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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF FRICTION COEFFICIENT EFFECTS ON DEFECTS IN HORIZONTAL TUBE BENDING PROCESS

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The aim of this paper is to investigate defects in a thin-walled tube bending process (without using mandrel and booster) and effects of friction between the dies and tube on wrinkles. In the tube bending process, there are several effective parameters such as wall thickness, outer diameter-to-wall thickness ratio, centerline bending radius-to-outer diameter ratio and friction coefficient. Any mismatch in the selection of the process parameters would cause defects inducing undesirable variations in wall thickness and cross-section distortion. In this work, firstly, tubes with several wall thickness values are bent, and the final depths of wrinkling and wall thickness change are reviewed. Then, to study the process numerically, numerical simulations are carried out. Then, a series of experimental tests are carried out to verify the simulation results. A comparison between numerical and experimental results shows a reasonable agreement. Finally, in order to obtain a suitable friction condition, the effects of friction coefficients on defects are studied. For this purpose, a series of simulations has been carried out. It shows that at a certain friction coefficient, a minimum wrinkling depth can be observed and variations in the friction coefficient between the dies and tube has no effective influence on wall thinning and thickening.

Keywords: tube bending, wrinkle, simulation, friction, wall thickness change

1. Introduction

Recently, curved thin-walled tubular elements have been attracting more applications in automobile, aerospace, and oil industries. Tube bending is used as a hydroforming process and application that needs high strength/weight ratio products (Manabe and Amino, 2002; Koc and Altan, 2001). There are some parameters to be controlled in order to reduce the defect. For example, geometry parameters and friction conditions are modified to restrain instability of the process. In the tube forming process, wrinkling can be avoided, but the wall thickness change is almost inevitable. From among the considerable number of studies dealing with the wrinkling and thinning of wall thickness in tube bending, only few studies have focused on methods to reduce the defect. Tang (2000) employed plastic-deformation theory to investigate the plastic deformation in pipe and tube bending and also explained the seven phenomena in tube bending, also mentioning their practical formulas. An experimental sample was also tested to illustrate that the results of the formulae are very similar to the experimental results. Yang *et al.* (2006) investigated the effect of friction on the cross-section quality of thin-walled tube NC bending. His results showed that the effects of frictions between all dies and tube on wall thinning are smaller than their effects on section distortion. Therefore, in order to improve the section quality, frictions between mandrel, wiper and tube should be decreased, but the frictions between the pressure die, bending die and tube should increase. Gaoa and Strano (2004) made a research on the effect of friction on the quality of tube pre-bending and hydroforming. In that paper, process variables such as the friction coefficient, tube material and pre-bent tube radius were analyzed. It was found that a lower friction coefficient can reduce thinning in the pre-bending process, and that a large pre-bending radius is beneficial to both pre-bending and subsequent hydroforming.

Zeng and Li (2002) introduced a tube push-bending process combining axial forces and internal pressure. Moreover, they also made research on effects of the internal pressure, friction condition and push distance on the tube deformation push-bending process. Yang and Lin (2004) studied the wrinkling in the tube bending process, where the effects of bending angle, geometrical dimensions, material properties and the original radius and strength coefficient of tubes on the minimum bending radius were analyzed. The role of the filling material on defects in the of thin--walled tube bending process was reported as a numerical and experimental study by Sedighi and Taheri Kahnamouei (2014). That paper investigated approaches to avoid common defects such as the wrinkling, cross section distortion and wall thickness variation in the bending process of a thin-walled tube. So, a series of experimental tests was carried out by filling the tube with melted lead and different types of rubbers. They showed that wrinkle initiation and cross section distortion can be avoided with a lost core made of low temperature melting metal like lead or tin. Jiang *et al.* (2011) used a three-dimensional finite element method to investigate deformation behavior of medium-strength TA18 high-pressure tubes during NC bending with different bending radii. The article showed that if a mandrel is used, the thickening ratio increases from the initial bending section to the bending section.

In the present study, firstly, the wrinkle phenomenon and the wall thickness change in a thin-walled tube are studied using theoretical, experimental and FE methods. In order to verify the finite element analysis results, some experiments have been done and comparisons drawn between the experimental and numerical results in Section 2. In Section 3, FEM analysis of effects of friction between the dies and tube on these defects is studied. Finally, in Section 4 the results are presented and discussed. The results show that at a certain friction coefficient a minimum wrinkling depth can be observed and variations in the friction coefficient between the dies and tube have no effective influence on the wall thinning and thickening.

2. Methodology

2.1. Analytical approach

Changes in wall thickness is related to many factors, such as material, size and shape, bending and wall factors, bending method, tooling and bending operation. When a tube is bent, then tensile or compressive stresses cause wall thinning or thickening. The wrinkling in the inner wall of the bending radius is one of the common defects in the tube bending process. It has a direct relation with the outer diameter-to-wall thickness ratio and the centerline bending radius-to-outer diameter ratio (Fig. 1).

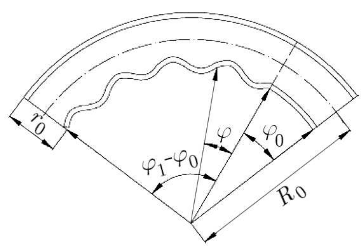

Fig. 1. Example of a wrinkled bending section of a tube and its parameters (Yang and Lin, 2004)

Based on the known energy principle, the critical moment of wrinkling onset is when the internal energy of the wrinkled shell (U) is equal to the work done by the external forces (T), and the wrinkling happens if the external forces are larger than the internal energy of the wrinkled shell (Yang and Lin, 2004). According to the wrinkling wave function proposed by Wang and Cao (2001) and Yang and Lin (2004), the depth of wrinkling in the normal direction w can be characterized with the following function

$$w = w_0\sqrt{\frac{R\cos\theta}{R_0}}\Big(1-\cos\frac{2\pi m\varphi}{\phi_1-\phi_0}\Big) \qquad w_0 = \frac{\sqrt{r_0R_0}(\phi_1-\phi_0)}{\pi m} \tag{2.1}$$

where r_0 is the tube diameter, R_0 is the bending radius, m is the wave number along the circumferential direction of the tube, φ is the curve coordinate in the tube bending direction which changes from ϕ_1 to ϕ_2.

When a tube is bent, two typical stress zones can be defined. One is the tension zone at the extrados of the bend; the other is the compressive zone at the intrados of the bend. These cause tube thickening at the intrados and thinning at the extrados, respectively, as shown in Fig. 2.

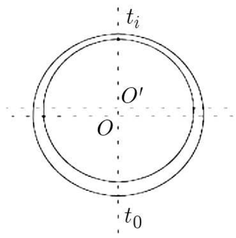

Fig. 2. Cross section of tube after bending

Based on plastic deformation theory, equations (2.2) give the rate of wall thinning and wall thickening for the extrados and intrados of the bend which has been proposed by Tang (2000)

$$t_{0\,max} = \Big(1-\frac{r_0}{4R_0}\Big)t \qquad t_{i\,max} = \Big(1+\frac{2R_0r_0+3r_0^2}{8R_0^2}\Big)t \tag{2.2}$$

where t is tube wall thickness.

2.2. Material properties and geometry

A uniaxial tension test is used to obtain mechanical properties of steel (USt37) and is listed in Table 1. The hardening behavior can be described by equation $\sigma = K(\varepsilon)^n$. The Coulomb friction model is used in the simulation process.

Table 1. Mechanical properties of the tube

Poisson's ratio	0.3
Maximum elongation [%]	44.2
Elasticity modulus [GPa]	210
Yield stress [MPa]	270
K	345
n	0.05

The tooling parameters are shown in Table 2. Circular tubes of diameter $r_0 = 50$ mm, wall thickness of $t_0 = 1.5$, 1.25, 0.9 mm, bending radius 150 mm and bending angle 45° were used in the experiments.

Table 2. Tooling geometry dimensions

Tooling parameter	Length [mm]	Dimension [mm]
Bend die	300(D)	52
Rotary die	150	52

2.3. Experimental setup

The experiment is performed to provide a general concept of the tube bending process and to verify the FE modeling. For this purpose, a hydraulic horizontal tube bending machine has been used. The horizontal bending is widely used for bending tubes, particularly for tight bending radii and thin wall tubes. The dies setup on the horizontal bending machine is shown in Fig. 3. The work piece is held between the bend die and rotary dies. The bend die strokes linearly and, synchronically, rotary dies are actuated to rotate on the tube, and the work piece bends to any requested angle.

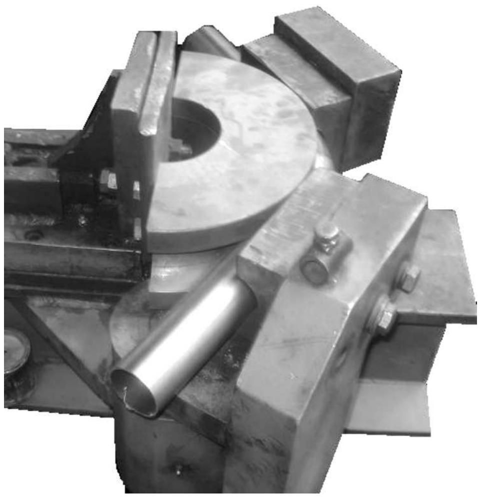

Fig. 3. Sketch of the tube horizontal bending

2.4. The FE model

A 3D finite element model is built using ANSYS software. The tube is modeled by shell 143 which is well suited to model nonlinear, flat or wrapped, thin to moderately thick shell structures. Three dimensional rigid elements for the dies models have been used. Shell 143 is 4-node 3D space shell element and has six degrees of freedom at each node: translations in the nodal x, y, and z-directions and rotations about the nodal x, y, and z-axis. The geometry, node locations, and the coordinate system for this element are shown in Fig. 4 (ANSYS Help, 2007).

The Coulomb friction coefficient between the tube and dies are assumed to be equal to 0.15 (Trana, 2002) and all dies and tube geometric parameters are the same as used in the experimental setup. In the tube bending process, there are three contact surfaces between the tube/bend die, tube/rotary dies. The "surface-to-surface contact" method has been employed to describe the mechanical constraints for different contact pairs using CONTACT174 and TARGET169. Figure 5 shows a representative finite element model with the initial tube blank and the tool set.

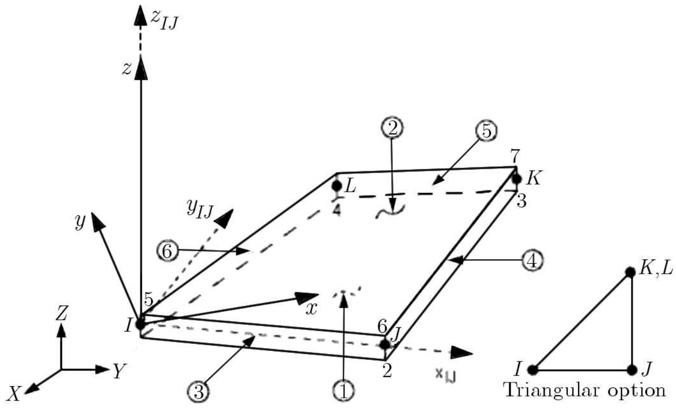

Fig. 4. Shell (143) geometry (ANSYS Help, 2007)

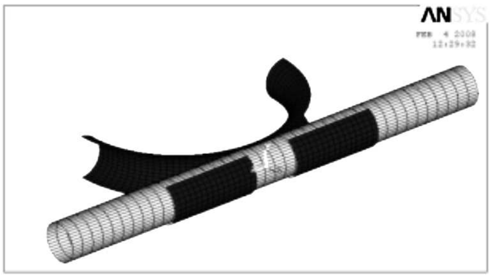

Fig. 5. FE model for the horizontal bending process

3. Experimental verification of the numerical model

In order to verify the finite element analysis results, some experiments have been done. In Fig. 6, a comparison between the experimental and numerical results are presented. No wrinkling can be seen in the tube with 1.5 mm thickness but in the tube with 1.25 mm and 0.9 mm thickness wrinkling is observed.

Also the wrinkling depth in the experimental and FE modeling results is compared in Fig. 7. It can be seen that the amount of wrinkling in the tube is in direct correlation with the tube wall thickness. An increasing in the wall thickness decreases the possibility of wrinkling. From Fig. 6 and Fig. 7 it can be concluded that the FE results are reasonable and can be used for further investigation of the friction coefficients effect on wrinkling.

FEM simulations and experimental results for the extrados wall thickness at the bend zone have been compared and they are shown in Fig. 8. It can be seen that the wall thickness at the outside of the bend is always decreased. Also by an increase in d/t ratio, the thinning value decreases. The maximum thinning reduction in 1.5 mm tube is equal to 6.5% and the minimum thinning reduction in 0.9 mm tube is equal to 3%. It can also be observed from Fig. 8 that the wall thickness has a great influence on the thinning when the bending radius and tube diameters are fixed.

Also experimental and FEM results for the intrados wall thickness at the bend zone have been compared and shown in Fig. 9. It can be seen that the thickness at the inside of the bend is increased, and the maximum thickness thickening reduction is equal to 10%.

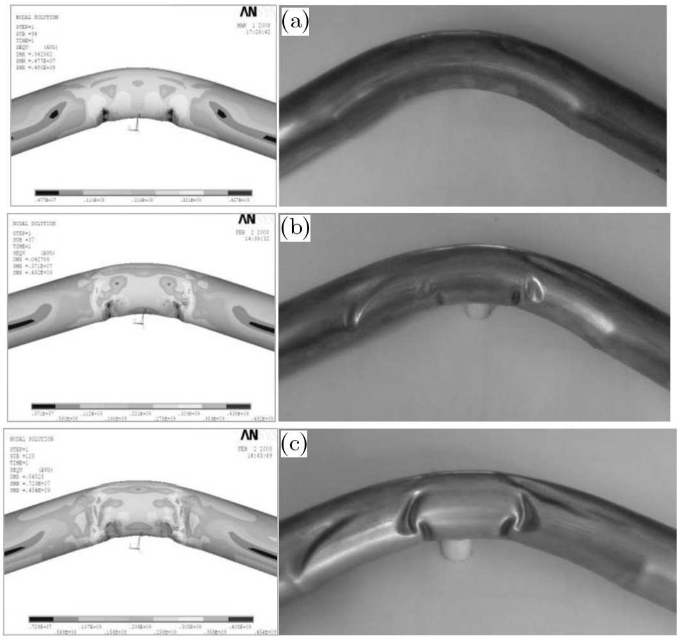

Fig. 6. Verification of the FE results by experiments. Wall thickness: (a) 1.5 mm, (b) 1.25 mm, (c) 0.9 mm

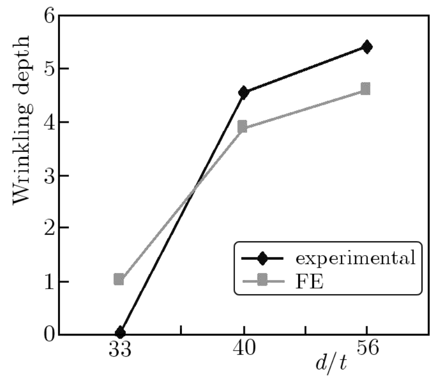

Fig. 7. Comparison of FE and experimental results

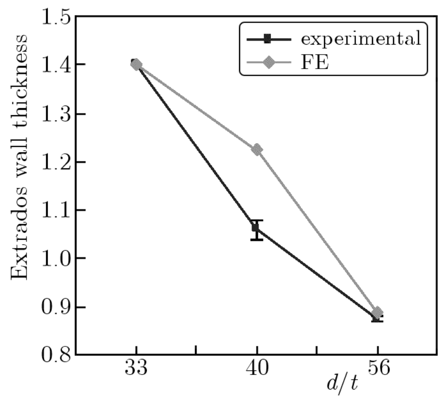

Fig. 8. Comparison of the thickness distribution in FE and experimental results at the extrados radius (without considering hardening and friction parameters)

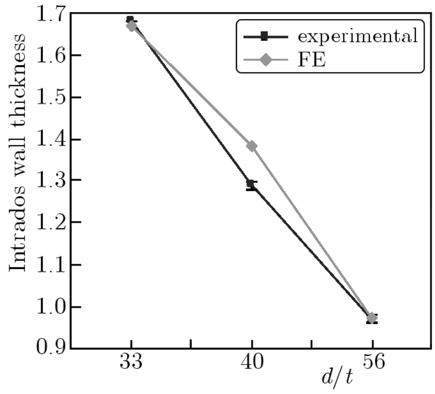

Fig. 9. Comparison of the thickness distributions in FE and experimental results at the intrados radius (without considering hardening and friction parameters)

4. Results and discussion

The friction conditions between the bend die, rotary die and tube have a large effect on the wrinkling in thin-walled tube horizontal bending, especially for small R/D and large D/t. In order to study the effects of friction on defects after verification of the FE model, a set of runs have been implemented. There are two different cases of friction in the horizontal bending process. One refers to friction between the bend die and tube; another refers to friction between the tube and rotary dies. For this purpose, two series of friction conditions are employed. These runs include values of the friction coefficient between the bend die and tube as 0.05, 0.1, 0.2, 0.3, 0.4, 0.5 and friction between the rotary dies and tube as 0.05, 0.1, 0.2, and 0.3. In the following, the obtained results will be discussed for four different subsections separately.

4.1. The effect of friction between rotary dies and tube on wrinkling

The FE modeling of the bending process for different amounts of friction between the rotary dies and tube have been carried out. Variations in the friction coefficient and wrinkling depths are shown in Fig. 10. It shows that the depth of wrinkling for all three thicknesses are decreased when the friction coefficient is decreased from 0.3 to 0.2 and the depth of the wrinkling is increased when the friction coefficient is reduced from 0.2 to 0.05. This shows that the least wrinkling depth will happen at a certain friction coefficient.

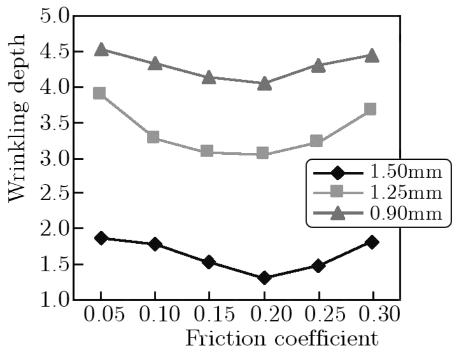

Fig. 10. Variations in wrinkling depth vs. friction coefficient between the tube and rotary dies

4.2. The effect of friction between rotary dies and tube on the wall thickness change

The effects of the friction coefficient between the rotary die and tube on the wall thickness are shown in Figs. 11 and 12. It can be found that it has no influence on the thinning and thickening of the tube wall.

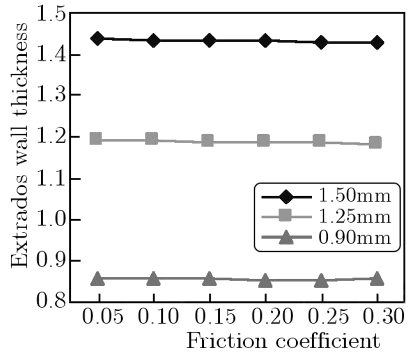

Fig. 11. Variations in wall thinning vs. friction coefficient between the tube and rotary dies (without considering hardening and friction parameters)

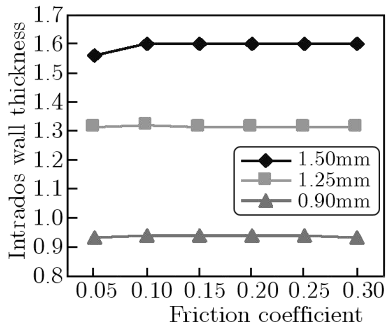

Fig. 12. Variations in wall thickening vs. friction coefficient between the tube and rotary dies (without considering hardening and friction parameters)

4.3. The effect of friction between bend die and tube on the wrinkling

Variations in the friction coefficient and wrinkling depths for different thicknesses (1.5, 1.25, 0.9 mm) are presented in Fig. 13. It shows that for all three thicknesses, the depth of wrinkling is decreased when the friction coefficient is reduced from 0.5 to 0.2. But when the friction coefficient is reduced from 0.2 to 0.05, the depth of wrinkling increases. It is found that the minimum wrinkling depth takes place at friction coefficient of 0.2.

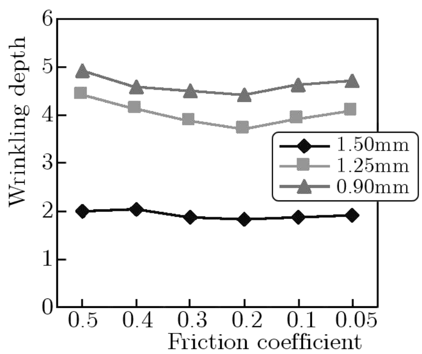

Fig. 13. Variations in wrinkling depth vs. friction coefficient between the tube and bend die

4.4. The effect of friction between bend die and tube on the wall thickness change

The effects of the friction between the bend die and tube on the wall thickness are shown in Figs. 14 and 15. Same as in the previous Subsection, it can be found that friction between the bend die and tube has no influence on the thinning and thickening of the tube wall.

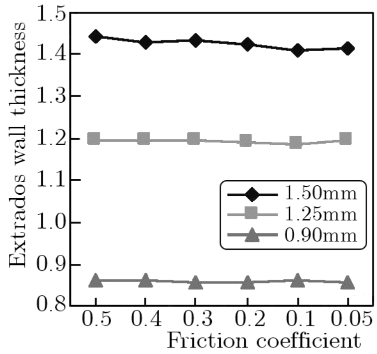

Fig. 14. Variations in wall thinning vs. friction coefficient between the tube and bend die (without considering hardening and friction parameters)

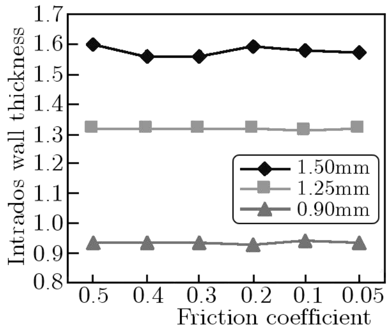

Fig. 15. Variations in wall thickening vs. friction coefficient between the tube and bend die (without considering hardening and friction parameters)

According to the results given in these figures, it can be concluded that friction between the tube, bend die and rotary dies have a significant and important effect on the wrinkling, and have no influence on the thinning and thickening of tube wall thickness in the tube horizontal bending process.

5. Conclusion

A 3D FE model has been created to study the effect of friction on defects in the bending process. The FE results have been verified by experimental tests and they are in good agreement. According to the results of the analysis, it can be concluded that:

- The minimum wrinkling depth occurs at a certain value of the friction coefficient.
- Friction conditions may affect the balance of internal energy between the wrinkled shell and the work done by the external forces. So, there should be a certain friction coefficient value for which a stable state exists between the two mentioned energies.
- Extremely low or high friction conditions are detrimental for the tube bending process. A perfect tubular part can be obtained at a suitable friction condition.
- Variations in the friction coefficient between the dies and tube have no influence on the thinning and thickening of the tube wall.

Finally, it should be noticed that there are other effective parameters in the tube bending such as bending speed, bending radius. Future works should address these factors in detail.

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