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Forming characteristics of tube free-bending with small bending radii based on a new spherical connection

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A R T I C L E I N F O

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A B S T R A C T

In tube free-bending, the connection of the bending die to the guide has a great influence on the stability of mechanical movement and the forming limit of the bent tube. The general connection of the bending die to the guide cannot realize the continuous stable movement of the bending die. Spherical connection of the bending die to the guide can guarantee a continuous changed tipping of the bending die, but has a limited minimal bending ratio (ratio of bending radius to tube outer diameter) of $R/D_0 \geq 3$ depending on the geometrical constrains. In this paper, a new spherical connection of the bending die to the guide was designed through geometric derivation, which can lead to a greater deflection of the bending die, to realize the bending ratio of down to $R/D_0 = 2.5$. Based on the designed spherical connection, the bending ratio of down to $R/D_0 = 2.43$ and $R/D_0 = 2.78$ of brass tube were realized in the finite element simulation and bending test respectively. And with the analytical model, simulation model and experimental bending results, the forming characteristics of bent tube with small bending radii based on the spherical connection structure were investigated. The main results show that the equivalent stress, displacement of the strain neutral layer (NL) increase with the decrease of bending radius, and the wall thickness thinning in outer bend shows little differences under tight and big bending radii due to the increased axial thrust.

1. Introduction

Tubular members are used as components in manufacturing of parts in numerous industries, because of their lightweight [1], high strength [2], and low consumption [3]. Their application ranges from simple household items [4] to sophisticated aerospace parts [5]. The tubular bending components made by traditional methods, such as stamping [6] and welding [7] cannot fulfill the requirements of high dimension precision and strict work performance. Meanwhile, for the tubular components with continuous varying radii and non-straight-section, the numerical control (NC) rotary draw bending technology has some limitations such as changing the bending die and re-clamping the tube [8–10].

Free-bending, as an advanced bending technique [11], has the great bending potential [12] and can achieve complex bending geometries [13] without changing the die and re-clamping the tube [14]. It is particularly suitable for forming the pre-bending components [15] with variable bending radii and bends in several planes [16]. The principle of free-bending technique [17] is feeding the tube through the stationary guider, as shown in Fig. 1. Meanwhile the bending die is shifting and tipping in order to bend the tube continuously within the bending zone, which is located between the guider and the bending die [18].

Different tool set-ups for bending die and guider lead to different limited minimal bending radii depending on the geometrical constrains of modes. Murata et al. [19] investigated the bending limits under a jig for die inclination control, regarding the smallest relation of R/D_0 for different wall thickness (between $t_0 = 0.5$ mm and $t_0 = 2.0$ mm). The comparison showed the minimal bending ratio of R/D_0 is approximately 2.5 for the tubes with a wall thickness larger than $t_0 = 1.0$ mm

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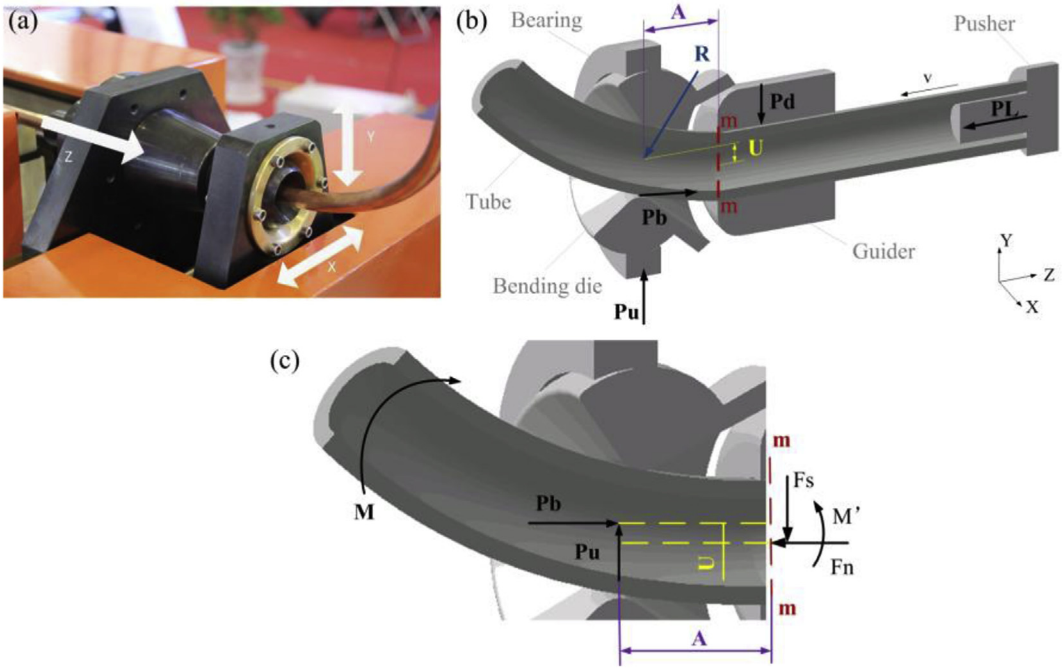

Fig. 1. Three-axis free-bending: (a) forming equipment; (b) technical principle; (c) bending moment calculation.

and for the tubes with a wall thickness of t_0 = 0.75 mm and/or t_0 = 0.5 mm, the minimal bending ratio R/D_0 was approx. 3.5 and 6, respectively. However the tipping of the bending die cannot be continuous changed by the jig. In another free-bending machine, the bent tube of the minimum bending coefficient of 1.7 can be obtained, where there is no connection of the bending die to the guider and the work stability cannot be guaranteed [20]. In 1997 Murata and Kato [21] invented a spherical connection of the bending die to the guider to a continuous changed tipping of the bending die. However, in the technical specification for the NPB-030M which has the spherical connection of the bending die to the guider, the minimal bending radius is only defined with a ratio of R/D_0 = 3.0 [22]. Because the smallest possible bending radius is defined by the positioning of bending die in relation to the guide, where the spherical connection between the guide and bend die is restricted in its deflection.

In this paper, the mechanical principle of the spherical connection of the bending die to the guider was presented through kinematic analysis and its advantages were illustrated compared with other conventional forms. Moreover, a new spherical connection was designed to reduce the minimum bending ratio to R/D_0 = 2.5. Using the designed tool set-up, the bending ratio of down to R/D_0 = 2.43 and R/D_0 = 2.78 of brass tube were realized in the finite element simulation and bending test respectively. Finally, theoretical derivation, finite element simulation and bending tests were also carried out for the investigation of the forming mechanism and characteristics of tube free-bending process with small bending radius based on the designed spherical connection structure.

2. Forming mechanism of tube free-bending

2.1. Mechanical analysis

The forming equipment, technical principle and bending moment of three-axis free-bending are shown in Fig. 1. The relative distance between the central axis of the guider and the central axis of the bending die in the Y direction is called deflection (U) which changes during the forming process. The distance between the center of the bending die and the exit of the guider is called approach (A) which is a set value in the forming process. In the bending process, a tubular blank is penetrated into the bending die with a certain velocity (v) by axial force (PL) and simultaneously, the bending die is moved by the bending force (Pu) applied by spherical bearing perpendicular to the tube axis. Based on the principle of force equilibrium, the tube must be subject to axial resistance (Pb) and the force (Pd) perpendicular to the tube axis from the bending die and the guider, respectively. For the tube on the left of section m-m, there must be the internal torque (M′), transverse force (Fs) and axial force (Fn) of the tube in the m-m section to balance external force and external torque (Fig. 1(c)). Therefore, internal force and internal torque in the section m-m can be calculated by Eq. (1) - Eq. (2). However it only applicable to the case where the bending die is not connected to the guider [23].

$$\text{Axial force}: Fn = Pb = PL\ ;\ \text{Transverse force}: Fs = Pu = Pd \quad (1)$$

$$\text{Bending moment}: M = M' = PL \times U + PU \times A \quad (2)$$

2.2. Analysis of stress and strain

In addition, the present chapter presents an analytical model to calculate the stress distribution in free-bending process considering the axial thrust. To simplify the model, the pertinent assumptions for the analysis are as follows: (1) Friction between the tube and tools is neglected; (2) A plane perpendicular to the tube axis before deformation remains plane and perpendicular to the axis after deformation; (3) Wall thickness of the tube is small in comparison to the length and radius of the tube. Hence deformation due to transverse shear is neglected; (4) One special characteristic of the free-bending is the reduced deformation of the cross section of the bent tube. Hence the circumferential strain (ε_φ) in plane is about equal to 0; (5) The material is incompressible and work hardening is considered. The relationship between stress and strain is as follows:

$$\sigma = \sigma_s + D(\varepsilon - \varepsilon_S) \text{ with } \varepsilon_S = \sigma_s/E \quad (3)$$

Where σ_s is the initial yield stress of the tube material; ε_S is the strain corresponding to initial stress; D is linear hardening coefficient; E is Young's modulus.

Fig. 2 and Fig. 3 show the stress-strain state and deformation geometry parameters of tube in free-bending. The meaning of each symbol