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The Effect of Normal Anisotropy on Thin-walled Tube Bending

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ABSTRACT

Thin-walled tube bending has common applications in the automobile and aerospace industries. The rotary-draw-bending method is a complex physical process with multi-factor interactive effects and is one of the advanced tube forming processes with high efficiency, high forming precision, low consumption and good flexibility for bending angle changes. However, it may cause a wrinkling phenomenon, over thinning and cross-section distortion if the process parameters are inappropriate. Wrinkles propagate in thin-walled tube, but in some cases, localize in a finite zone and lead to failure. Wrinkling prediction in thin-walled tube bending processes has been an important and challenging subject in the related industry. In this paper, the plastic deforming behavior and wrinkling mechanism for a thin-walled tube is simulated and the results are compared with the available experimental ones. Next, the effect of anisotropy on ovalization, thickness and wrinkling of tube is investigated using Finite Element Method (FEM). Numerical results are presented showing the effects of various kinds of materials and geometric parameters on wrinkling using anisotropic yield function.

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1. INTRODUCTION

Thin-walled tubes are applied in many branches of engineering like aircraft, spacecraft, cooling towers, steel silos and tanks for bulk solid and liquid storage, pressure vessels, pipelines and offshore platforms. The rotary-draw bending process of thin-walled tubes has been attracting more and more applications due to its high forming precision advantage and satisfying the increasing needs for high strength per weight ratio products. However, the inner side of thin-walled tubes may experience a wrinkling phenomenon if the process parameters are inappropriate especially for tubes with large diameter and thin wall thickness. It is because of the compressive stress during the bending process, which leads to the process failure or even dies damage in the case of severe wrinkling. Possible wrinkling at two locations are identified, before the material enters the bending die and at the bending intrados. How to predict this phenomenon rapidly and accurately is one of the urgent key problems to be solved for the development of this process at present. It is well known that the problem resolution relies heavily on the experience and involves repeated trial-and-error in practice. These expensive procedures spend excessive manpower, raw material, and time in designing and adjusting the process and dies. Moreover, it makes the production efficiency abate drastically and even so, contented outcomes may not be obtained. Many studies are conducted by researchers in the literature including experimental, analytical and numerical simulation methods. An energy approach was presented by Wang and Cao [1] to provide the minimum bending radius, which does not yield wrinkling in the bending process, as a function of tube and tooling geometry and material properties. Peek [2] investigated to what extent the wrinkling wavelengths may be influenced by the approximations of small strains and the theory of thin shells. Regarding the shell theory approximations, it is found that the three-dimensional continuum theory predicts slightly shorter critical wrinkling wavelengths, especially for lower diameter-to-wall-thickness ratios. Hallai and Kyriakides [3] investigated the influence of Lüders banding and of the tube D/t on the inelastic response and stability of tubes under rotation controlled pure bending and the extent to which the tubes can be

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safely bent. The problems were studied using a combination of experiment and analysis. A wrinkling wave function was proposed by Yang and Yan [4] and established a simplified wrinkling prediction model to predict the minimum bending radius for tubes based on thin-shell theory, forming theory, the energy principle and wave function. Strano [5] proposed a computer-based methodology that called Tube ProDes for process design of the rotary draw bending of tube. Orban et al. [6] developed a finite element model to simulate rotary draw bending and used the local variation of normal-to-surface velocity for wrinkling detection, then provided basis for developing an adaptive loading scheme to optimize end boost without inducing wrinkles in bent tube. Li et al. [7] established one analytical model of the mandrel (including mandrel shank and balls) and deduced some reference formula in order to select the mandrel parameters preliminarily, then carried out experiments to verify the analytical model. The rotary draw bending process was simulated focusing more on wrinkle formation by Kumar [8]. Then, the effects of various process parameters on the formation of wrinkles were analyzed and optimum process parameters were selected to get wrinkle-free bend. An energy-based wrinkling prediction model for thin-walled tube bending was developed using the energy principle, combined with analytical and finite element (FE) numerical methods by Li et al. [9]. A 3D elastic–plastic finite element model and a wrinkling energy prediction model under multi-die constraints was established considering the characteristics of the bending processes of aluminum alloy thin-walled tubes with large diameters by Yang et al. [10].

Some researchers considered the sheet anisotropy in the tube bending process. Takahashi et al. [11] performed comparisons between theoretical predictions and experiments on two kinds of anisotropies; anisotropies of flow stress and r-value obtained by tensile tests in various directions in the extended sheet specimen, and anisotropy of flow stress of tube specimen between torsion and tension. A numerical analysis presented by Kim and Son [12] for evaluating a wrinkling limit diagram for an anisotropic sheet subjected to biaxial plane-stress.

Corona et al. [13] revisited the problem of inelastic bending of tubes with the aim of resolving the discrepancy between wrinkle wavelengths. The spring back mechanism and rule of thin-walled tube bending were revealed based on the numerical simulation of the whole process by Gu et al. [14]. An analytical model for thin-walled tube bending was developed and then based on ABAQUS platform, a series of 3D-FE models were developed to simulate the bending process with large diameter and small bending radiuses. Also, numerical study on the deformation behaviors of bending process was conducted by Li et al. [15]. The deformation behaviors of thin-walled tube in rotary draw bending under push assistant loading conditions with multiple defects were revealed by Li et al. [16]. They presented an analytical description of push assistant loading conditions and proposed some indices for evaluation of push assistant loading roles, then the interactive effects of push assistant loading conditions on wall thinning, cross-section deformation and wrinkling was investigated extensively using 3D-FE simulation considering push assistant loading functions combined with experiment.

In this paper, the plastic deforming behavior and wrinkling mechanism for thin-walled tube is simulated and the results are compared with the available experimental ones. Then, the effect of anisotropy on ovalization, thickness and wrinkling of tube is investigated using FEM. Numerical results are presented showing the effects of various kinds of materials and geometric parameters on wrinkling using anisotropic yield function.

2. THE ROTARY-DRAW BENDING PROCESS

The whole process of thin-walled tube bending includes three processes: bending tube, retracting mandrel and spring back. In the thin-walled tube rotary-draw bending process, as shown in Figure 1, both sides of the tube are subjected to various tooling's strictly contacting force, such as bend die, clamp die, pressure die, wiper die and mandrel. The tube is clamped against the bend die; drawn by the bend die and the clamp die, the tube goes past the tangent point and rotates along the groove of the bend die to the desired bending degree and the bending radius. So, the process needs precise coordination of various dies and strict controlling of forming parameters. Among the above tooling, mandrel is positioned inside the hollow tube to provide the rigid support.

Figure 2 shows FEM model for rotary-draw bending process. The four-node double curved thin shell is applied to describe three-dimensional deformable tube.

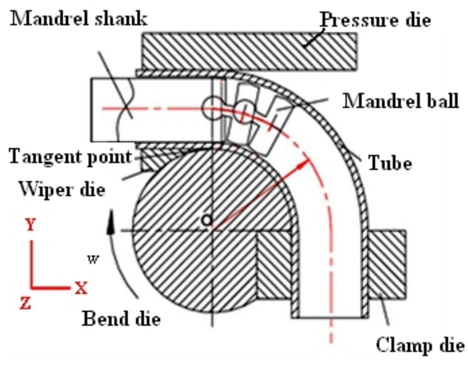

Figure 1. Forming principle of rotary draw bending method.

Five integration points are selected across the thickness to describe the tube bending deformation. The external and internal rigid tools are modeled as rigid bodies using 4-node 3D bilinear quadrilateral rigid element to describe smooth contact geometry curved faces. The results of this paper are compared with the experimental data [7]. The geometry parameters are reported in Table 1.

The tube material is aluminum alloy LF2M with mechanical properties as shown in Table 2. The Swift's power-law plastic model is used as:

$$\bar{\sigma} = K\bar{\varepsilon}^{n} \tag{1}$$

where K and n are the strength coefficient and the work-hardening exponent, respectively [10].

At tube bending process the following five contact interfaces between tube and dies are: tube/mandrel (ball), tube/wiper die, tube/bend die, tube/clamp die and tube/pressure die. The classical Coulomb model has been chosen to represent the interfaces' friction conditions:

$$\sigma_f = \mu|\sigma_n| \tag{2}$$

where σ_f is the frictional stress, μ represents the friction coefficient $(0<\mu<0.5)$ and σ_n is the stress on the contact surface. The tube's bending deformation depends on the contact and friction between various tube portions and different dies. According to the different contact conditions, the friction coefficient can be classified into 4 kinds: 0.05, 0.1, and 0.25 and ''Rough'', in which ''Rough'' type refers to no relative slipping when nodes contact each other and is suitable for the tube/clamp die friction conditions. The other friction coefficients assigned to different contact interfaces as shown in Table 3.

3. HILL ANISOTROPY CRITERIA

Thin-walled tubes are produced via extrusion process usually and have anisotropic properties. To express the behavior of anisotropic materials, different equations have been introduced in the literature where quadratic equation of Hill is more popular among them and its constants can be easily calculated by performing tensile tests. The following function depicts Hill yield function to study the effect of anisotropy:

$$\bar{\sigma}^2 = F(\sigma_{yy}-\sigma_{zz})^2 + G(\sigma_{zz}-\sigma_{xx})^2 + H(\sigma_{xx}-\sigma_{yy})^2 + 2L\sigma^2_{yz} + 2M\sigma^2_{zx} + 2N\sigma^2_{xy} \tag{3}$$

The constants in this equation can be obtained using the following relations:

$$\sigma^y_{zz} = \sqrt{\frac{2}{H+F}}\sigma^y_{xx};\quad \sigma^y_{yy} = \sqrt{\frac{2}{G+F}}\sigma^y_{xx};\quad \sigma^y_{xy} = \sqrt{\frac{1}{L}}\sigma^y_{xx};\quad \sigma^y_{yz} = \sqrt{\frac{1}{M}}\sigma^y_{xx};\quad \sigma^y_{xz} = \sqrt{\frac{1}{N}}\sigma^y_{xx} \tag{4}$$

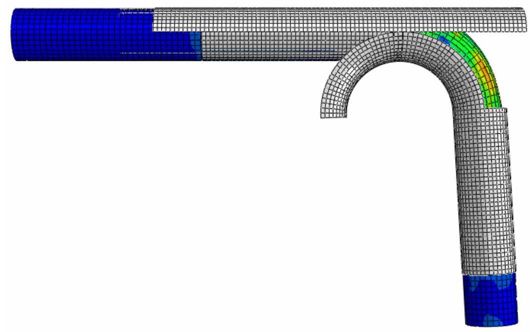

Figure 2. Illustration of FEM model for rotary-draw bending process

TABLE 1. Geometrical parameters of simulations

Parameters	Value
Tube outside diameter(D)	38mm
Wall thickness(t)	1mm
Bending radius(R)	57mm
Mandrel diameter(d)	35.60mm
Nose radius(r)	6mm
Extension length(e)	6mm
Number of balls(n)	1
Balls thickness(k)	12mm
Space length between mandrel Shank and ball(p)	15mm
Mandrel length	153mm
Pressure die length	250mm
Clamp die length	115mm
Wiper die length	120mm

TABLE 2. Mechanical properties of tube

Material parameter	
Ultimate tension strength (MPa)	190
Extensibility (%)	22
Poisson's ratio	0.34
Initial yield stress (MPa)	90
Hardening exponent, n	0.262
Strength coefficient K	398
Young's modulus E (GPa)	56
Density (kg/m^3)	2700

TABLE 3. Friction conditions at various contact interfaces

Contact interface	Friction coefficients
Tube/wiper die	0.05
Tube/pressure die	0.25
Tube/clamp die	Rough
Tube/bend die	0.1
Tube/mandrel	0.1
Tube/balls	0.1

In these formula, the yield stress in the extruding direction (σ_{xx}^{y})has been selected as a reference yield stress. It must be noted that in the finite element model, the x axis is in the extruding direction, the z axis is in the circumferential direction and the y direction represents the radial direction.

A convenient method to determine the coefficients in Equation (3) is conducting three tensile tests, using specimens cut from the tube at the angles 0°, 45° and 90° with respect to the extruding direction, with the additional conditions:

$$H+G=2; \quad N=L=M \tag{5}$$

Lankford coefficients (the ratio of the true width strain to the true thickness strain in different angles to the extruding direction) are defined as follows [17]:

$$r_0=\frac{H}{G}; \quad r_{90}=\frac{H}{F}; \quad r_{45}=\frac{2N-F-G}{2(G+F)} \tag{6}$$

To define the anisotropic behavior of the material, the six ratios of yield stresses to the reference yield stress in extruding direction *i.e.* x direction ($\sigma_0=\sigma_{xx}^{y}$) are used. These ratios are:

$$R_{11}=\frac{\sigma_{xx}^{y}}{\sigma_0}=1; \quad R_{22}=\frac{\sigma_{yy}^{y}}{\sigma_0}; \quad R_{33}=\frac{\sigma_{zz}^{y}}{\sigma_0};$$
$$R_{12}=\sqrt{3}\frac{\sigma_{xy}^{y}}{\sigma_0}; \quad R_{13}=\sqrt{3}\frac{\sigma_{yz}^{y}}{\sigma_0}; \quad R_{23}=\sqrt{3}\frac{\sigma_{xz}^{y}}{\sigma_0} \tag{7}$$

The normal anisotropy index (r) and the planar anisotropy (Δr) are calculated using the following formulas:

$$\bar{r}=\frac{1}{4}(r_0+2\,r_{45}+r_{90})$$
$$\Delta r=\frac{1}{2}(r_0-2\,r_{45}+r_{90}) \tag{8}$$

From a design viewpoint, the desired type of anisotropy is that in which the tube is isotropic in the cylindrical shell and has an increased strength in the thickness direction, which is referred to as normal anisotropy.

TABLE 4. Normal anisotropic cases

Case	r	R_{11}	R_{22}	R_{33}	R_{12}	R_{13}	R_{23}
1	0.5	1	0.866	1	1.060	1.060	1.060
2	0.6	1	0.894	1	1.044	1.044	1.044
3	0.7	1	0.921	1	1.030	1.030	1.030
4	0.8	1	0.948	1	1.019	1.019	1.019
5	1.1	1	1.024	1	0.992	0.992	0.992
6	1.2	1	1.048	1	0.985	0.985	0.985
7	1.3	1	1.072	1	0.978	0.978	0.978
8	1.4	1	1.095	1	0.973	0.973	0.973
9	1.5	1	1.118	1	0.968	0.968	0.968
10	2	1	1.224	1	0.948	0.948	0.948

In normal anisotropy $r_0=r_{45}=r_{90}$. In this paper, the effect of normal anisotropy on the wrinkling of tube under bending is investigated. Different distributions of Lankford coefficients are chosen and several conclusive results are presented. Lankford coefficients and Hill yield function parameters associated with these cases are given in Table 4 based on the previous results [11].

The values of yield stress coefficients in Table 4 were obtained using Equations (4)–(6). It must be noted that 1-axis and 3-axis are in the sheet plane (1 in the extruding direction and 3 in the transverse direction), while 2-axis is normal to the sheet plane.

4. RESULTS

At first, the validity of results is verified comparing with findings of Li et al. [7]. Simulations show that the initial tube circular cross section deforms to oval, through the arc of bent tube, which is in agreement with the experiments. The parameter of ovalization in tube cross-section is defined as:

$$\text{Ovalization Ratio}=\frac{\text{Major Diameter-Minor Diameter}}{\text{Initial Tube Diameter}}\times 100\ \% \tag{9}$$

As can be seen in Figure 3, parameter of ovalization in tube cross-section for the middle of the bending angle is used to compare the results, which indicates good agreement between the results of two researches. Von misses stress contour in bending angle of 104° is shown in Figure 4.

Now, the normal anisotropy effect on wrinkling and tube deformation in rotary-draw bending process is studied. In Figure 5, the effect of normal anisotropy on ovalization of tube cross-section is shown. In this case, the bending angle is 90° and the ovalization of tube cross-section is calculated in angle 45°. This diagram shows increasing the normal anisotropy coefficient results increase in ovalization of tube cross-section.

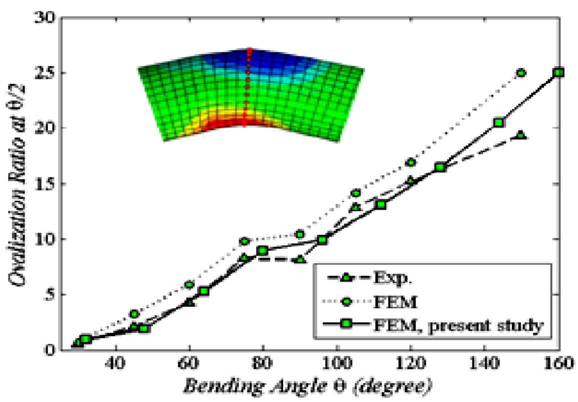

Figure 3. Comparison of the ovalization parameter in this research and results from other references [7]

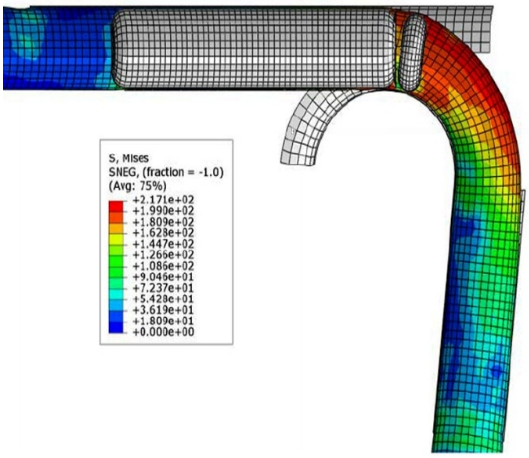

Figure 4. Von mises stress distribution in the bending angle of 104 º

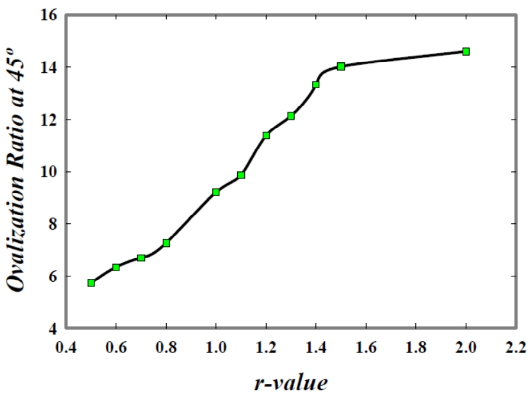

Figure 5. Anisotropy effect on ovalization of tube cross-section

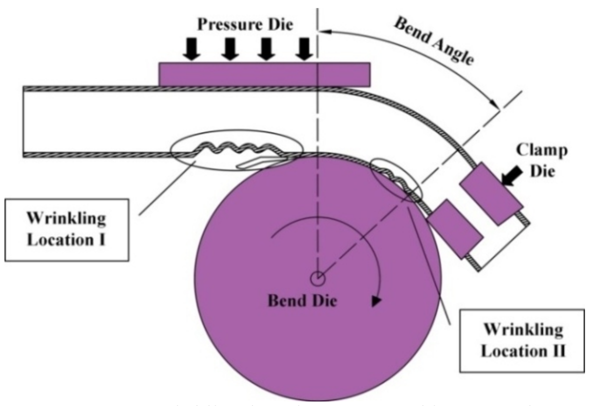

Figure 6. Two wrinkling locations occurred in rotary-draw bending process

Based on the experimental findings, depending on the applied conditions, possible wrinkling at two locations, before the material enters the bending die and at the bending intrados will occur as is shown in Figure 6. The simulated process in this paper, leads the tube to be wrinkled in both locations.

To study the anisotropy effects on wrinkling, regions I and II are considered. Figure 7 illustrates the node numbers 1 to 35 on the tube edge which will be entered to the intrados of bent tube.

The Y value is considered for the study of anisotropy effects on wrinkling. According to Figure 7, for nodes located in left hand side of line AB, the value of Y is equal to the distance of nodes from the line CD and for nodes located in right hand side of line AB, the value of Y is equal to the distance of nodes from the point O (which is the center of bending die).

When the tube does not wrinkle, Y value is almost equal to 38 mm, considering the distance of point O from axis of tube which is 57mm and tube radius of 19 mm. If the tube wrinkles, the value of Y will deviate, which is a characteristic of wrinkling. In this section, all geometrical features are similar to previous case except tube thickness. For having a great wrinkle wavelength and observing wrinkles on the tube, tube thickness is considered 0.5 mm.

The anisotropy effects on wrinkling are shown in Figures 8 and 9. In Figure 8, anisotropy coefficients are 0.5, 0.8 and Figure 9 is related to the anisotropy coefficients of 1.1 and 2. It is seen that the wrinkling of tube is decreased by increasing the normal anisotropy index (r). Furthermore, comparison of the results of anisotropic cases with isotropic ones indicates the effect of normal anisotropy on the tube wrinkling is considerable and it cannot be ignored.

In Figure 10, the contour of tube thickness, for four cases with normal anisotropy coefficients 0.5, 0.8, 1.1 and 2 are shown. It is evident that increasing the normal anisotropy coefficient results in increasing of wall thickness.

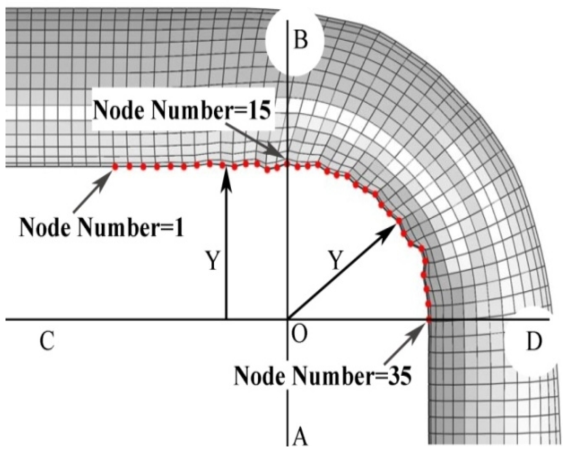

Figure 7. Node numbers and definition of Y value to study the anisotropy effects on wrinkling

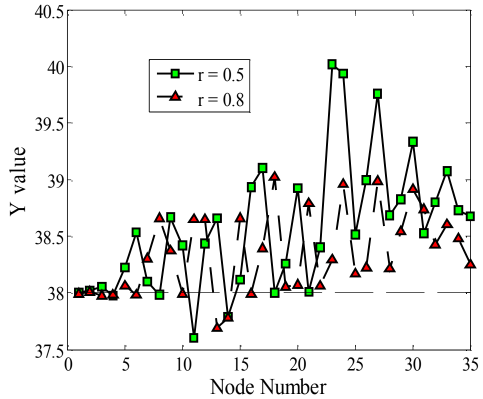

Figure 8. Wrinkling of intrados for r <1

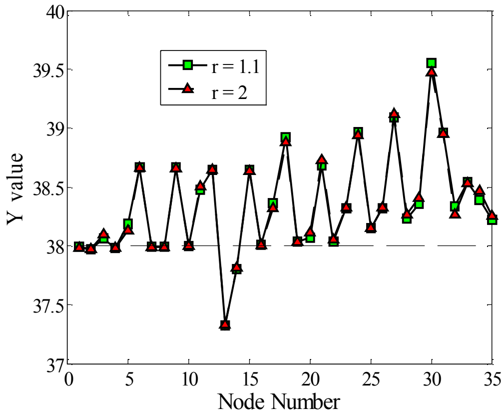

Figure 9. Wrinkling of intrados for r> 1

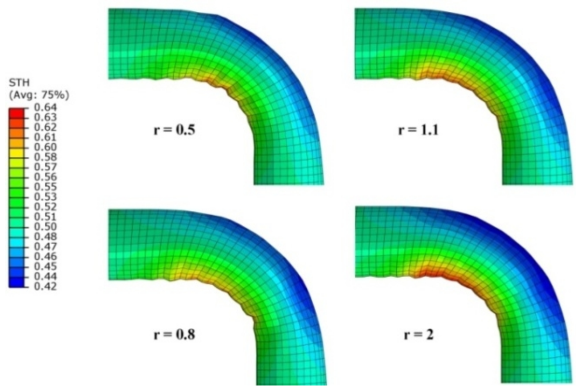

Figure 10. Tube thickness contours for different r values.

5. CONCLUDING REMARKS

The thin-walled tube bending process was simulated with the aim of investigating the effect of tube anisotropy on ovalization, thickness and wrinkling of tube which is exposed to the most severe conditions. An anisotropic tube material with Hill quadratic yield criterion was employed and normal anisotropy was considered in this study. Based on this investigation, the following conclusions can be drawn:

1. The larger normal anisotropy index (r) results higher ovalization ratio.
2. The maximum value of tube wall thickness is increased by increasing the normal anisotropy index (r), for r<1.
3. The wrinkling of tube is decreased by increasing the normal anisotropy index (r). Furthermore, the effect of normal anisotropy on the tube wrinkling is considerable and cannot be ignored.

6. REFERENCES

1. Wang, X., and Cao, J., “Wrinkling limit in tube bending”, ***Journal of Engineering Materials and Technology***, Vol. 123, (2001), 430-435.
2. Peek, R., “Wrinkling of tubes in bending from finite strain three-dimensional continuum theory”, ***International Journal of Solids and Structures***, Vol. 39, (2002), 709-723.
3. Hallai, J. F., and Kyriakides, S., “On the effect of Lüders bands on the bending of steel tubes. Part I: Experiments”, ***International Journal of Solids and Structures***, Vol. 48, (2011), 3275–3284.
4. Yang, H., and Yan, L., “Wrinkling analysis for forming limit of tube bending processes”, ***Journal of Materials Processing Technology***, Vol. 152, (2004), 363-369.
5. Strano, M., “Automatic tooling design for rotary draw bending of tubes”, ***International Journal of Advanced Manufacturing Technology***, Vol. 26, (2005), 733-740.
6. Orban, H., Lin, G., Koc, M., and Hu, S. J., “Wrinkling detection in tube bending”, ***Transactions of NAMRI/SME***, Vol. 35, (2007), 105-112.
7. Li, H., Yang, H., Zhan, M., Sun, Z., and Gu, R., “Role of mandrel in NC precision bending process of thin-walled tube”, ***International Journal of Machine Tools & Manufacture***, Vol. 47, (2007), 1164–1175.
8. Kumar, A., “Optimizing the rotary draw tube bending process to avoid wrinkling”, ***International Journal of Modelling and Simulation***, Vol. 28, (2008), 281-291.
9. Li, H., Yang, H., and Zhan, M., “A study on plastic wrinkling in thin-walled tube bending via an energy-based wrinkling prediction model”, ***Modelling and Simulation in Materials Science and Engineering***, Vol. 17, (2009), 1-33.
10. Yang, H., Yan, J., Zhan, M., Li, H., and Kou, Y., “3D numerical study on wrinkling characteristics in NC bending of aluminum alloy thin-walled tubes with large diameters under multi-die constraints”, ***Computational Materials Science***, Vol. 45, (2009), 1052–1067.
11. Takahashi, H., Moro, J., and Tsuchida, S., “Plastic Anisotropy in Aluminium Drawn Tubes”, ***Metals and Materials***, Vol. 4, (1998), 380-385.
12. Kim, Y., and Son, Y., “Study on wrinkling limit diagram of anisotropic sheet metals”, ***Journal of Materials Processing Technology***, Vol. 97, (2000), 88-94.
13. Corona, E., Lee, L. H., and Kyriakides, S., “Yield anisotropy effects on buckling of circular tubes under bending”,

International Journal of Solids and Structures, Vol. 43, (2006), 7099–7118.

14. Gu, R. J., Yang, H., Zhan, M., Li, H., and Li, H. W., "Research on the springback of thin-walled tube NC bending based on the numerical simulation of the whole process", ***Computational Materials Science***, Vol. 42, (2008), 537–549.
15. Li, H., Yang, H., Yan, J., and Zhan, M., "Numerical study on deformation behaviors of thin-walled tube NC bending with large diameter and small bending radius", ***Computational Materials Science***, Vol. 45, (2009), 921–934.
16. Li, H., Yang, H., Zhan, and Kou, Y. L., "Deformation behaviors of thin-walled tube in rotary draw bending under push assistant loading conditions", ***Journal of Materials Processing Technology***, Vol. 210, (2010), 143–158.
17. Duchene, L., "FEM study of metal sheets with a texture based", Ph.D. Thesis, Liege University, (2003).

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چکیده

خمش لوله های جدار نازک، معمولا در صنایع هوافضا و ماشین سازی کاربرد دارد. فرآیند خمش کششی دورانی یکی از فرآیندهای پیچیده و پیشرفته شکل دهی فلزات با راندمان بالا بوده که پارامترهای متفاوتی بر آن حاکم می باشد. اگر پارامترهای حاکم بر این فرآیند نامناسب باشند، ممکن است عیوبی همچون چروکیدگی، نازک شدگی دیواره بیرونی و اعوجاج مقطع عرضی لوله بوجود آید. در حالت کلی چروکیدگی در لوله منتشر می شود، اما در حالت های خاص ممکن است که چروکیدگی در یک ناحیه انباشته شده و منجر به تغییر شکل های نامطلوب گردد. لذا پیش بینی چروکیدگی در فرآیند خمش لوله های جدار نازک در صنایع وابسته یک موضوع مهم و چالش انگیز می باشد. در این تحقیق، نحوه تغییر شکل پلاستیک و چروکیدگی لوله در فرآیند خمش شبیه سازی می شود و نتایج بدست آمده با نتایج موجود در مقالات مقایسه می گردد. پس از آن اثر ناهمسانگردی بر روی چروکیدگی، نازک شدگی دیواره بیرونی و اعوجاج مقطع عرضی لوله مورد بررسی قرار می گیرد.

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