



Technical paper

Part 1: Analytical modeling of symmetric multi-nose tube hydroforming

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ABSTRACT

Part 1 of this series of papers presents an analytical model for a multi-nose tube hydroforming process based on a mechanistic approach. In this process, the tube is surrounded by a number of evenly distributed circular dies. The model was established based on equilibrium conditions, yielding criteria, geometrical relationships, and a volume constancy condition. The system of equations was derived and solved for various process parameters. The model validation was performed using finite element analysis and experiments. The model has the ability to predict process parameters such as stresses, strains, internal pressure, geometry variables, and thinning rate distribution. The model could be applied to regular planar tube hydroforming of polygonal shapes such as square, pentagon, or octagon. Details for establishing governing relationships for polygonal shape hydroforming from the multi-nose analytical model are given in Part 2 of this series of papers.

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1. Introduction

Numerical and analytical modeling can greatly reduce time and cost associated with experimental trials aimed at establishing a workable tube hydroforming (THF) process. Such modeling is largely responsible for the rapid development of THF technology in the last decade. Numerical modeling via finite element analysis (FEA) has been used to study material flow characteristics and the likelihood that sound parts could be produced by hydroforming [1,2]. By combining FEA and other techniques, researchers have developed loading paths (feed vs. pressure curves) for THF. Accurate loading path is critical input to a THF machine. The various techniques employed in load path determination are based on trial and error FEA simulation, optimization, adaptive, and fuzzy load control approached [3–5].

Although numerical-based FEA greatly facilitates THF process design, it does not provide parametric representation. This would preclude analyzing the interrelationships of process variables, unless a series of FEA simulations were carried out. On the other hand, closed-form solutions/analytical modeling facilitates understanding the interacting variables for a given process. Analytical modeling allows the designer to identify those variables that may have significant influence on the process. Another benefit of analytical models is that they may require only a few seconds to execute, enabling parametric studies to be carried out quickly. Furthermore, preliminary THF process designs whose accuracy may not be critical are ideal cases for analytical models. Analytical models can also

be incorporated in one-step FEA solvers. In the last decade, a number of THF models for predicting part failure, formability, process window, and models for determination of field variables have been developed. Asnafi [6] introduced a model (for the bulged part) that was able to relate axial forces, yield strength, limiting length, and friction. A model to study failure mechanisms such as bursting and wrinkling for circular tube expansion was introduced by Xia [7]. Koc and Altan [8] introduced a model for predicting buckling, wrinkling, and bursting based on plasticity, membrane, and thin-thick-walled tube theories. Their model was able to predict axial force, internal pressure, counter force, and thinning rate. Kima et al. [9] studied the onset of bursting failure in THF under combined internal pressure and axial feeding. Their model could be used to establish the hydroforming limit and bursting failure diagrams as well as for studying the effect of plastic anisotropy on plastic instability, limit stress, and bursting pressure.

Jain and Wang [10] presented a mathematical analysis pertaining to the effect of pressure on plastic instability of a dual THF process. This model demonstrated that change in stress as the tube deforms has significant influence on tube forming capability. Hwang and Lin [11] presented a new model for tube bulging in an open die, which considers the anisotropic effect. The model was successfully validated by FEA and experiments. A study on the plastic instabilities for axisymmetric tube bulging using a modified Hill's assumption for localized necking was carried out by Boumaiza et al. [12]. Their new criterion was useful in determining the geometrical effects on the localization of deformation for pressurized tubes. Ngaile and Yang [13,14] developed analytical models for THF that can output field variables similar to those obtainable through FEA. Their first model featured characterization of a pear-shaped tribotest for

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Nomenclature

R_t	tube radius
R_d	die radius
α_d	die-tube contact angle after deformation
t_o	initial tube thickness
t	deformed tube thickness
ξ	number of dies
ψ	free expansion angle
θ	die-tube contact angle
RR	free expansion arc radius
RR_p	free expansion arc center position
λ	die radius to tube thickness ratio
l_i	arc length of inside layer
l'_i	arc length of deformed inside layer
l_o	arc length of outside layer
l'_o	arc length of deformed outside layer
l_n	arc length of middle layer
l'_n	arc length of deformed middle layer
V_o	original volume of one corner of the tube
V	volume of one corner of the deformed tube
V_c	volume of one arc section of the deformed tube
V_f	volume of one free expansion section of the deformed tube
L_o	length of half of a linear section in the polygon THF
$\bar{\sigma}$	effective stress
n	strain hardening exponent
$\bar{\epsilon}$	effective strain
μ	friction coefficient
$\sigma_{\theta,i}, \sigma_{\theta,m}, \sigma_{\theta,o}$	hoop stress
$\sigma_{r,i}, \sigma_{r,m}, \sigma_{r,o}$	radial stress
$\sigma_{z,i}, \sigma_{z,m}, \sigma_{z,o}$	longitudinal stress
$\epsilon_{\theta,i}, \epsilon_{\theta,m}, \epsilon_{\theta,o}$	hoop strain
$\epsilon_{r,i}, \epsilon_{r,m}, \epsilon_{r,o}$	radial strain
$\epsilon_{z,i}, \epsilon_{z,m}, \epsilon_{z,o}$	longitudinal strain
ϵ_N	strain at the initial contact point N
ϵ_Q	strain at the exit point Q
P	internal pressure
F_h	hoop force
F_f	friction force
K	strength coefficient

THF. In this model, a closed-form solution for field variables was introduced based on a mechanistic approach to evaluate contact pressure, effective stress and strain, and friction coefficient. Their second model was focused on the prediction of hydroforming pressure, corner fill, wall thinning, stress and strain distribution, and deformed tube shape for a family of planar tube hydroforming.

Analytical modeling for THF can also be advanced by incorporating the considerable research on plastic instability of tubular structures aimed at supporting various types of loading such as flexural/bending load, a combination of bending and internal pressure loading, or bend-stretch. The difference in the research focus between tubular structure for load carrying applications and THF is that the former focuses on the onset of tube plastic deformation, whereas the latter focuses on the regime when excessive plastic deformation has occurred. The plastic theories developed for tubular structures can be seen to be complementary to THF. Extensive studies have been carried out on the collapse of tubes under combined bending and pressure by Corona and Kyriakides [15–17]. They used analytical models in studying collapse modes and performed failure analysis on tubes subjected to combined bending and pressure loading. In an attempt to investigate bend-stretch forming of extruded tubes, Miller et al. [18] developed a technique

to avoid buckling and minimize springback and distortion by optimizing the stretch loading and the required pressure. Aguirre [19] studied steel tubes' failure modes under pure bending by using a simple unstable constitutive model. Chu and Xu [20] proposed a general theoretical outline to assess failure modes in aluminum tube hydroforming. A mathematical model to predict the condition of localized burst was presented. In addition, a closed-form solution for critical axial stresses was derived based on Neale–Hutchinson's constitutive equation and deformation theory of plasticity. In another study, Chu and Xu [21] established the Process Window Diagram (PWD) for aluminum tube using the mathematical model proposed in [20]. The PWD offer a quick tool to evaluate part formability. Chu and Xu [22] investigated the prediction of Forming Limit diagrams for tube hydroforming by incorporating nine combination of loading parameters based on plastic stability. Bardi et al. [23] presented an analytical model to evaluate wrinkle formation and evolution based on post-buckling analysis of circular tubes under internal pressure and axial compression. The analytical model was based on the J2 flow deformation theory of incremental stress–strain calculations. Using Bardi's model, Chen and Ngaile [24] developed a model that predicts established wrinkle formation and uses it to determine the optimal preform for THF.

This work focuses on developing an analytical model for multi-nose tube hydroforming based on a mechanistic approach. The model is aimed at predicting field variables such as stress, strain, and thinning distributions and the fluid pressure required at any tube deformation stage.

2. Objectives and approach

Part 1 of this series of papers is aimed at introducing a parametric representation of a THF process for multi-nose-shaped tubes. Based on a mechanistic approach, a system of equations is derived to predict the forming pressure, final deformed shape, thinning rate, and state of stresses and strains.

Fig. 1 shows various multi-nose configurations before and after hydroforming with three, four, and six dies respectively. The tube is constrained with multi-dies arranged regularly around the tube. The given geometrical parameters are tube radius R_t , die radius R_d , number of dies ξ , and dividing angle 2ω . The geometrical relationships between these parameters are illustrated in Fig. 2. The tube initially establishes a contact point at each die-tube interface denoted by point N. After the tube hydroforming process has completed, two regions will be formed. The first is a contact region between the die and the deformed tube. The die-contact section is bounded by the initial contact point N and an exit point, Q as shown in Fig. 2(a). The second is a non-contact region called the free expansion section which is bounded by two exit points Q–Q. The exit point, Q is assumed to connect the die-contact section and the free expansion section. The length of the die-contact section is defined by the contact angle α_d , and the length of the free expansion section is defined by the free expansion angle ψ . The basic model assumptions are:

- The tube is homogeneous and isotropic.
- The elastic deformation is negligible and flow stress of the material follows the power law.
- Plane strain condition holds with the assumption of a long tube.
- The deformation of the tube is subdivided into die-contact and free expansion sections.
- The deformed shape of free expansion is assumed to be a circular arc.
- The hoop force is continuous along the hoop direction; and the average hoop strain is assumed to be continuous.
- The tube is subjected to bending and stretching load.

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