel balls and the tube on the thinning and the ovality are investigated by commercially available PAM-STAMP program for AA6061-W condition material. The results are compared with available results in the literature.

Keywords: Rotary draw bending, tube bending, tube bending radius, tube bending ratio

1. INTRODUCTION

Tube bending processes are somehow complex manufacturing processes. They are more difficult and complex than sheet metal bending because it has a tendency to collapse or fold during bending. When tube is bent, inner side of the tube wall is subjected to compression stresses, while outer side of the tube wall is subjected to tensile stresses [1]. Due to these stresses, defects such as wrinkling, cross section distortion, and crack may occur on the tube. These defects are not permitted or permitted within a tight tolerance range in industries such as aerospace and automotive.

Rotary draw bending, compression bending, roll bending, ram and press bending, and stretch bending are very common tube bending processes [2]. All these manufacturing methods have advantages and disadvantages when they are compared to each other. Rotary draw bending method is generally preferred method for bending of thin-walled tubes with tight bending radius. The process enables high-quality products with high dimensional accuracy.

As the tube wall thickness and bending radius decrease in tube bending processes, the probability of errors such as wrinkling, ovality, and cracks on the tube increases. In such cases, the use of a mandrel allows a much smaller bending radius. In the ASM handbook, for cold drawn annealed steels with an outer diameter of 50 mm, the minimum bending radius that can be obtained without using a mandrel is 889 mm (for tubes with a ratio of outer diameter value to wall thickness less than 30), this value can be reduced to 27 mm with the use of mandrels [2]. For tubes whose ratio of outside diameter value to wall thickness is less than 15.

There are several critical parameters in the rotary draw bending process that can influence bend quality. Many researchers in the literature have examined effects of various parameters on the process analytically, numerically, and experimentally [3-11]. Safdarian and Kord [3], investigated the effects of mandrel diameter, mandrel position, and pressure of pressure die on the thinning and ovality of the bent tube experimentally. Cheng et al. [4] investigated the effects of process parameters on wall thinning and cross section distortion for AA5052-O tube. Mandrel extension length and mandrel ball diameter parameters are the focus parameters examined in this study. Heng et al. [5] investigated effects of mandrel diameter, mandrel extension length, and ball numbers on bending with finite element analysis. Masoumi et al. [6] investigated the effects of mandrel on rotary draw bending method.

Correct determination of the mandrel position and geometry is one of the most important issue in thin-walled and small bend radius bends. In this study, the effects of mandrel extension length and mandrel ball diameter values on wall thinning and cross section distortion were investigated by PAM-STAMP analysis program for AA6061-W tube material with 50.8 mm outer diameter and 1.6 mm wall thickness. The centerline bending radius was selected as 152.4 mm.

2. FEM SIMULATION

The process was simulated by PAM-STAMP program to bend a tube to centerline bending radius of 152.4 mm. The tube bend angle was determined as 90 degrees. Details of the finite element model are shown in **Figure 1.**

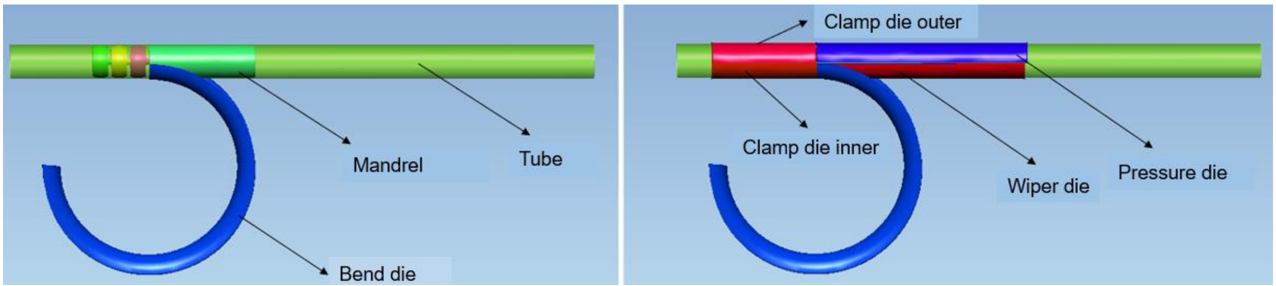

Figure 1 Simulation of rotary draw tube bending

5 different mandrel positions and 4 different mandrel ball diameters were used, and other parameters were kept constant in order to determine effects of mandrel positions and diameters. **Table 1** summarizes the constant die parameters.

Table 1 Constant die parameters

Constant die parameters	Value (mm)
Length of clamp dies	150
Length of pressure die	300
Length of wiper die	300
Bend die radius	152.4

The dies used in the bending process were selected as rigid objects and movement capabilities were assigned in the required directions. In the bending process, pressure die modeled stationary. The force exerted by the pressure die on the tube has been chosen at a negligible level. The force exerted by the clamp die on the tube was chosen as 80,000 N. Mandrel and mandrel balls and bend die and clamp die were defined as multibody system. The friction coefficients used in different interfaces are seen in **Table 2**.

Table 2 Friction values at interfaces

Contact interface	Value
Tube - pressure die	0.1
Tube - wiper die	0.1
Tube - bend die	0.1
Tube - clamp dies	0.5
Tube - mandrel	0.1

In the analysis, 30,15, 0, -15 and -30 values were used as variables as the mandrel position. These positions are the position of the mandrel shank tip relative to the bend tangent line. For example, a value of 30 means that the mandrel shank moves 30 mm forward in the direction of the bend region. **Figure 2** illustrates mandrel shank position.

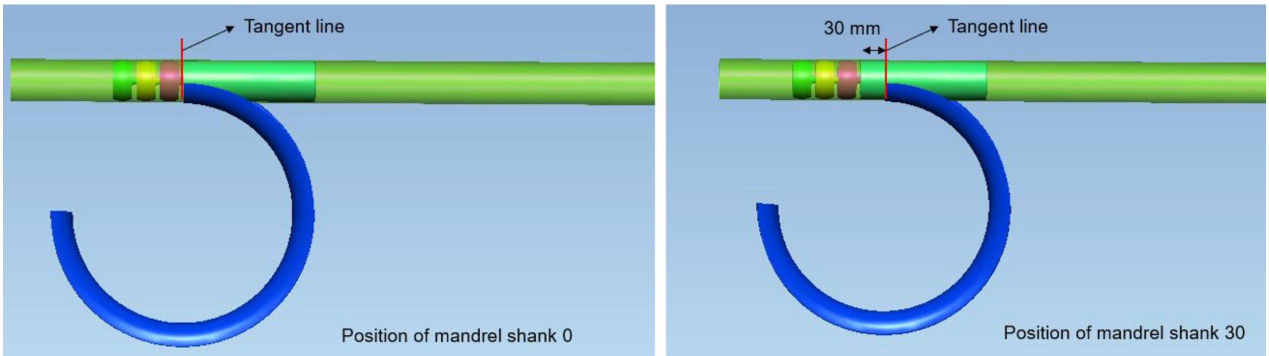

Figure 2 Mandrel shank positions

During the analysis, different mandrel ball diameter values were used as the second variable. Diameter of the mandrel ball was determined by entering the gap values of 0.2, 0.5, 1.5, and 3 between the mandrel ball and the tube in the analysis program. The specified values refer to the gap value between the mandrel ball and the tube. Other parameters about mandrel were kept constant during the bending.

In order to examine the material behavior, the coefficients for the plastic deformation behavior and anisotropy properties of the AA6061-W material were entered into the analysis program and used in all simulations. In order to observe whether there is crack in the analysis results, the FLD diagram of the material was also entered to the program and used in post processing operations. With the help of FLD diagrams, the safe and crack risk areas of the bent tube were observed. Wrinkling and crack areas on the tube are displayed in **Figure 3**. Wrinkle free tube is seen in **Figure 4.**

Figure 3 Wrinkled tubes and FLD diagrams

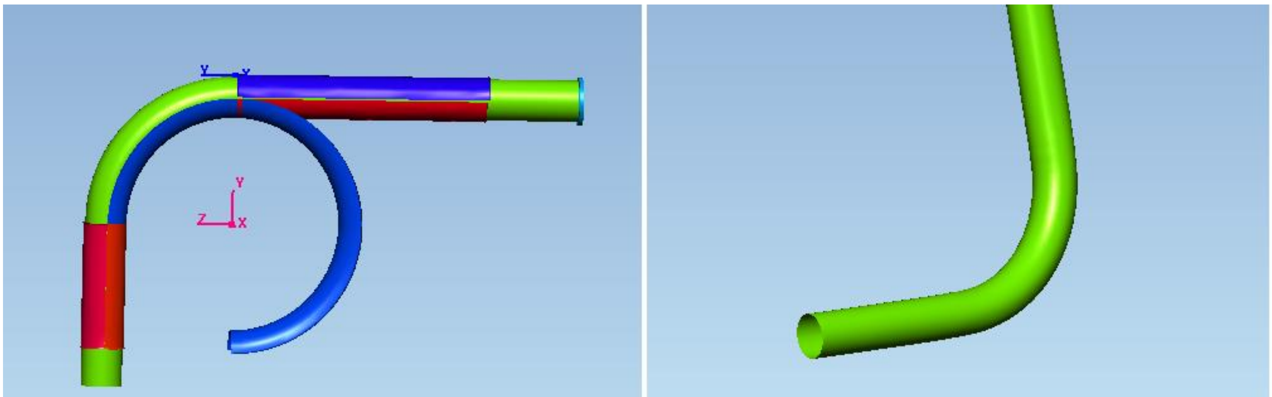

Figure 4 Wrinkle free tube

3. RESULTS AND DISCUSSION

After the analysis results were determined, the maximum wall thinning value was obtained from the relevant post processing interface and listed in **Table 3**. In order to calculate the cross-section distortion (ovality) values, the cross-section areas corresponding to the 45 degree bending angle were subtracted and the required values for Equation 1 were measured and ovality values calculated and also listed in **Table 3**.

$$Ovality\ (\%) = \frac{Dmax - Dmin}{D} \times 100 \tag{1}$$

where:

$Dmax$ – maximum diameter of the tube in the 45° section

$Dmin$ – minimum diameter of the tube in the 45° section

D – initial diameter of the tube

When the analysis results for ovality in **Table 3** are examined, it can be understood that the cross-section distortion value of the tube decreases when the mandrel shank position is changed from 0 to 15. It was observed that the cross-section distortion values increase in case the mandrel shank position is brought to 30. The ovality values were increased compared to the 0 position after the mandrel position was changed from 0 to -15 and -30 values. In addition, results reveal that the ovality values in the tube cross-section area increases as the gap values between the mandrel and the tube increase. This is due to the fact that the bending area cannot be adequately supported internally due to the gap. These results are consistent with the findings in the literature [3,5].

Based on analysis results in **Table 3**, the maximum thinning value increases as the mandrel shank position goes from 0 to 30. This is due to the contact of the mandrel balls and the tube surface with the larger surface area in the bend region. As the mandrel gets closer to the bending area, the increase in the maximum thinning values is consistent with the studies in the literature [4-6]. In addition, it was observed that the maximum thinning values generally decrease as the gap between the mandrel and the tube increases. The reason could be less friction between the mandrel balls and the tube surface.

In the ovality analysis, results indicate that the lowest ovality value was obtained in the analysis where the mandrel shank position is 15 and the gap value between the mandrel and the tube was 0.2. The value where the maximum thinning value was the smallest when the mandrel shank position was -15 and the gap value between the mandrel balls and the tube was 3.0.

Table 3 Finite element analysis results

Position of mandrel shank (mm)	Mandrel gap (mm)	Ovality (%)	Max thinning (%)	Wrinkling occurrence	Crack occurrence
0	0.2	3.1	12	NO	NO
0	0.5	3.6	10.9	NO	NO
0	1.5	6.34	10.3	NO	NO
0	3.0	10.1	10.1	NO	NO
15	0.2	2.5	12.4	NO	NO
15	0.5	3.1	12.7	NO	NO
15	1.5	3.9	12.2	YES	NO
15	3.0	4.0	12.0	YES	NO
30	0.2	6.9	31.8	YES	YES
30	0.5	7.6	31.4	YES	YES
30	1.5	11.4	31.8	YES	YES
30	3.0	9.66	53.6	YES	YES
-15	0.2	3.8	12.1	NO	NO
-15	0.5	4.3	11.5	NO	NO
-15	1.5	6.2	10.4	NO	NO
-15	3.0	10.0	10.0	NO	NO
-30	0.2	3.26	11.9	NO	NO
-30	0.5	4.1	11.1	YES	NO
-30	1.5	6.1	12.2	YES	NO
-30	3.0	10.7	16.3	YES	NO

4. CONCLUSION

The effects of the mandrel shank positions and the gap values between the mandrel balls and the tube on the thinning and the ovality were investigated by the finite element analysis for the AA6061-W tube. The following results can be drawn as follows:

1) Incorrect selection of the mandrel position and the gap value between the mandrel balls and the tube may cause over thinning, ovality, crack, and wrinkling. It is quite important to choose these parameters correctly.
2) The mandrel position and the gap value between the mandrel balls and the tube have a significant impact on ovality. As the gap between the mandrel balls and the tube decreases, the ovality value decreases. If it is aimed to reduce the ovality value, as little space as possible should be left between the mandrel balls and the tube. This causes an increase in the maximum thinning value on the tube. Optimum bending parameters should be determined considering the required product quality.
3) As the contact surface between the mandrel balls and the tube increases, the thinning of the tube wall thickness increases.
4) Moving the mandrel shank position forward more than necessary compared to the tangent line causes excessive thinning, wrinkles, and cracks.

REFERENCES

[1] GROOVER, M.P. *Fundamentals of Modern Manufacturing: Materials, Processes and Systems* (6th ed.). USA: Wiley, 2016.

[2] Bending and Forming of Tubing, ASM Handbook, Volume 14B: Metalworking: Sheet Forming, 2016.

[3] SAFDARIAN, R., KORD, A. Experimental investigation of effective parameters in the tube rotary draw bending process. *Mater. Res. Express.* 2019, vol. 6, no. 6.

[4] LI, Ch., YANG, H., ZHAN, M., XU, X., LI. G. Effects of process parameters on numerical control bending process for large diameter thin-walled aluminum alloy tubes. *Trans. Nonferrous Met. Soc.* 2009, English Ed., vol. 19, no. 3, pp. 668–673.

[5] LI, H., YANG, H., ZHAN, M., SUN, Z., GU, R. Role of mandrel in NC precision bending process of thin-walled tube. *Int. J. Mach. Tools Manuf.* 2007, vol. 47, no. 7–8, pp. 1164–1175.

[6] MASOUMI, H., MIRBAGHERI, Y., NEDOUSHAN, R. Jafari., SALEM, M., KALANTARI, M. Effect of Mandrel Its Clearance and Pressure Die on Tube Bending Process via Rotary Draw Bending Method. *Int. J. Adv. Des. Manuf. Technol.* 2012, vol. 5, no. 521, pp. 47–52.

[7] ZHAO, G.Y., LIU, Y.L., YANG. H., LU. C.H., GU, R.J. Three-dimensional finite-elements modeling and simulation of rotary-draw bending process for thin-walled rectangular tube. *Mater. Sci. Eng. A.* 2009, vol. 499, no. 1–2, pp. 257–261.

[8] OLIVEIRA. D.A., WORKSWICK. M.J., GRANTAB. R. Effect of lubricant in mandrel-rotary draw tube bending of steel and aluminum. *Can. Metall. Q.* 2005, vol. 44, no. 1, pp. 71–78.

[9] WANG, Xi., CAO, Jian. Wrinkling limit in tube bending. *J. Eng. Mater. Technol. Trans. ASME.* 2001, vol. 123, no. 4, pp. 430–435.

[10] YANG, H., LIN, Y. Wrinkling analysis for forming limit of tube bending processes. *J. Mater. Process. Technol.* 2004, vol. 152, no. 3, pp. 363–369.

[11] LI, H., YANG, H., ZHAN, M., GU, R.J. A new method to accurately obtain wrinkling limit diagram in NC bending process of thin-walled tube with large diameter under different loading paths. *J. Mater. Process. Technol.* 2006, vol. 177, no. 1–3, pp. 192–196.