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On twist springback prediction of asymmetric tube in rotary draw bending with different constitutive models

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ABSTRACT

Springback and twist deformation of asymmetric AA6060-T4 aluminum tube in rotary draw bending process are studied experimentally and numerically. Of particular interest is the influence of constitutive model on the twist springback prediction results. The whole forming and springback process of this aluminum tube is performed using the finite element code ABAQUS. Several material models are analyzed, all considering isotropic and kinematic hardening combined with one of the following plasticity criterion: von Mises, Hill'48 and Yld2000-2d. The material parameters of these constitutive models are determined from the tensile and forward-reversal shear tests of the tube. The material tests show that transient Bauschinger effect and curve crossing phenomena are observed for this tube subjected to reversal loading. The capability of two hardening model, naming isotropic and combined isotropic/ kinematic hardening model, to capture these behaviors are discussed. Comparison between the wist springback prediction results by different constitutive models shows that the springback angle is more sensitive to the hardening model while the twist deformation is more sensitive to the yield criterion. The stress distributions of the tube during different forming stages are analyzed and some explanations concerning their influence on springback mechanism are given. A detailed study on the tangent and hoop stress distributions of the tube also explains some source of the twist deformation for this asymmetric tube.

1. Introduction

In the last decade, the number of tubular aluminum frame components for automotive application has increased significantly due to its weight reduction and corresponding improvements in fuel consumption [1,2]. The aluminum tube components are best produced by extrusion, then cold formed to the required shape and finally are assembled to form a space frame. Among the types of tube forming processes, rotary draw bending is a very common, useful and flexible bending method due to its low production cost, variety of tooling options and process automation [3]. However, a big technical hurdle in bending aluminum tube is the serious springback after release of the forming loads since its Young's modulus is much smaller than for steel [4]. Moreover, in the case of tubes with open or asymmetric section, twist deformation often occurs during the bending process and it significantly affects the dimension accuracy of the product. For the past decades, defects in tube bending such as wrinkling, flattening, cross-section distortion, had been studied thoroughly. However, scientific works about twist and its numerical prediction are rare. Since twist and springback seem to be strongly coupled, it is of importance to study them simultaneously [5].

Springback prediction based on the finite element method (FEM) is a vital tool for developing various methods to overcome this drawback. To ensure accurate springback prediction, appropriate plastic yield criterion and hardening model that properly describe material behavior is very critical [6,7]. Over the years, a lot of yield functions have been introduced to describe the initial plastic anisotropy of metals. A detail review of the anisotropic yield criterion development can be found in [8–10]. The most commonly used yield criterion is still Hill's anisotropic quadratic yield function (Hill'48). The relative simplicity of this model makes it attractive to use, and is the reason for its numerical efficiency. But, the Hill'48 criterion is often criticized for its application to metals with low *r*-values [4]. Another widely used yield function is Yld2000-2d [11], which is based on two linear stress transformations. Several works have showed that it has a satisfactory correlation with the experimental data for aluminum [11–14].

Besides the yield loci, FE springback prediction is also strongly dependent on work-hardening model, especially on how the

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model describes the material's mechanical behavior under a strain-path change, such as the stress reversal occurring during the bending to unbending transition process [6,15,16]. Over the years, the Bauschinger effect, i.e. a drop of flow stress after reloading in the reverse direction, has received much attention since it present a high impact on the amplitude of springback [17]. Recently, other phenomena occurred in non-proportional loading such as cross-hardening [18], permanent softening and curve-crossing [19,20], are also attracting more and more attention in the work-hardening modeling. All these phenomena show that describing the evolution of the flow stress during the forming process simply using isotropic work-hardening model does not provide an accurate simulation of the real forming process.

In the recent years, several efforts have been conducted to improve springback prediction of thin-walled tube in rotary draw bending process. Liu et al. [3] has improved the springback prediction of a circular thick-walled TA18 tube by considering the strength-differential effect of the material. Zhu et al. [21] showed that springback prediction for rectangular H96 tube in rotary draw bending process with the Yoshida–Uemori hardening model achieved better results than that with the isotropic and mixed kinematic-isotropic hardening models, because the former model captures the Bauschinger effect and permanent softening behaviors of the material better than the others. Zhu et al. [22] indicated that the influence of material constitutive model on the accuracy of springback prediction after rotary draw bending was greater than that caused by simplifying FE model or using different mass scaling factors. All their studies show the relevance of constitutive model on the springback prediction of tubes in rotary draw bending. However, very few works concerning twist springback, in which twist deformation accompanies with bending angle changes during release of the loads, have been conducted.

Indeed, automotive components such as frames or rails are usually designed to be asymmetric tubes or sheets. In the form of these elongated components, occurrence of twist springback can no't be avoided. Recently, there has been growing interest in twist springback in tube or sheet forming processes. Gangwar et al. [23] present a theoretical analysis for determining springback of arbitrary shaped thin tubular section of materials having arbitrary stress–strain relationship under torsion loading, in which the springback angle and residual angle of twist can directly be calculated from the shear stress–strain curve. Takamura et al. [24] explored the mechanisms of twist occurred in a hat curved channel products by studying the twist torque and its transition during the drawing and die removal processes. They found 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. [5] investigate the influence of the blank alignment relative to the tools on twisting magnitude. Their results show that misalignment of the ultra thin metallic sheet sample with respect to the tools, and asymmetric flow of side walls are the main factors that gives rise to twisting. More contributions on twisting of rails, i.e. flexible-rail [25], twist rail [26] and S-rails [27,28], can be found in their corresponding works. All the above efforts provide a trigger for the source of twist springback occurring in rotary draw bending.

In this paper, the twist springback of a typical asymmetric aluminum tube in rotary draw bending has been studied experimentally and numerically. The influence of constitutive models in twist springback predictions is the main focus. In Section 2, twist springback evaluation of this tube in thin-walled rotary draw bending process is presented. In Sections 3 and 4, detail of different constitutive models and material modeling for this aluminum tube are addressed. And finally in Section 5 and Section 6, the finite element modeling of this rotary draw bending process and the predicted results are discussed.

2. Twist springback evaluation in thin-walled tube bending

The whole process of thin-walled tube rotary draw bending (RDB) includes three processes: bending tube, retracting mandrel and springback. The tool setup for RDB is illustrated in Fig. 1(a). In bending process, pulled by bend die and clamp die, the extruded tube rotates along the grooves of bend die to the desired bending degree and the bending radius. Meanwhile, the pressure die is to apply enough pressure force and bending moment to the tube and push it against the wiper die tightly. The wiper die, the vulnerable part with very thin feather edge, is often placed behind bend die to prevent the tube from wrinkling. The axis force from booster can help to minimize the bend tube's wall thickness variance and deformation. Among the above tooling, mandrel with flexible cores is positioned inside the tube to provide the rigid support and reduce the cross-section distorting. Fig. 1(b) shows detail of the cross-section and the dies of the studied tube.

The twist springback of this asymmetric thin-walled tube includes two main forms of deformation behaviors. In the longitudinal direction, the value of springback can be expressed as the change of bending angle

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

where α and α' are the bending angles before and after unloading process, respectively, as shown in Fig. 2(a).

In the cross-section, the value of twist can be decomposed into two parts: the rotary angle of central axis of closed section (rectangular tube) ϕ_c and the warping angle of open section (flange) ϕ, which represent twist of the closed section part and open section part, respectively, as shown in Fig. 2(b).

According to the mechanics of torsion moment and twist angle, it can be figure out that the twist deformation of open section part is much larger than that of closed rectangular part under the same load condition. Therefore, twist angle of closed rectangular part can be ignored since its value is small enough. More detail about the theory of this deduction is addressed elsewhere. For

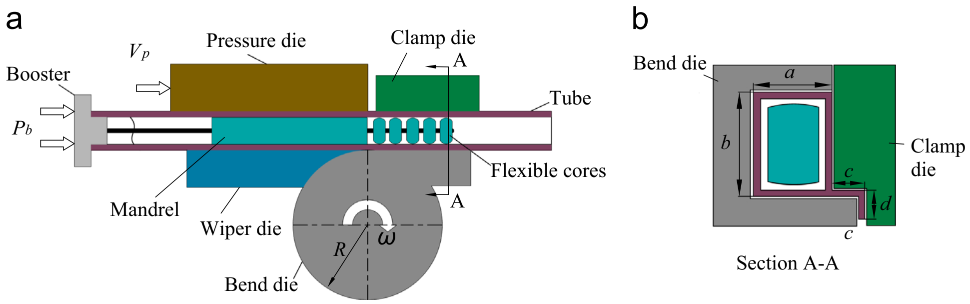

Fig. 1. Illustration of tools setup for mandrel-rotary draw bending process.