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An analytic model for tube bending springback considering different parameter variations of Ti-alloy tubes

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ABSTRACT

Springback after unloading is an issue that directly reduces the accuracy of bent tubes, especially for Ti-alloy tubes which are of high strength and low Young's modulus. The Young's modulus, E; wall thickness, t; and neutral layer, D_e, of a tube vary during the bending process. These variations may influence the bending deformation of components, thus on springback. Considering these variations, an analytic elastic-plastic tube bending springback model was established in this study based on the static equilibrium condition. When these variations were considered individually or combined, the resulting springback angles were all larger and closer to the experimental results than the results when variations were not considered for a $D6\,\mathrm{mm} \times t0.6\,\mathrm{mm}$ Ti-3Al-2.5V Ti-alloy tube. The t variation contribution is the largest and decreases the prediction error by 41.2%–45.3%. D_e variation ranks second and decreases the error by 21.2%-25.3%. E variation is the least significant, decreasing the error by only 2.4%. Furthermore, the influence of the stable Young's modulus E_a on the springback is larger than the initial Young's modulus E_0. Therefore, for the bending springback of tubes with a small difference between E_0 and E_a and under a normal bending radius, E variation effects can be neglected. While for tubes with large differences between E_0 and E_a, and high springback prediction requirements, the E variation should be replaced by E_a. The influences of the initial tube sizes, material properties and bent tube sizes of the Ti-3Al-2.5V tube on springback were obtained using the newly developed model.

1. Introduction

When metal tubes undergo bending to form bent tubes, elastic-plastic deformation occurs. The elastic deformation will recover after unloading, i.e., springback will occur. The springback directly influences the precise form of the bent tube. When the springback value exceeds the permissible error, the geometric shape cannot satisfy the requirement, which significantly reduces the performance of the bent tube. This phenomenon is especially remarkable for tubes with high strength and low Young's modulus, such as Ti-alloy tubes. Thus, tube springback analyses after bending deformation have gained significant interest.

With the development of numerical simulation technology, the finite element method (FEM) has become one of most common methods used to analyze stainless steel, Al-alloy and Ti-alloy tube springback after bending. Via FE simulation, Murata et al. (2008) investigated the springback of Al-alloy and stainless steel tubes in the draw bending and press bending. They found that the hardening exponent had little effect on the springback. Paulsen and Welo (1996) conducted three-dimensional (3D) elastic-plastic finite element analyses (FEA) focused on the bending of Al-alloy profiles. They found that springback was influenced by the strain-hardening characteristic and the amount of axial loading, including that decreased strain hardening and increased tension reduced springback. Liao et al. (2014) performed FEA on twist springback prediction of asymmetric tube in rotary draw bending with different constitutive models. They found that the springback angle is sensitive to the hardening model. Xue et al. (2015) developed an FE model of mandrel rotary draw bending for accurate twist springback prediction of an asymmetric aluminium alloy tube. They found that the interfacial frictions have significant effects on twist springback of the tube. Through FE simulations, Zhan et al. (2014) found that Young's modulus variations had no effect on the variations trends of springback angles or the springback radius with the bending angle of Ti-alloy tubes. However, it did cause the values increase. Gu et al. (2008) established an FE model for the

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numerical controlled (NC) bending of thin-walled Al-alloy tubes and obtained the effects of geometry, materials and process parameters on springback. The results showed that the springback angle increases with the relative bending radius and Poisson ratio. Jiang et al. (2010b) developed an FE model for simulating the entire bending and springback process of a Ti-3Al-2.5V tube. Using the model, Jiang et al. (2010a) revealed the coupling effects of the bending angle and material properties on the springback angle of the Ti-3Al-2.5V tube. They found that, regardless of the bending angle, the Young's modulus, strength coefficient and hardening exponent have significant effect on the springback angle. Huang et al. (2015) embedded the variation law of the contractile strain ratio (CSR) with deformation into the FE simulation for the NC bending of Ti-3Al-2.5V tubes. Through considering this CSR variation, Zhan et al. (2015) found that the prediction accuracy of the Ti-3Al-2.5V tube springback angles can be improved.

Considering that theoretical analysis can quickly solve for the springback and reflect the associated mechanism, law and major influence factors, it is important to analyze tube bending springback using analytic methods. In recent years, multiple analytic models have been developed to predict tube bending springback based on the classical springback theory, in which the springback bending moment and the bending moment are assumed equal in quantity and opposite in direction. Based on the classical springback theory, Al-Qureshi and Russo (2002) derived an analytic formula for predicting springback and residual stress distributions of thin-walled aluminum tubes. However, in their study, the material was presumed to be elastic-perfectly plastic, which does not reflect the response of metal tubes during bending deformation. Thus, to improve tube bending springback prediction accuracy, analytic models have been derived by assuming the material to be elastic-plastic hardening material. Megharbel et al. (2008) modified Al-Qureshi's model by assuming the material to be elastic-exponent hardening plastic material. Based on the classic springback theory, Li et al. (2012) deduced a springback equation by assuming the material to be an exponent hardening plastic material and considered neutral layer variation (or offset) effects. However, the elastic deformation was neglected in their analysis. In addition, making use of the triangle similarity relation of the tangential deformation during tube bending loading and unloading, E et al. (2009b) deduced a calculation formula for a 1Cr18Ni9Ti tube bending springback. They found that the springback angle decreases with the plastic modulus and relative wall thickness, but increases with the hardening exponent and Young's modulus.

As commonly known, the wall thickness and neutral layer vary with tube bending deformation. Using an FEA on NC bending of two Ti-3Al-2.5V tubes with outside diameters of 8 mm and 14 mm, respectively, under various normal bending radii, Jiang et al. (2011) discovered that the wall thicknesses along the crest lines of two bent tubes both resemble plateaus when the bending angle exceeds the critical angle. The maximum thinning reached 7% and 12.5% for the 8 mm and 14 mm tubes, respectively, and the maximum thickening reached 11% and 16% for both tubes, respectively. Through theoretical analyses, Tang (2000) considered that the neutral layer should move toward the bending center to balance the moment of the internal force because the outer wall is thinner than the inner wall during pure tube bending. E et al. (2009a) found that the amount of neutral layer movement is inversely proportional to the relative bending radius based on theoretical analyses. Stachowicz (2000) found that the neutral layer of a copper elbow shifts outwards the bending center when the stress pattern is asymmetric by the theoretical analysis. Through 3D numerical analysis for a torque superposed spatial bending (TSSB) of high strength steel square profiles, Hudovernik et al. (2013) also found that there exists stress neutral layer shifts outwards the bending center. In recent years, the Young's modulus of tubes has been observed to vary with the deformation level. Through repeated loading-unloading experiments, Zhan et al. (2014) found that the Young's modulus of Ti-3Al-2.5V tubes rapidly decreased in the initial stage, then slowly decreased until stabilizing in the final stage. The variation can be approximately expressed as an exponential model. These Young's modulus, wall thickness and neutral layer variations influence bending deformation and springback of components. However, most existing analytic tube bending springback models did not consider these variations. Furthermore, most existing analytic tube bending springback models are based on the classical springback theory, where the springback bending moment and the bending moment are assumed equal in quantity and opposite in direction. However, for a bent tube undergoing an elastic-plastic deformation, after unloading, residual deformation, residual stress and residual bending moment still exist. This means that the springback bending moment should not equal the bending moment, which no longer meets the unloading principle of the classical springback theory. Therefore, an analytic springback model was derived in this study based on the static equilibrium condition and the deformation compatibility of deformation and aimed at improving the accuracy of tube bending springback predictions. In the model, the material was assumed to be an elastic-plastic hardening material and Young's modulus, wall thickness and neutral layer variations were considered. This model was evaluated by investigating the contributions of Young's modulus, wall thickness and neutral layer variations to the springback of a Ti-3Al-2.5V Ti-alloy tube. Then, the model was compared to existing springback analytic models and experimental results. Finally, the model was used to determine the influencing laws of various springback factors on the Ti-alloy tube.

2. Theoretical basis

2.1. Fundamental assumptions

Deformation processes are extremely complicated during tube bending and springback. The following assumptions are given to develop a springback prediction model for tube bending:

(1) The tube material is continuous and exhibits elastic-plastic and exponent-hardening behaviors, which satisfy the stress-strain relationship showing in Eq. (1).

$$\sigma = \begin{cases} E\varepsilon & \text{when} \quad \sigma \le \sigma_s \quad \text{or} \quad \varepsilon \le \varepsilon_s \\ K(\varepsilon + b)^n, & \text{when} \quad \sigma > \sigma_s \quad \text{or} \quad \varepsilon > \varepsilon_s \end{cases} \tag{1}$$

where E is Young's modulus, K is strength coefficient, n is hardening exponent, b is a constant, σ is the flow stress, ε is strain, σ_s is the yielding stress, ε_s is the yielding strain and at yielding point $E\varepsilon_s = K(\varepsilon_s + b)^n$.

The Young's modulus variation with deformation is assumed to be a function of equivalent strain during elastic-plastic tube bending, as shown in Eq. (2).

$$E = \begin{cases} E_0, \sigma \le \sigma_s \\ E_\mu, \sigma > \sigma_s \end{cases} \tag{2}$$

where E_0 is initial Young's modulus and E_μ is the Young's modulus relative to plastic deformation in the current moment, which can be expressed as Eq. (3) (Chatti and Hermi, 2011 and Zhan et al., 2014).

$$E_\mu = E_0 - (E_0 - E_a)(1 - e^{\xi\bar{\varepsilon}}) \tag{3}$$

where ξ is a mechanical parameter that determines the rate of decrease of E_μ, $\bar{\varepsilon}$ is the equivalent strain and E_a is the stable Young's modulus for an infinitely large equivalent strain in Eq. (3).