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Modelling of mandrel rotary draw bending for accurate twist springback prediction of an asymmetric thin-walled tube

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ABSTRACT

Of particular interest and complexity are twist springback of an asymmetric thin-walled tube in mandrel rotary draw bending (MRDB), which is a complex non-linear physical process with coupling multi-factor interactive effects. The aim of this paper is to explore the source of twist springback and develop a more effective numerical model. First, this paper analyses the torsion moment and twist angle relationship subjected to non-homogeneous loading. Second, non-quadratic anisotropic yield criterion (Yld2000-2d) integrated with mixed isotropic and kinematic hardening can be used to describe the material properties including anisotropy and Bauschinger effect. The corresponding mechanical tests are performed through uniaxial tension tests and monotonic and forward–reverse shear tests. Third, to improve the accuracy of the finite element model, the surface-based coupling HINGE constraint for flexible mandrel is developed and compared with the previous models. The frictions on various die–tube interfaces are identified by means of numerical inverse model. The validity of the FE model is assessed by comparing the predicted twist springback with the experimental one. The results show that the developed FE model with surface-based HINGE constraint has higher precision of twist springback prediction. The interfacial frictions have significant effects on twist springback of asymmetric thin-walled tube.

1. Introduction

Thin-walled tubes (TWT) have the advantages of light weight and a high bending rigidity, which make them suitable both for general structures with curved parts and for automotive components. With the improvement of the digital technology, CNC is applied for mandrel rotary draw bending (MRDB) to improve accuracy and repeatability. This means that the process makes it possible to become automation and mass production. However, the twist springback phenomenon is inevitable due to unbalanced elastic–plastic deformation and residual stress release after the dies are removed. This leads to difficulty at the assembly stage since the inaccurate geometry of product. In practice, the efficient control of the twist springback is still treated by the know-how experience and "try and error" experiments. Meanwhile, the predicted result by analytical method deviates far from the experimental ones since the complicated multifactor forming conditions are difficult to be considered in the formulas (Yang et al., 2010). Besides the experimental and analytical methods, the finite element method (FEM) has become the primary tool for deep analysis of tube bending deformations. But the precision and the computational efficiency of the springback prediction models are still not high enough, which mainly depend on the modelling techniques. Efficient modelling and control of springback in MRDB are in great demand.

In the past decade, many studies have been conducted on springback in tube bending processes via numerical method, in which the effects of basic forming parameters such as material characteristics and loading boundary conditions are investigated in terms of individual case. Zhan et al. (2006) proposed a numerical–analytical method to predict the springback angle of TWT bending, while the stress/strain states of bent-tube are obtained by the rigid-plastic FE simulation. Zhao et al. (2009) established a three-dimensional elastic–plastic finite element model of circular TWT rotary draw bending process using ABAQUS/Explicit code. They introduced some basic solutions of modelling techniques, e.g., contact boundary condition treatment, material properties definition and meshing technology. To improve the accuracy and the computational efficiency of the FEM, more detailed modelling conditions were considered by Zhu et al. (2012), such as the Bauschinger effect of material, the loading boundary conditions for the clamp die and the pressure die, the reasonable modification of the flexible mandrel constraint and the simplified half-tube model. Their results showed that the influence of material constitutive model on springback prediction is greater than that caused by simplifying FE model

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or using different mass scaling factors. Based on their improved FE model, Li et al. (2012) investigated the springback characterization and behaviours of high-strength Ti–3Al–2.5V tube in cold rotary draw bending and proposed a two level springback compensating methodology. A further improvement on the springback prediction accuracy of FE model considering the strength-differential effect was studied by Liu et al. (2012). In modelling, to reflect the strength-differential effect of the materials, the tube was partitioned into three regions, viz. outside region, transition region and inside region. Li et al. (2014) attempted to develop a comprehensive map of tube bending limits considering a wide range of tube sizes and material types.

The above studies provide useful knowledge for springback of TWT in bending process. However, these researches have paid less attention on material anisotropy and tended to focus on tube profiles with symmetric cross sections such as circular, square and rectangular, rather than on asymmetric or hybrid cross sections. Indeed, automotive parts such as frames and flex-rails are usually designed to be asymmetric tubes or sheets. In the form of these parts, twist springback can be encountered to some extent. Recently, there has been growing interest in twist springback in tube or sheet metal forming processes. Gangwar et al. (2011) present a theoretical analysis for determining springback of arbitrary shaped thin tubular section of materials having arbitrary stress–strain relationship under torsion loading. Being different to twist springback in the occurrence of residual stress released, the extrinsic parameter of torsion loading is provided as known condition. In sheet metal stamping, Takamura et al. (2011) show that twist torque around the longitudinal axis using the stress distributions can be obtained by FE analysis. Through the investigation of twist torque and its transition during the drawing and die removal processes, they find that the negative torque generated by side wall opening occurring in the die removal process is the dominant factor in positive twist. Pham et al. (2014) investigate the influence of the blank alignment relative to the tools on twisting magnitude. Their results show that the change in the section of the sample, specifically the misalignment of the ultra thin metallic sheet sample with respect to the tools is the main factor that gives rise to twisting. For some samples, aligned or not, twisting is caused by sliding (asymmetric flow of side walls) of one of the two ends of the sample during the draw bending process. The above efforts provide a trigger for the source of twist springback occurring in MRDB. As a major factor affecting material flow, the friction on various die–tube interfaces may pay considerable effect on twist springback of MRDB.

The present work aims to explore the plasticity mechanism and develop a more effective numerical model for twist springback. A typical asymmetric aluminium alloy thin-walled tube which has evident twist springback phenomenon in MRDB is addressed as the study subject. First, a novel evaluation of twist springback derived from section property and plasticity deformation theory is proposed and analyzed. Second, a further improved FE model of complex twist springback has been developed. Some key modelling techniques related to constitutive model, boundary constraint of flexible mandrel and interfacial friction are developed to improve the prediction accuracy and the computational efficiency. Finally, the mechanism and the influence of interfacial friction on twist springback are deeply analyzed and discussed.

2. Deformation analysis of thin-walled tube bending

2.1. Description of twist springback

The whole process of thin-walled tube mandrel-rotary draw bending (MRDB) includes three processes: bending tube, retracting mandrel and springback. The tools setup for MRDB is illustrated in Fig. 1. In bending process, the extruded tube rotates along the grooves of bend die and clamp die to the desired bending degree and the bending radius, while a sliding pressure die forces tube to conform to the die radius. The wiper die, the vulnerable part with very thin feather edge, is often placed behind bend die to prevent wrinkling of the part. Due to acute contact condition, the edge of wiper die may be worn heavily. To avoid abrasion and extend the life of wiper die, the rake angle die is set by rotating the die along the bend die cavity away from the line of tangency. The axis force from boost block can help to minimize the bend tube's wall thickness variance and deformation. Booster force improves material flow in the forming zone and leads to less thinning of the wall on the outside of the bend and less cross section distortion. So the process needs precise coordination of various dies and strictly controlling of forming parameters. Among the above tooling, mandrel with flexible cores is positioned inside the tube to provide the rigid support.

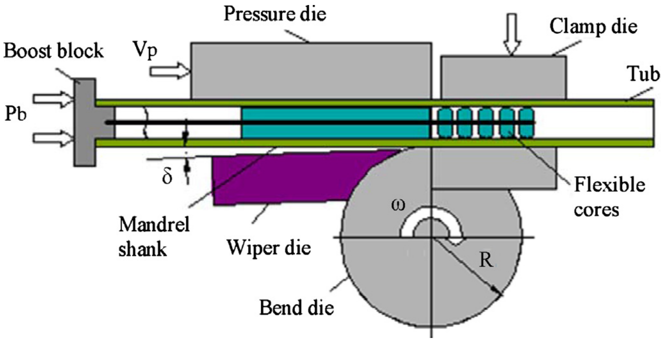

Fig. 1. Tools setup and illustration of mandrel-rotary draw bending process.

In this paper, twist springback of the asymmetric thin-walled tube (see Fig. 2) includes two main codes of deformation behaviours. In the longitudinal direction, the amount of springback can be expressed as the value of springback angle

$$\Delta\theta = \theta - \theta' \tag{1}$$

where θ and θ' are the bending angles before and after springback, respectively, as shown in Fig. 2a.

In the circumferential direction (cross sections), the amount of twist can be decomposed into two parts: the rotary angle of neutral axis of closed section (rectangular tube) and the warping angle of open section (fin). φ_c and φ represent twist of the closed section and the open section, respectively, as shown in Fig. 2b. The dark line (Deform) is the section shape of the extruded tube after removal from tooling and the dotted light line (Undeform) is the design intent.

In the next section, the torsion moment and twist angle relationship are analyzed, in which figures out that the twist deformation of open section part should be much larger than that of closed rectangular part under the same process configurations. Therefore, twist angle of closed rectangular part can be ignored. In this work, the twist springback angle of open section part can be given by

$$\varphi = \arctan\frac{\Delta(U_2)}{L_f} \tag{2}$$

where $\Delta(U_2)$ is the maximum displacement of open section part in the vertical direction (U_2), and L_f is the length of fin, as shown in Fig. 3.

2.2. Torsion moment–twist angle relationship

To analyze the twist deformation of thin-walled tubes, the concept of shear flow, q, needs to be understood. When a moment (or