Effect of Mandrel, Its Clearance and Pressure Die on Tube Bending Process via Rotary Draw Bending Method

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Abstract: One of the most prominent processes in industry is bending. Rotary draw bending method is known to be the most conventional approach for thin wall tube bending. Pressure die is an effective tool which boosts the tube bending process and eventually improves the bending quality. Other effective parameters include mandrel and the amount of clearance between tube and mandrel. In the present study, the process was modeled by finite element method and the precision of the model was validated via comparing practical results. Subsequently, using the validated model, the effects of pressure die movement and the mandrel and its clearance were investigated. Specifically, the force vicissitudes and bending quality with respect to mandrel clearance and pressure die movement were evaluated. It was shown that reducing the clearance between mandrel and tube, results in force increase while the bending quality was improved. Also it was indicated that the pressure die movement has less effects on process forces and flattening the tube.

Keywords: Booster Die, FEM, Mandrel, Rotary Draw Tube Bending

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1 INTRODUCTION

Tube bending can be performed via various techniques such as rotary draw bending, compression bending, roll bending and press bending [1]. Among several techniques, rotary draw approach offers the largest range for tube bending; specifically it is the most appropriate method for thin-wall tubes due to accomplishment of mandrel [1]. As shown in Fig. 1, this process consists of the following components: bend die, clamp die, pressure die, wiper die and mandrel; while the mandrel and wiper die are used for thin-wall tubes applications.

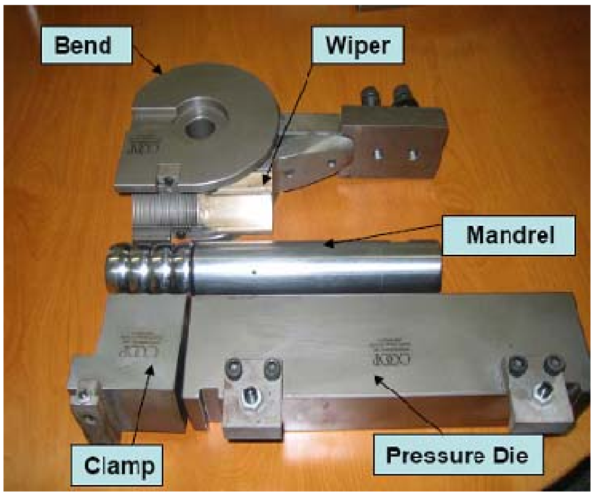

Fig. 1 Major components in rotary draw bending technique

Several studies have been carried out concerning the computer aided simulation of rotary draw bending technique. In Ref. [2], the mandrel role in thin-wall tube bending is studied using ABAQUS software. In Ref. [3], rotary draw bending of a thin-wall tube with square section is simulated. Some other researchers contributed their investigations to wrinkling and flattening phenomena in aluminum thin-wall tubes bending, using ABAQUS software [4]. Li et al. [5], discussed the stresses and wrinkling in thin-wall tubes during the bending process through ABAQUS simulations. In addition, they studied the mandrel effects in wrinkling and flattening parameters during the bending process.
Some studies focused on analyzing forces and moments in tube bending process, applying stress analyzing equations. Due to discarding the effects of mandrel, as well as work-hardening pushing force effects, in all of these works, the results do not show satisfactory compatibility with practical tests and consequently may not be reliable.

In Ref. [6], various parameters have been investigated using stress analysis approach. Some of the researchers [7] improved the equations presented in Ref. [6] and applied effects of axial tensile force and internal pressure within stress analysis.
In the present study, the rotary draw bending process was simulated using ABAQUS FEM software. To validate the simulation results, practical tests were carried out and the tube bending parameters, such as tube thickness in bending zone, and forming forces were compared with simulation results. The calculated moment via simulation was compared with moments obtained through the tests and eventually simulation error was acquired. A proper agreement between simulation results and test results were observed. Considering that the simulation results was validated, the effects of pressure die movement and mandrel role and the clearance between mandrel and tube, were investigated via simulations.

2 TUBE BENDING SIMULATION USING ABAQUS SOFTWARE

Tube bending process was simulated using Abaqus FEM software as shown in Fig. 2. The boundary conditions were defined as displacement base in order to calculate forces and moments. The C3D8R element was used for tube meshing and R3D4 element was applied to dies [2]. Tube and dies dimension used in simulation are listed in Table 1. The friction coefficient between tube and pressure die was set as 0.3, while it was 0.5 between tube, bending die and clamp, as well as 0.1 between tube, wiper die and mandrel parts. The elastic and plastic properties of AISI304 steel was used in simulations.

Table 1 Tube bending parameters

Parameter	Value
Tube outer diameter	38mm
Tube thickness	1.58mm
Bend die radius	79mm
Clamp die length	114mm
Wiper die length	203.2mm
Diameter of ball segment	34.6mm
Mandrel shank length	203.2mm
Steps of ball segments	17.93mm
Bend degree	3.1415rad
Length of pressure die	248.186mm

As it is shown in Fig. 2, the bent tube shows no wrinkles within internal zones. In various bending modeling pointed out in the following sections of this paper, all of the modeling characteristics are as indicated and only specific parameters are changed.

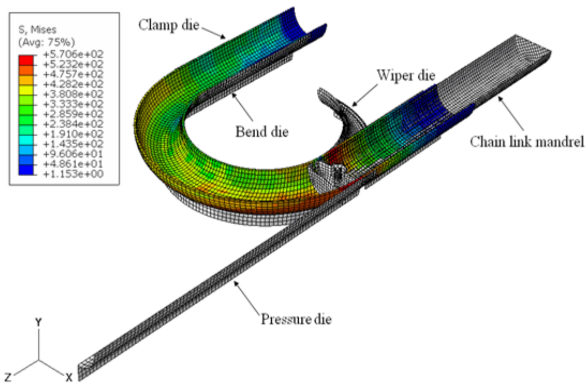

Fig. 2 Bending process modeling of tube with 38mm diameter, 79mm bend radius and 1.58mm thickness

3 THE SIMULATION RESULTS

According to the simulation results, the maximum moment required for tube bending, reaches to 3520 N.m. Moreover, the tube thickness was measured in 10 different points which is demonstrated in Fig. 3 and the measured values are presented in Table 2.

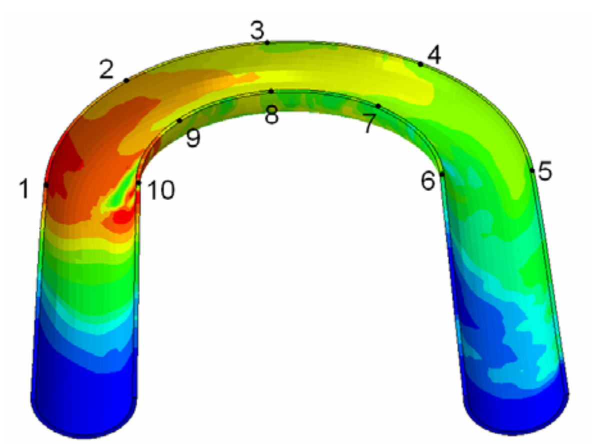

Fig. 3 Indicated points for thickness measurement

4 PRACTICAL TESTS

To investigate the bend quality, as well as validating the simulation results, an AISI304 steel tube with 38mm outer diameter, 1.58mm thickness and 79mm bending radii, was bent experimentally. As shown in Fig. 4, the outer and inner wall thicknesses were measured in 10 different points in accordance with Fig. 3, using ultrasonic thickness measuring device. The measured values are presented in Table 3.

Table 2 Predicted values of the thicknesses

Point number	Thickness(mm)
1	1.44
2	1.37
3	1.36
4	1.36
5	1.48
6	1.58
7	1.7
8	1.7
9	1.69
10	1.68

Fig. 4 Measuring the bent tube thickness by ultrasonic thickness measuring device

The experimental results show 15.18% decrease in outer wall thickness and 7.6% increase in inner wall thickness. To obtain the required bending moment, two pressure gauges were installed on entry and outlet hatches of bending die cylinder, and a 38mm diameter tube was bent. In each experiment, the pressure gauge outputs were recorded and an average difference between recorded pressures of 47.5bar was observed. Subsequently, the obtained average pressure was converted into bending moment as calculated to be 3900N.m.

5 VALIDATING THE SIMULATION RESULTS

In this section, primarily the dependency of the solution to element size is discussed and successively, the simulation and experimental results were compared to validate and confirm the simulation results. Repeating the simulation with three different element sizes, only negligible variations of forces and moments were observed. For instance, Fig. 5 shows the required moment for tube bending of three models, indicating that the patterns are quite close to each other obviously.

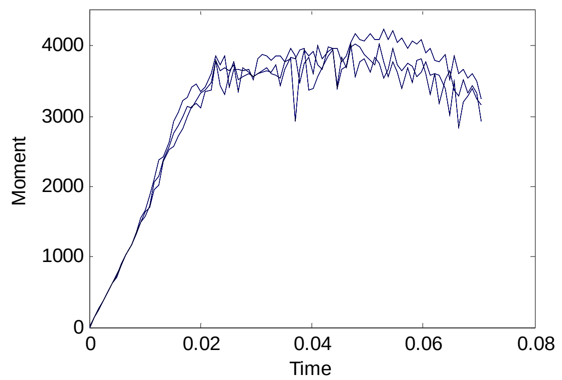

Fig. 5 Comparing the calculated moments of three elements (1, 3 and 5 mm sizes)

Table 3 Measured thicknesses during experiment

Point number	Thickness(mm)
1	1.44
2	1.37
3	1.36
4	1.36
5	1.48
6	1.58
7	1.7
8	1.7
9	1.69
10	1.68

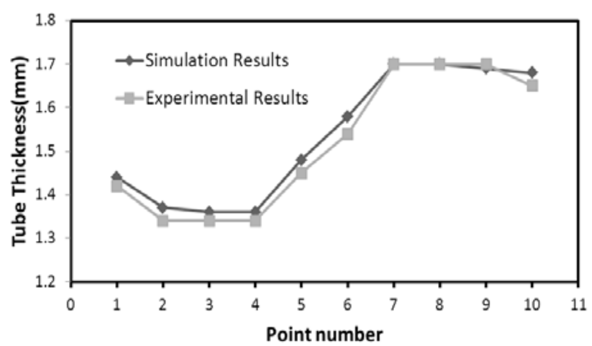

Fig. 6 Comparison between thicknesses from simulation and experiments

Table 4 Comparison between moments from simulation and experiments

Predicted moment	$3.9\times10^{6}\,N.mm$
Measured moment	$3.52\times10^{6}\,N.mm$
Calculated error	%9.74

As demonstrated in Fig. 6, comparing the measured thickness values between experiment results with the thickness values obtained from simulation indicates that the simulation error can be calculated to be 2.5%. On the other hand considering Table 4, and comparing the obtained moments from experiments with calculated moments from simulations, indicates that the simulation error is 9.74%, which is satisfactory.

6 THE EFFECTS OF MANDREL AND CLEARANCE BETWEEN TUBE AND MANDREL

As the modeling validation was confirmed in previous sections, the effects of mandrel on the process may be studied via FEM simulation. For this purpose, three models were compared with each other at different bending situations and different forces. In the first model which its results were presented in previous sections, the clearance between mandrel and tube was 0.12mm. In the second model, the mandrel was omitted from the process while in the third model, the clearance between mandrel and tube was set to be 0.06mm.

Figure 7 illustrates the comparison between the required moments for bending in three different models. It can be observed that if the mandrel is not implemented, the required process forces will be considerably reduced. In addition, comparing two different clearances it can be concluded that reducing the clearance between mandrel and tube, remarkably increases the forces in tube bending process.

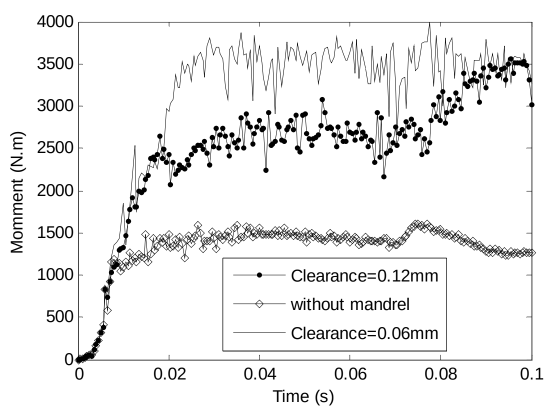

Fig. 7 Comparison between required torques for bending in three different models (model without mandrel, model with mandrel and 0.12mm clearance, model with mandrel and 0.06mm clearance)

To study the effects of mandrel and its clearance on bending quality, the amount of tube flattening in points 3 and 8 were investigated (Fig. 3). The procedure of calculating the flattening value is demonstrated in Fig. 8 and equation 1.

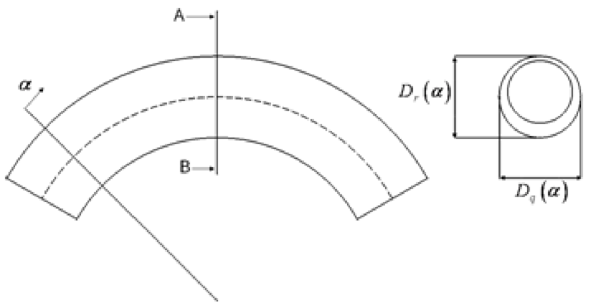

Fig. 8 Calculation of the flattening value

$$\text{Flattening} = \frac{D_r(\alpha) - D_o}{D_o} \times 100\% \quad (1)$$

Table 5 Comparing the flattening amounts obtained from FEM simulation

Simulation	Flattening
Without mandrel	6.95%
Clearance = 0.12mm	2.84%
Clearance = 0.06mm	2.71%

Considering the amounts of flattening from Table 5, it can be concluded that using mandrel will improve bending quality dramatically, and on the other hand reducing the clearance between mandrel and tube results in improvement of the bending quality as well. Although using mandrel with small clearance improves the bending quality, the forces of the process will be increased significantly.

Therefore it can be concluded that only in cases in which high bending quality is required, using mandrel is recommended. However, if even more quality is demanded, the clearance should be further reduced. Nonetheless, for bending processes with low accuracy, in order to reduce the required force, it is recommended either to exclude the mandrel or apply greater clearance.

7 THE EFFECTS OF TUBE BOOSTER ON THE PROCESS

In tube bending process, the pressure die which is illustrated in Fig. 1, can be fixed in place or move alongside with the tube. The movement of pressure die alongside the tube is known as boosting. In the following, the effects of boosting on process forces and procedure is discussed using three different models. In the first model, the pressure die was fixed which resulted in no movement. In the second model, the pressure die speed was equal to tube speed while in the third model the pressure die speed was greater than the tube speed.

The comparison of the required bending moment between these three models is shown in figure 9. According to this figure, if the pressure die is fixed in place, the process forces are increased. While when the pressure die moves alongside the tube, the process forces are decreased, though the effects are quite small. However, figure 10 shows the required force to displace the pressure die in models, when the pressure die moves alongside with the tube. It can be observed that the required force to displace the pressure die is much smaller when the pressure die speed is kept equal to tube speed rather than when the pressure die speed is greater than the tube speed.

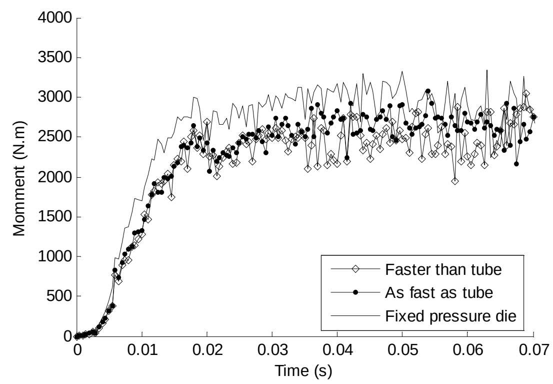

Fig. 9 Comparison of required bending moment between three different models (model with fixed pressure die, model with moving pressure die in a speed equal to tube's speed, model with moving pressure die in a speed greater than tube's speed)

Considering the fact that this force is originated from the friction between the tube and the pressure die, it can be concluded that when the pressure die speed is equal to tube speed, the minimum laminar force would be applied to outer surface of the tube. Improved surface qualities and more uniform thicknesses have been achieved practically when the pressure die displacement was kept in correct pattern. One of the reasons is the lower applied friction force to the outer surface of the tube.

To investigate the pressure die movement effects on dimensional precision of the bending, the flattening of the tube in three different models was compared. The amounts of calculated flattening of the tubes in various simulations are presented in Table 6. It can be seen that the amounts of flattening in different models are the same.

Table 6 Comparing the amounts of calculated flattening in different models

Simulation	Flattening
With fixed pressure die	2.84%
Pressure die velocity equals tube	2.84%
Pressure die velocity more than tube	2.71%

Eventually, the displacement of booster die has not shown any specific effect on final form of the bending and its dimensional precision. The major effect of such displacement can be observed in final thickness of the tube.

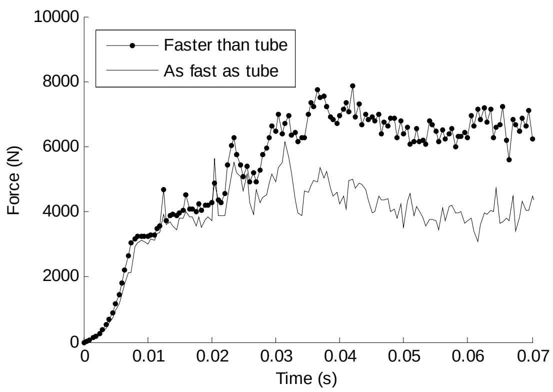

Fig. 10 Comparison of the required force for displacing the pressure die between two models (model with moving pressure die in a speed equal to tube's speed and model with moving pressure die in a speed greater than tube's speed)

In practice, the most application of the booster die is neither to reduce the forming forces, nor to improve the dimensional precision, but its implementation is to reduce extensive thinning of outer section of the bend which may results into failure.

8 CONCLUSION

In the present paper, the rotary draw tube bending process was modeled. In order to validate the simulation results, a comparison was made between the modeling results and the experimental results. Following that, the model was used to investigate the effects of pressure die movement and mandrel clearance, where the following conclusions were obtained:

- Using mandrel increases the process forces significantly, while the dimensional precision is improved as well.
- Though using mandrel or reducing its clearance, increases the process forces, the bending quality would be improved remarkably.
- Pressure die displacement has no considerable effects on process forces and bending quality.
- When the pressure die moves in a speed equal to tube's speed, the least friction force would be applied on tube's surface.

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