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Buckling in low pressure tube hydroforming

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ABSTRACT

Tube hydroforming is an innovative forming process in which the tube is pressurized by a fluid medium and formed into a complex shape. There are two types, low and high pressure hydroforming. In the high pressure process, the tube is expanded by an internal pressure to fill the die cavity. In the low pressure approach a constant pressure is maintained inside the tube which is crushed to shape by the action of a punch or an upper die movement. It is known that in low pressure hydroforming the required pressure and die closing force are much lower compared to the high pressure process. Implementation of advanced high strength steel tubes in tube hydroforming is a promising way to lower weight by reducing the material thickness. Using high strength materials increases buckling tendency in low pressure tube hydroforming. In the current study, a method using a plastic energy principle is proposed for estimating the minimum pressure required for the low pressure hydroforming of a buckle free component. The present investigation addresses the side wall of the tube as a vertical column pinned at each end. The proposed model shows that the method can predict the minimum pressure required with sufficient accuracy. The model also reveals that the minimum pressure required depends on the yield stress of the tube material, the tube material thickness and the straight length of the tube section that is in contact with the die. Applying sensitivity analysis it is determined that the required pressure is strongly affected by the yield stress of the tube material.

1. Introduction

Hydroforming is increasingly used in the automotive industry. High Pressure Tube Hydroforming (HPTH) uses an internal fluid pressure of 80–400 MPa [1] to expand the tube into a closed die cavity but due to the excessive fluid pressure and press tonnage that would be required application for the forming of Advanced High Strength Steels (AHSS) is limited. Thus a new technology called low pressure tube hydroforming (LPTH) has gained increasing attention in the automotive industry, for the forming of high strength steels to structural sections as shown in Fig. 1 [2,3]. In this method, a fluid filled tube is crushed to the required shape by the action of a punch or a moving die. In LPTH the internal pressure is less than 10% and the die closing force is less than half [2–5] of that required in HPTH. Thus the process is a promising alternative for the forming of high strength steels.

Analytical and experimental studies on the process parameters and the material behavior during HPTH can be found in the literature. A diffuse necking criterion was proposed by Boumaiza et al. [6,7] for the prediction of neck formation and strain gradients in the HPTH of cylindrical tubes, while the bursting failure diagram for tube hydroforming was developed and analyzed by Kim et al. [8]. This was based on the incremental theory of plasticity and the assumption of anisotropic material behavior. The study observed that the bursting pressure increases with decreasing r_0-value and reduces with the r_{90}-value. Another study adopted the Swift criterion for diffuse plastic instability based on Hill's general theory and applied it for the numerical and analytical prediction of fracture locations and of the bursting pressure for HPTH of a cylindrical tube [9]. In addition previous studies reported that in HPTH the forming results depends on the loading path and material parameters such as the strain hardening exponent and material anisotropy [10,11], while an analytical model for the prediction of bursting was proposed by Song et al. [12] that considered the combined effect of internal pressure and axial feed. The working window with failure modes and loading paths can be seen in [13–17]. Additionally an analytical model for planar tube hydroforming was proposed by Yang and Ngaile [18] and used to predict the final shape of the formed tube as well as the corner filling conditions, wall thinning and the required internal pressure. Some other analytical studies have focused on the effect of interface friction and material properties on the thickness distribution in the tube after forming and the

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Fig. 1. Possible part shapes formable with low pressure tube hydroforming [2].

dissipation of tension forces along the tube/die interface [19]. Based on the deformation theory a model for planar tube hydroforming was created [20–22].

In contrast to the HPTH process which has been investigated in detail by the numerous investigations stated above only a limited amount of literature has focused on the LPTH process. These were limited to the effect of material properties on part quality in the LPTH of triangular [23] and rectangular [24] shapes. Due to the low pressure in the process, the tube in the straight wall region in contact with the die is prone to buckle. Previous studies are limited to identify specific internal pressures for particular forming cases [2,3] but no empirical relation has yet been developed to estimate the pressure required to prevent buckling in LPTH. Thus, in this study, first a simplified analytical model is developed to determine the minimum pressure required to avoid buckling during a simple low pressure tube hydroforming operation. After that the model is validated by numerical analysis and used to perform a sensitivity analysis to investigate the effect of process and material parameters on the minimum pressure required to avoid buckling.

2. Low pressure tube hydroforming

In low pressure tube hydroforming, a round tube is first pressurized using a fluid and then forced into a die by a moving punch (Fig. 2). The outer perimeter of the un-deformed and the formed tube stays approximately the same and Eq. (1) is assumed to apply.

$$P_f = P_i \tag{1}$$

where,

P_f – Perimeter of the formed tube $(2L + 2W + 2\pi r)$

P_i – Perimeter of the initial tube (πD_o)

If the fluid pressure is too low the tubes are prone to buckle which is considered as a geometrical defect (Fig. 3). It is therefore important to understand the factors that contribute to buckling and identify the minimum pressure required to eliminate the defect. To achieve this an analytical model is developed and described in the following section.

3. Analytical model

As mentioned above the tube material buckles due to insufficient pressure and this generally occurs on the tube side wall. To start with an analytical model the deformed wall section of the tube is considered to be a vertical column and its length is measured from the end of the two corner radii as shown in Fig. 4.

During forming, the column is loaded with a vertical force (Fig. 5(a)) in the axial direction leading either to compression or buckling as shown in Fig. 5(b) and (c) respectively.

The initial column has a length "L" and a thickness "t_o". Due to the deflection "δ" the length of the column will either shorten due to compression or as a consequence of buckling. In pure compression, the length of the column will decrease and the thickness increase following the condition of incompressibility. For buckling, the arc length is assumed to remain unchanged.

3.1. Plastic energy (PE) in axial compression

The Plastic Energy (PE) is defined as the work required to compress the column plastically as shown in Fig. 6. The energy due to plastic deformation by axial compression is given in Eq. (2).

$$PE = F \cdot \delta \tag{2}$$

Force is flow stress multiplied with the applied area giving

$$F = \sigma_s \cdot A \tag{3}$$

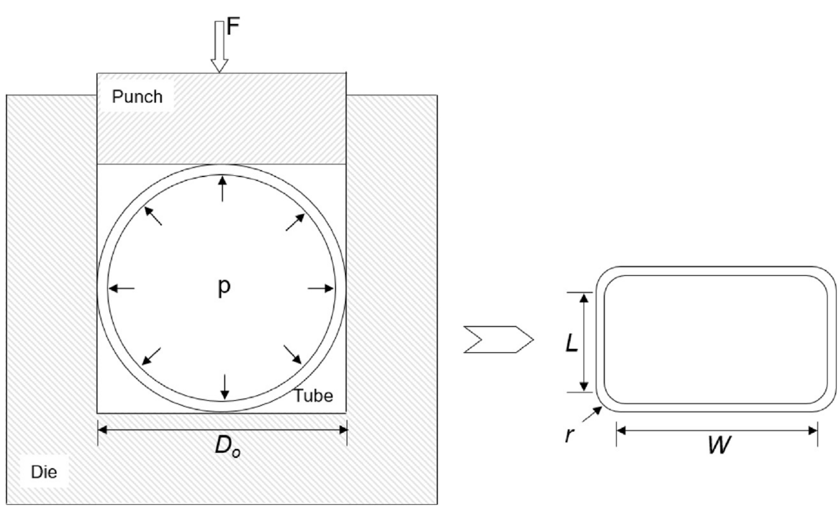

Fig. 2. Low pressure tube hydroforming.