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A theoretical study of the expansion metal tubes

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ABSTRACT

As an important type of energy absorption devices, the expansion of metal tubes over a mandrel conical die are investigated by proposing a theoretical model, in which the deformation mechanism enlightened by finite element simulation is adopted. Different to the previous theoretical analysis that base on the momentum equations, the present model starts from the energy conservation point of view. That is, in the steady stage deformation of an expansion tube, the external work done by the compressional force should be dissipated by expansion in circumferential direction, bending in meridional direction, and friction.

The theoretical model provides the predictions of steady compressional force and the tube radius after expansion, for rigid, perfectly plastic (R-PP) material, with or without strain hardening effect. Compared with the existing experimental data, and also the corresponding finite element simulations, the steady compressional force predicted by current theoretical analysis are both quite accurate.

1. Introduction

Tubes under axial compression are widely used in the design of energy absorbers. The deformation mechanisms of tubes under axial compression could be progress buckling [1–3], bending [4], inversion [5,6], expansion or even splitting [7,8]. Among these deformation mechanisms, the expansion of the tube has long stroke and stable reaction force, which are good properties for energy absorbers [9–11].

As shown in Fig. 1a, a circular tube is compressed over a rigid conical mandrel die with increasing radius than that of the original tube. During the deformation process, the circular tube will be expanded into a coaxial tube with a larger final radius, and the work done by the compressional force should be dissipated by plastic deformation. The advantages of the expansion tubes were concluded by some researchers. Besides the long stroke and stable reaction force, it is less sensitive to the impact load. For example, under inclined compressional load whose angle between the tube axial direction is less than 15°, the expansion tubes still work well [12]. Furthermore, the plastic strain caused by tube expansion is lower than those of the inversion tubes. Inversion of tubes is only possible when the material is ductile without significant strain hardening, and the overall dimensions of the die radius must be within a compatible range with suitable material properties, in order to achieve the desirable performance [11]. Hence, the lower plastic strain will enable the application of expansion tubes for less ductile material.

In the published researches about expansion tubes, some are mainly concentrated on the flaring process in metal forming, i.e., expanding the tube using a die to obtain a desirable shape. For example, Lu et al. [13] investigated the kinetic process of the flaring, and gave an relationship among the stroke of the die, the geometrical parameters and the deformation at the tube end. Based on the equilibrium at the contact interface, Fischer et al. [14] proposed an analytical model to predict the contact force as a function of the displacement of die. In this model, the variation of the thickness at the expanding zone was assumed to be distributed linearly, and would be decided by the balance between the contact pressure power and the plastic dissipation power. To obtain a solution of this model, the effects of strain hardening and friction were neglected. Seibi et al. [15] proposed a theoretical model to study the steady stage of the expansion. The friction and thickness variation were considered, while the strain hardening was neglected. Additionally, the contact pressure was also assumed to be uniformly distributed at the interface. Then, Karrech et al. [16] improved Seibi's model by relaxing the assumption of uniform contact pressure and considering the strain hardening effect. This model provides quite accurate predictions of the contact force and the dissipated energy, for tubes with thin wall thickness, i.e. the ratio of radius to thickness is larger than 20.

Besides the above mentioned theoretical analyses, numerical and experimental studies were also presented for the expansion tubes. Varying the geometrical parameters and friction, Almeida

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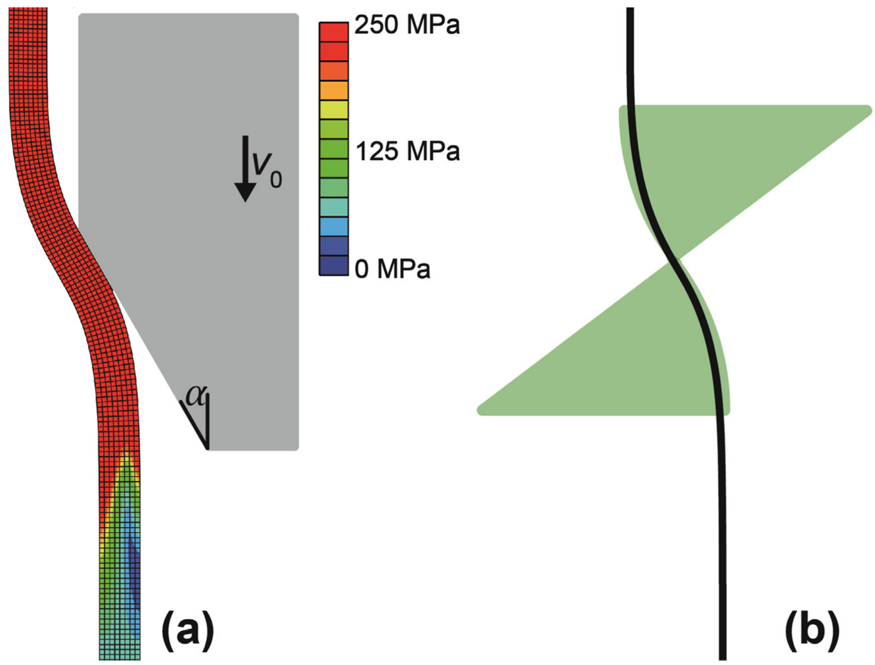

1. (a) The contour of Mises stress given by FEM for r_0=72 mm, $\alpha = \pi/6$, t = 8mm and Y = 250 MPa; (b) The midline along thickness direction of (a), and two arcs to fit the deformation section.

et al. [17] studied both the expansion tubes and the reduction tubes. Ductile fracture, local buckling and wrinkling were observed in the results; and friction was found to be a key role of whether the instability phenomena would happen. Daxner et al. [18] studied the instable limit of flaring process using dies with large radiuses. By simulations and experiments performed, it was revealed that the elastic-plastic buckling was the main instability mode for long tubes, while periodically necking and ductile fracture for the short tubes.

Shakeri et al. [9] first introduced the expansion of the tube as an impact energy absorber in 2007. They used a rigid solid cylinder as the die and pressfitted it into a deformable tube. As the die was compressed in, the transition section of the tube was observed as a part of the conical shell. Based on this deformation mode, the contact force and the conical angle was predicted with idealized rigid perfectly plastic material and frictionless interaction property.

Then, Yang et al. studied the expansion with a conical mandrel die with experiments and simulations [11]. The contact force was found to rise with oscillation and reach a steady state for long stroke. Depending on geometrical parameters, the expansion was classified into three modes by the contacting situation. They also discussed the specific energy absorption capacity, which was found to be higher for larger conical angle.

Yan et al. [10] proposed a theoretical model to predict the contact force adopting the hardening of material and friction. The shear deformation was considered and the corresponding increment of the contact force was adopted. The conical angle and the friction were found to be major factors that influenced the energy absorption. And a gap between the rigid die and the expanded tube was explained as a results of the inertia.

The expansion of the tube was also applied in petroleum as Solid Expandable Tubular (SET) technology [19]. SET has been widely used to rehabilitate the oil well for its lower cost. Al-Abri et al. [20] developed a theoretical model for thick-wall expansion with large plastic deformation, and discussed the influences of geometrical parameters and friction on the expansion power.

The studies mentioned above provided comprehensive understanding of the expansion tubes. Among theoretical models, the deformation mode was always assumed to consist of three straight lines in axial profile which were corresponding to the un-deformed section, the expanded section, and the expanding section contacting with the conical die. This deformation mode assumption will yield discontinuity of the slopes at the intersecting points between different sections. All theoretical methods have simplifications and assumptions. For the problem of expanding tube, the assumption of deformation profile adopted will affect the prediction accuracy. As shown in Fig. 2, since the change of the curvature is considered, the current two-arc profile is closer to the real deformation of the tube. Apart from the deformation profile adopted, the materials employed in theoretical models are also varying. In the previous study, Xu's model [10] and Shakeri's model [9] were proposed for the linear strain-hardening material and R-PP material, respectively; and Seibi's model [15] adopted the R-PP assumption to study strain-hardening material. All these models agree well with their own experimental data. However, the data numbers of their own experimental are obviously smaller than that of FE simulations. It is found that for different die angle, or

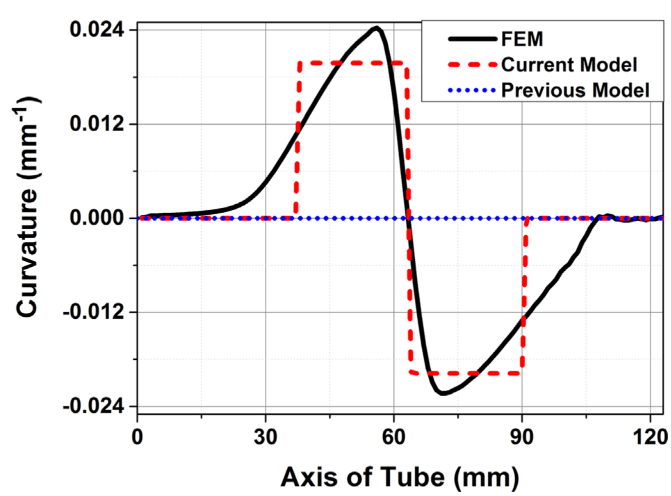

Fig. 2. Curvatures along tube axis (r_0=72 mm, t_0=8mm, $\alpha = \pi/6$).