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A fast algorithm for strain prediction in tube hydroforming based on one-step inverse approach

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ABSTRACT

This paper presents recent developments of a simplified finite element method called the inverse approach (IA) for the estimation of large elastoplastic strains and thickness distribution in tube hydroforming. The basic formulation of the IA, proposed by Guo et al. (1990), has been modified and adapted for the modeling of three-dimensional tube hydroforming problems in which the initial geometry is a circular tube expanded by internal pressure and submitted to axial feed at the tube ends. The application of the IA is illustrated through the analyses of numerical applications concerning the hydroforming of axisymmetric bulge, made from aluminum alloy 6061-T6 tubing, the hydroforming of square section hollow component and the hydroforming of a free Tee extrusion from welded low carbon steel LCS-1008 tubing. Verifications of the obtained results have been carried out using experimental results together with the classical explicit dynamic incremental approach using ABAQUS® commercial code to show the effectiveness of our approach.

1. Introduction

Nowadays, tube hydroforming (THF) is still being one of the most important manufacturing techniques used in sheet metal forming. The increasing application of hydroforming techniques in the automotive and the aircraft industries as well as manufacturing components for sanitary use is due to its advantages compared to classical processes as stamping or welding. Tube hydroforming is a perfect technique for manufacturing tubes of complex shapes with high level of repeatability and offers an effective integration of structural components manufactured using a minimal space. Tube hydroforming has many other advantages compared to conventional stamping processes, according to Nikhare et al. (2010), these advantages include weight reduction, strength improvement and higher geometry accuracy of the final manufactured part. Historical overviews and discussion of future trends in tube hydroforming can be found in Ahmed and Hashmi (1997), Koç and Altan (2001), Singh (2003) or Hartl (2005).

In THF the main parameters that may affect the general feasibility of the final product are: tube material and dimensions, tools geometry, as well as the magnitude and the loading path of the hydraulic pressure and the axial feeding. If one of these parameters is not carefully adjusted, defects such as bursting or wrinkling may appear according to Langa et al. (2009), Di Lorenzo et al. (2010). Since the recent past, the feasibility of a product was mainly carried out by engineers using trial-and-error iterative procedures that are expensive and error prone. Over the last decade, the numerical simulation of tube hydroforming using the finite element (FE) method has received significant attention as an alternative to the trial-and-error methods; however, there is still lack of a fast and robust control of hydroforming process parameters at the early design stage; where the classical based dynamic explicit method is not convenient to use due to large amount of data needed to carry out a simulation see Hosford and Caddell (2011).

Ahmetoglu et al. (2000) provided fundamental issues related to material and lubrication requirements, material shaping capabilities, tool design and process control in tube hydroforming of low carbon steel and aluminum alloy 6061-T6 tubes. It has been achieved through the establishment of a consortium between part manufacturers, and material and equipment suppliers in the Ohio State in the US.

Koç et al. (2000) used a design of experiments technique in conjunction with FEM to facilitate the economical prediction and optimization of the height as a function of geometrical parameters subject to thinning of the wall thickness at the protrusion region. Results in their study suggest that comprehensive and detailed investigations of tribology in hydroforming should be conducted. Mac Donald and Hashmi (2001) used LS-DYNA 3D to compare bulge with a solid medium against a hydraulic medium. In their

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Nomenclature

0	initial
δ	virtual
h	thickness
P	intensity of pressure
p, q	point on the mid-surface, in distance z
s	curvilinear coordinate
z	distance of point to the mid surface
u, v, w	displacements in local coordinate
U, V, W	displacements in global coordinate
$\boldsymbol{u}_p$	displacements of p
$\boldsymbol{x}, \boldsymbol{dx}$	position vector, its variation
$\mathbf{n}, \mathbf{t}$	normal and tangent vectors in the mid surface
$\boldsymbol{N}, \boldsymbol{M}$	membrane forces, bending moments
$\boldsymbol{F}_{\text{int}}, \boldsymbol{F}_{\text{ext}}$	internal and external forces in global coordinate
$[\boldsymbol{B}_m], [\boldsymbol{B}_f]$	membrane strain, bending strain
$[\boldsymbol{K}_t]$	tangent matrix
$[\boldsymbol{T}]$	transformation local-global matrix

Greek symbols

r, φ, Z	cylindrical coordinate
$\lambda_1, \lambda_2, \lambda_3$	principal stretches
$\boldsymbol{\chi}, \boldsymbol{e}$	curvature, membrane strains
$\varepsilon, \bar{\varepsilon}$	strain, equivalent strain
$\sigma, \bar{\sigma}$	stress, equivalent stress

investigation, they examined the effect of varying friction between the bulging medium and the tube and the history of development of the bulge and stress conditions in the formed component. They concluded that the use of a solid bulging medium allows for greater branch height, less thinning of the branch top and less stress in the formed component when compared to the hydraulic bulging process. Kim et al. (2002) introduced a backward tracing technique to predict an appropriate pre-formed configuration and determine the initial tube dimensions from the desired final shape. The developed program was applied to a hydroforming process of a box expansion in order to get the uniform wall thickness after hydroforming, and the conceptual application has been proved to be successful on its effectiveness and feasibility.

Kridli et al. (2003) investigated corner filling by 2D simulations, using ABAQUS/Standard, and experiments. They examined the effects of the strain-hardening exponent, initial tube wall thickness and die corner radii on corner filling and thickness distribution. They concluded that thickness distribution is a function of die corner and strain-hardening behavior and the initial tube wall thickness affects the pressure while maintaining the same thinning. Kwan and Lin (2003) used the FE program DEFORM-3D to investigate the cold hydroforming process of a T-shape tube. They examined the influences of the process parameters such as the internal pressure, the fillet radius, and counterforce on the minimum wall thickness of formed tube. They found a suitable range of the process parameters for producing an acceptable T-shape tube that fulfills the industrial demand. Jain et al. (2004) introduced “dual hydroforming” where the counter pressure as a new process parameter to achieve favorable tri-axial stress state during deformation process. They observed that the counter pressure provides back support to the tube material and excessive thinning and premature wrinkling could be prevented and thus, larger tube expansion could be achieved. Ray and Mac Donald (2004) used a fuzzy logic control algorithm in conjunction with LS-DYNA finite element code for simulation and optimization of the forming load path to avoid the failure of the tube. They sustain that by means of a minor modifications in the strain limit setting in the load control algorithm; their method can be used to determine the optimal and feasible forming load paths for asymmetric or axisymmetric components with relatively complex geometries. Abrantes et al. (2005), used FEA program LS-DYNA to establish a basic understanding of both free bulge and calibration against closed dies in tube hydroforming process. They observed that formation of winkles, resulting in folding and unfolding of tube regions, causes a differenced springback effect along the longitudinal axle of the tube. From the equivalence curves it was possible for them, to program the parameters in order to obtain balanced axial displacements for the punch strokes.

Kashani Zadeh and Mashhadi (2006) used ABAQUS FE code to quantify the effects of coefficient of friction, strain hardening exponent, and fillet radius on the parameters, protrusion height, thickness distribution, and clamping an axial forces. Yuan et al. (2006) investigated via FEM and experiments the hydroforming of automotive rectangular section structural components. They explored the effect of loading path on the failures and thickness distribution and the reasons were analyzed for the failures, such as bursting and folding. Mohammadi and Mosavi Mashadi (2009) determined the loading paths for copper joint hydroforming via FEM and a fuzzy controller. They determined rules to increase axial feeding by introducing the calibration indicator, in order to have a product with appropriate mechanical properties. The presented method can enable automatic determination of optimal loading paths for the hydroforming of complex structural parts in a short time. Alaswad et al. (2011) conducted a finite element study along with response surface methodology for design of experiment to construct models for three responses (bulge height, thickness, and wrinkle height) for X shape bi-layered tube hydroforming. They found that, tube geometry has an important influence on the shape of the hydroformed junction. They concluded that, the usage of a larger die corner radius leads to higher bulges and smaller wrinkles. However, critical thickness reduction can be avoided for large tube diameters if a big thickness is assigned for both layers.

In all of the previous cited research works dedicated for the design and the analysis of tube hydroforming process parameters, generally the classical incremental approach based on dynamic explicit formulation is used by means of commercial codes such as LS-DYNA® or ABAQUS®. Although, the classical incremental methods can provide accurate solutions for complex forming problems, the simulations using these methods are very expensive in terms of solving CPU-time and also for engineer’s time to set up and run the problem: complex die CAD meshing, material data, initial tube mesh, etc. see Numisheet (2008). Therefore, since the last twenty years, significant research has been devoted to the development of alternate approaches allowing fast solutions of the forming problems. These methods have become valuable tools in the preliminary design stage of components or structures mainly used in the automotive industry. The one-step methods are based on the general assumption of knowledge of the final geometry of the 3D part and the total deformation theory of plasticity. The unknowns are material positions of points on the initial geometry as well as strains and thickness variation.

The inverse approach developed by Guo, Batoz and their coauthors since 1990 (Guo et al., 1990), is very attractive since authors showed that the IA can estimate large strains in deep drawing with a very good accuracy compared to incremental analysis or to the experiments (Batoz et al., 1998; Guo et al., 2000). More recently Naceur et al. (2006, 2008) introduced new enhancements on the IA to take into account the loading path in deep drawing simulation in order to improve the stress state obtained at the end of forming.

While the IA formulation has gained a great success and attracted many research groups for the fast simulation of sheet metal forming, unluckily its development has been only limited to the deep drawing simulation. Based on our knowledge only a very