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Conversion Conditions for the Deformation Modes in Tube Conical Nosing

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The tube conical nosing process can be resolved into three deformation instantaneous states, namely, free bending - inflection straight - forced conical nosing. The right transformation has important effects on forming quality of nosing parts. The conversion conditions from free bending to inflection straight and nosing failure causes were derived based on the energy method. The calculating formulate for critical semi-cone angle was proposed and verified by finite element simulation. It was found: the bigger the hardening exponent, the larger the value of critical semi-cone angle; the geometric parameters have litter effect on the value of critical semi-cone angle while the materials are same. The thin-walled nosing parts with large semi-cone angle would wrinkle and the multi-pass forming process should be adopted. When the semi-cone angle of part is greater than the critical angle, it leads to curl.

1. Introduction

Conical nosing of tubular materials is one of the most popular and simplest processes in the forming of tubes (Сторожев et al., 1980). The tube conical nosing process can be resolved into three deformation instantaneous states, namely, free bending (AB) - inflection straight (B point) - forced conical nosing (BC) under axial load (Figure 1a) (Tellabide et al., 2017). When semi-cone angle is bigger, bending section AB would not inflectionn straight in point B but still bending to produce curling (Figure 1b). Therefore, conical nosing of big semi-cone angle is the process forming between nosing and instability, only satisfy forming mechanics conditions, the tube can inflection straight after certain degree of the bending deformation, resulting in nosing. The inflection straight can be produced in the forming is the key for nosing. The present study of tube nosing focused on the process parameters and the friction influence on forming limit (Hideki et al., 1998; Asghar et al., 2013). There is few research about large semi-cone angle cone nosing. However, for thin-wall precision cylindrical parts, especially the tins, the shapes are different for attract customers, the application of large semi-cone nosing cylindrical pieces are more and more, as a result, in recent years the study of thin walled cans parts is attention. Literature (Chen et al., 2011) analyzed the deformational behavior of the material in each stage necking process for the mouth area concave nosing cans to distinguish the material forming process control for different laws. Literature (Gao et al., 2010) proposed a novel method of forming thin-wall special-shaped curved face cylindrical parts with large diameter variation by using viscous medium pressure nosing process. Literature (Kitazawa et al., 1987) study the influences of the different material, different semi-cone angle, different wall thickness and diameter for conical die nosing and inner curling. Literature (Huang, et al., 2005) confirmed the existence of the limit of semi-cone angle in conical nosing with finite element analysis, but not explain the relationship between semi-cone angle and material properties from mechanism. For the study of tube forming conversion condition, more research focused on curling and flaring (Huang et al., 1993, Arvind et al., 2017; Tan et al., 2013). In this paper, semi-cone angle value of conical nosing and conversion conditions were studied based on deformation energy combined with the finite element simulation technology.

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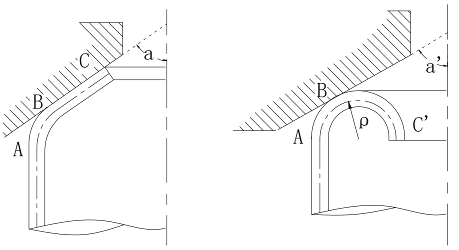
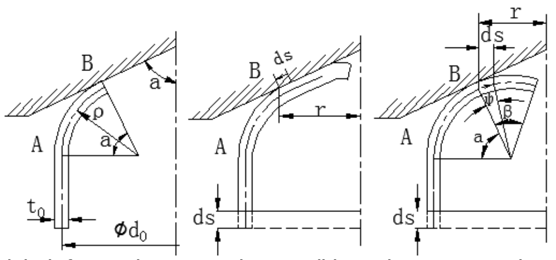


a) Nosing b) Inword curling

Figure 1: Schematic illustration of (a) Nosing and b) Inword curling

2. Mechanical model of tube nosing under conical die

Figure 2 is a simplified model of conical nosing. In the initial bending deformation stage, the tube blank is not complying with the die, it forms a circular arc, only the end touch die (as shown in Figure 2 AB section). The initial bending deformation behaviour and the bending radius are the decisive factors which affecting the subsequent deformation. As shown in figure 2a, t0, d0 are the initial thickness and diameter of tube blank respectively. Assumes ρ is the initial free bending radius of tube blank, α is the central angle of bending part (that is the die semi-cone angle). Figure 2a is the deformation status of T moment, after ds deformation, tube would occur two kinds of model forming: nosing or curling based on semi-cone angle, as shown in figure 2b and 2c. By comparing incremental deformation energy of the two kinds of deformation zone, judge whether the tube blank will inflection straight at point B that would result in nosing deformation transformation.



(a) deformed state at time T; (b) nosing state at time T+ dT; (c) curling state at time T+ dT

Figure 2: Geometrical modeling of deformed shape

According to an infinitesimal element ds, as shown in Figure 2a, the increment of dissipation of energy in plastic meridional bending at the entrance to the bending zone on point A is

$$\delta W_b = 2\int_0^{t_0/2} \pi\sigma_s d_0 \eta d\eta \delta\alpha \tag{1}$$

in which η is the thickness direction coordinates of bending zone, the stress based on the plane strain condition and $ds=\rho\delta\alpha$, Then, the δw_b can be represented as

$$\delta W_b = \frac{2\pi d_0 k ds}{n+2}\left(\frac{1}{\rho}\right)^{n+1}\left(\frac{t_0}{2}\right)^{n+2} \tag{2}$$

The tube end bend to point B to form a curl whose radius becomes ρ, the circular direction increment of nosing energy from A to B can be described as

$$\delta W_{\mathrm{zhou}} = 2\pi r t_0 ds \int \sigma_s d\varepsilon_\theta \tag{3}$$

Based on the principle of conservation of energy,

$$Fds = \delta W_b + \delta W_{zhou} \tag{4}$$

in which F is forming force, so the free bending forming force is

$$F = \pi d_0 t_0 k\left(\frac{1}{2}\right)^{n+1}\left(\frac{\rho}{d_0}\right)^{n+1}\left(1-\cos\alpha-\frac{n}{2}\sin^2\alpha\right) + \frac{2\pi d_0 k}{n+2}\left(\frac{1}{\rho}\right)^{n+1}\left(\frac{t_0}{2}\right)^{n+2} \tag{5}$$

For $\partial F/\partial \rho = 0$, so the minimum bending radius is

$$\rho = \frac{1}{2}\sqrt{t_0 d_0}[(n+2)(1-\cos\alpha - \frac{n}{2}\sin^2\alpha]^{\frac{-1}{2(n+1)}} \tag{6}$$

3. Criteria for nosing and curling

The occurring deformation modes of tube nosing and curling on a conical die, such as nosing and curing as shown in Figure 1, are investigated in order to determine the critical semi-cone angle as a criterion to distinguish between nosing and curing based on energy balance.

3.1 Total deformation energy of tube necking

Within the infinitesimal element deformation zone ds as shown in Figure 2b, the tube end point B proceed reverse bending deformation, and intimate contact with the die.
The increment strain of circumferential is

$$d\varepsilon_\theta = ds\sin\alpha / r \tag{7}$$

in which r is the section radius of deformation zone.
The increment of unbending energy $\delta W_{unb}$for the necking phase which takes place at point B, it can be represented as

$$\delta W_{unb} = \frac{4\pi r_b k ds}{2+n}\left(\frac{t_b}{2}\right)^{2+n}\frac{1}{\rho^{1+n}} \tag{8}$$

in which r_b, t_b are the section radius and thickness respectively.
Then the increment of total deformation energy for nosing phase, δW_n, is

$$\delta W_n = \int_0^\beta (2\pi r\rho t d\sigma d\varepsilon_\theta)d\varphi + \delta W_{unb} + \delta W_{AB} \approx 2\pi k t_b (\frac{\rho}{r})^n ds\rho\left[(\beta - a)\sin\alpha - n\sin(\alpha-\beta)\right] + \frac{4\pi r_b k ds}{2+n}\left(\frac{t_b}{2}\right)^{2+n}\frac{1}{\rho^{1+n}} + \delta W_{AB} \tag{9}$$

in which β is the central angle as shown in Figure 2c, and δW_{ab} is the increment of bending energy from A to B.

3.2 Total deformation energy of curing

In this deformation model, the tube end B keep up bending as in Fig 2c. The strain increment of circumferential direction is

$$d\varepsilon_\theta = dr / r = ds\sin(\alpha+\psi)/r \ ; \ d\sigma_s = k\varepsilon^n = k(ds\sin(\alpha+\psi)/r)^n \tag{10}$$

There is no unbending, then the increment of total deformation energy for curing phase, δW_c, is

$$\delta W_c = \int_0^\beta (2\pi r_b \rho t_b d\sigma_s d\varepsilon_\theta)d\psi + \delta W_{AB} = 2\pi k t\left(\frac{\rho}{r}\right)^n ds\rho\left[(\cos\alpha - \cos\beta) - \frac{n}{2}(\sin^2\beta - \sin^2\alpha)\right] + \delta W_{AB} \tag{11}$$

3.3 Critical semi-cone angle

From the analytical study above, after the infinitesimal element ds deformation, the tube end is to unbend and fit to the die surface, total deformation energy is δW_n the On the other hand, when total deformation energy is δW_c , the tube end is to separate from the die and then curl. If tube nosing is successful,

$$\delta \mathrm{W}_c > \delta W_n \tag{12}$$

Based on the relationship of

$$\delta \mathrm{W}_c = \delta W_\mathrm{n} \tag{13}$$

from (9), (11), (13), the bending radius is

$$\rho=(2+n)^{\frac{-1}{2(1+n)}}\sqrt{\frac{rt}{2}}\left\{\cos\alpha-\cos\beta-\sin\alpha[\beta-\alpha-n\sin(\beta-\alpha)]-\frac{n}{2}(\sin^2\beta-\sin^2\alpha)\right\}^{\frac{-1}{2(1+n)}} \tag{14}$$

if $\rho = \text{costant}$, the following relation can be obtained

$$\begin{aligned}&2\cos\alpha-\cos\beta-\sin\alpha[\beta-\alpha-n\sin(\beta-\alpha)]\\&-\frac{n}{2}(\sin^2\beta)+n\sin^2\alpha=1\end{aligned} \tag{15}$$

The angle β which makes the bending radius a minimum can be obtained by extreme value,

$$\beta=\sin^{-1}\left(\frac{\sin\alpha}{1+n\sin^2\alpha}\right) \tag{16}$$

With (15) and (16), the following equation can be get

$$\begin{aligned}&2\cos\alpha+n\sin^2\alpha+\frac{\sqrt{1+(2n-1)\sin^2\alpha+n^2\sin^4\alpha}}{1+n\sin^2\alpha}-\sin\alpha\left(\pi-\sin^{-1}\left(\frac{\sin\alpha}{1+n\sin^2\alpha}\right)\right)\\&+\alpha\sin\alpha+n\sin^2\alpha\left(\frac{\cos\alpha-\sqrt{1+(2n-1)\sin^2\alpha+n^2\sin^4\alpha}}{1+n\sin^2\alpha}\right)-\frac{n}{2}\left(\frac{\sin\alpha}{1+n\sin^2\alpha}\right)^2=1\end{aligned} \tag{17}$$

It provide the relationship of the critical semi-cone angle and the material performance.

4. Discussion

Figure 3 provides a curve of material hardening exponent n and critical semi-cone angle α from Eq. (17) when other forming parameters are given. It can be seen that with increase of material hardening exponent n, the critical semi-cone angle for nosing increases slowly, i.e. the larger the n, the bigger the critical semi-cone angle, but variation range is small, about 54° to 60°. Only semi-cone angle is less than the critical angle, the tube nosing can proceed.

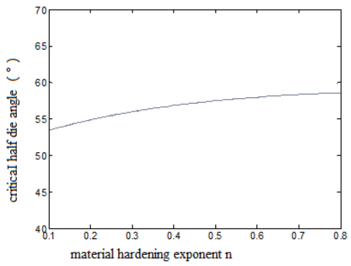


Figure 3. The effect of material hardening exponent on the critical half die angle

5. Simulation

In addition to the analytical study above, the change in forming mode is studied by the FE software Abaqus, Because the experiments in nosing thin-walled tubes were performed under a quasi-static constant displacement rate of the upper-table of the press, no inertial effects on forming mechanisms are likely to occur and therefore no dynamic effects in deformation mechanics are needed to be taken into account. These operating conditions allowed numerical modelling of the process to be performed with the finite element flow formulation and enabled the authors to utilize the abaqus/explicit that has been extensively validated (Arvind et al., 2017).

The material is aluminum tube, the tube diameter is 25.4mm, thickness is 0.4mm. The material properties as follows

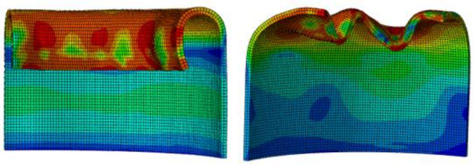
Table 1: The material properties

Materials	0.2% Yield strength (MPa)	n	Stress–plastic relationship
3. Aluminum tube	180	0.14	$\bar{\sigma}=530\bar{\varepsilon}^{0.14}$
4. Aluminum tube	132	0.226	$\bar{\sigma}=369.86\bar{\varepsilon}^{0.226}$

For tube nosing is axial symmetry forming, only quarter model is calculated to improve the computation speed. Figure 4 is the FEM model.

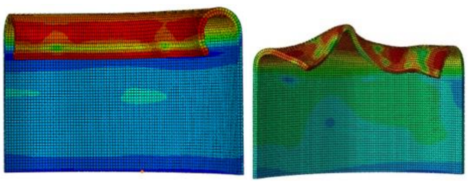
Figure 4: Finite element model

Fig.5–7 show that for the tube blank with material hardening exponent n equating to 0.12, 0.226, 0.354, the critical semi-cone angles for nosing are approximately 55◦, 56◦, 58◦ respectively. These results by FEM have a good agreement with those of the analytical study (as shown in Figure 3). For thin-tube conical nosing, when the necking coefficient is bigger (semi-cone angle is larger), multi-stage process should be adopt to avoid wrinkle as in Figs.5-7 (Chen et al., 2011)



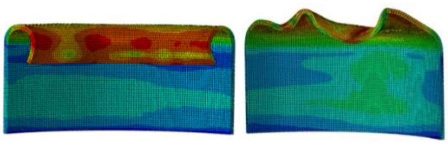
(a) 56°(curing) (b) 55°(nosing)

Figure 5: The deformation of aluminum when n=0.14



(a) 57°(curing) (b)56°(nosing)

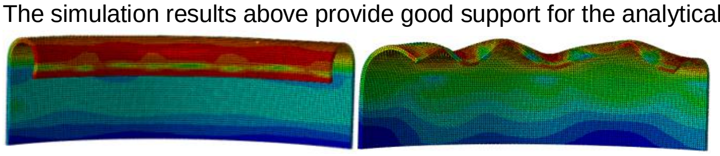
Figure 6: The deformation of aluminum when n=0.226



(a) 59°(curing) (b)58°(nosing)

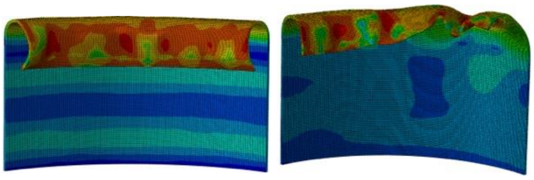
Figure 7: The deformation of aluminium when n=0.354

In addition, keeping tube material hardening exponent nonchanged (n= 0.226) the effect of material geometrical parameters on critical semi-cone angle is discussed (as shown in Fig.8-9), the results show that for tube with different outside diameter and thickness all can nosing when the semi-cone angle is 56◦. That means that the geometrical parameters of the tube blank have very little effect on critical semi-cone angle. The simulation results above provide good support for the analytical study.



(a) 57°(curing) (b) 56°(nosing)

Figure 8: The deformation of aluminium when n=0.226, d=45mm



(a) 57°(curing) (b) 56°(nosing)

Figure 9: The deformation of aluminium when n=0.226, t =0.2mm

6. Conclusions

Based on a mechanical model, the mechanism of tube nosing are investigated by FEM combined with analytical analysis. Calculation are as follows:

1. In tube conical nosing, the bigger the material hardening exponent, the bigger the semi-cane angle, but the variation range is small (54°-60°).
2. When semi-cone angle is less than the critical angle, nosing forming can successful, generally multi-stage forming should adopt to avoid wrinkle. when semi-cone angle is greater than the critical angle, deformation pattern will be converted to curling.
3. The geometric parameters of tube blank almost does not affect critical semi-cone angle. When the nosing coefficient is small (semi-cone angle is larger), the part should adopt mult-stage forming process.

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