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Review

On process parameter estimation for the tube hydroforming process

Mikael Jansson*, Larsgunnar Nilsson, Kjell Simonsson

Division of Solid Mechanics, Department of Mechanical Engineering, Linköpings universitet, SE-581 83 Linköping, Sweden

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Abstract

Tube hydroforming is a forming process where an inner pressure combined with axial feeding deforms the tube to the shape of a die cavity. One of the main concerns when designing such a process is to avoid burst pressure, i.e. the process state where the hardening of the material is unable to resist the increase in inner pressure and wall thickness reduction. The success of a hydroforming process strongly depends on the choice of process parameters, i.e. the combination of material feeding and inner pressure. Especially in hydroforming processes, where the free forming phase is substantial, the process is proved to be very sensitive to the inner pressure. By transforming the problem into a deformation controlled rather than a force controlled process, the results from the process parameter estimation become more reliable but on the other hand less intuitive. In this context, three distinct parameter estimation procedures are suggested. Firstly, a self feeding based procedure is proposed with the intention of being a fast method to be used as a first estimate of suitable process parameters. Secondly, an iterative optimization problem set up is presented. Thirdly, and finally, an adaptive simulation procedure based on process response approximations is proposed, which only requires a limited number of simulation runs.

Keywords: Aluminium alloys; Hydroforming; Adaptive process; Optimization

Contents

1. Introduction

Several papers have been published in the field of designing load curves for tube hydroforming. Apart from fast and crude methods, two main approaches to the problem can be identified, namely optimization methods and adaptive simulation approaches. In the optimization procedure, design sensitivities are used to establish an optimal solution in an iterative way. In the adaptive method, the solution is continuously monitored for defects and the process parameters are accordingly updated. Thus no iterations are required in the latter case. In Ref. [1], the authors classify the tube hydroforming process based on the loading parameters, namely (1) pressure driven, (2) pressure dominant, (3) feeding dominant and (4) feeding driven. Further, the characteristics of the respective class are described in terms of failure modes and process windows. It is concluded that the pressure dominant process is the most challenging load curve determination problem since it involves a high risk for wrinkling, bursting and leakage. Thus, processes which are included in this category are most beneficial for load curve optimization.

A direct differentiation method in combination with sequential quadratic programming is used in Ref. [2] for optimizing

* Tel.: +46 13 285867; fax: +46 13 282717.
E-mail address: mikja@ikp.liu.se (M. Jansson).

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Table 1
Material data for AA6063-T4

σ_{00} (MPa)	σ_{45} (MPa)	σ_{90} (MPa)	σ_{11} (MPa)	σ_{22} (MPa)	R_{00}	R_{45}	R_{90}
78	76	74	23.4	85	0.47	0.12	1.5

a tube expansion and a sub-frame. A B-spline curve is used to describe the stroke and pressure relationship. The objective function is chosen to minimise the thinning and constraints are used obtain the desired shape. Another example of an iterative solution can be found in Ref. [3], where a conjugate gradient method is used either in batch mode, where all parameters are determined simultaneously, or in sequential mode, where the parameters are determined in sequential order. The latter approach was found to be superior. Since hydroforming is a highly nonlinear process, not only due to the material nonlinearity but also due to the wrinkle formation and material instabilities such as bursting, a response surface method (RSM) would be an appropriate choice of method. This method was used in Ref. [4] for determining loading paths both for open and for closed die hydroforming. The authors compared the thickness uniformity and bulge height of a T-joint from load curves with one, two and four strokes to pressure points, and found that enhanced formability could be expected when multiple strokes were used.

If instead an adaptive procedure is considered, the method tends to give a solution with axial feeding while the pressure is held constant until a wrinkle is detected. The pressure is then increased with no axial feed to eliminate the wrinkle [5–7]. In Ref. [8], the increments in pressure and end feed are determined through the material stress–strain relation and Hill's yield criterion. Given an increment in effective plastic strain, the algorithm finds the end feed and pressure increment to obtain a certain strain path. Instead of using mathematical models for optimization, some authors suggest a fuzzy logical approach, see e.g. [9,10]. The basic principle is an adaptive simulation approach, where the algorithm is based on simple logical terms, e.g. if the severity of a wrinkle is rated as high then a high increase in pressure is applied to the next loading increment.

In this work, suggestions on how to perform process parameter estimation procedures based on a deformation controlled process are presented. Firstly, an estimate method based on the self feeding approach is presented. Secondly, an iterative optimization problem is set up and evaluated. Finally, an adaptive simulation procedure is proposed which uses trial runs and response approximations to choose the appropriate loading path of the hydroforming process.

The disposition of the paper is as follows. In Section 2, the geometry and FE model of the studied hydroforming problem are presented. In Section 3 the self feeding approach is described in a force and deformation controlled manner. When designing load curves, the quantification of wrinkling is crucial and this topic is discussed in Section 4. In Section 5, the process parameter estimation is formulated as an optimization problem and the process parameters are found by using the response surface method. The proposed adaptive procedure is described in Section 6, which is followed by a discussion and conclusions in Sections 7 and 8.

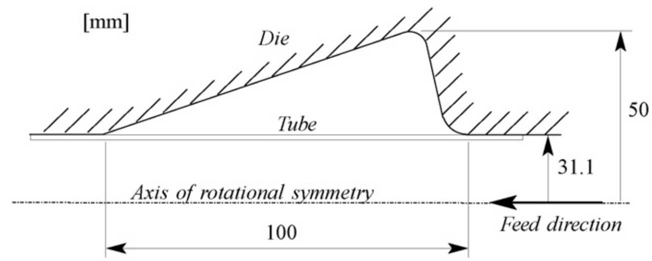

Fig. 1. Conical die shape.

2. Geometry and FE model

In order to evaluate the process parameter estimation procedures proposed in this work, a conical die geometry has been used, see Fig. 1. The FE model has previously been validated against experiments with good results [11]. The conical shape yields a gradually increasing circumferential expansion, which proposes a load curve with extensive feeding. The material is fed through the cone base end. The material used is aluminium alloy 6063-T4, see Table 1, and the elasto-plastic material model used follows the YLD2000 yield criterion [12], with parameter values according to Table 2[13,14]. Further, a Young's modulus of 68.300 MPa and a Poisson's ratio of 0.3 have been used to model the elastic behaviour.

The explicit solver in LS-DYNA [15] is used for all simulations. The tube is modelled using 7392 Belytschko Tsay elements with 10 integration points through the thickness, see Fig. 2. The tool surfaces are modelled as rigid with a friction coefficient of 0.09 between the tube and the tool. The nominal thickness varies along the circumference with minimum and maximum nominal thicknesses of 3.125 and 3.228 mm, respectively. A total simulation time of 10 ms has been used, which is found to be sufficiently long in order to eliminate all dynamic effects.

The inner pressure is applied by a control volume, which is bounded by the tube. The pressure can either be prescribed by a load curve or determined from a prescribed mass flow, with the latter being preferred. The pressure is determined from

$$p(t) = K \ln\left(\frac{V_0(t)}{V(t)}\right) \quad (1)$$

where K is the bulk modulus of the fluid (2050 MPa), $V_0(t)$ is the volume of the uncompressed fluid and $V(t)$ is the volume of the compressed fluid. The volume of the fluid in the uncompressed

Table 2
YLD2000 parameter values for AA6063-T4

α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8
0.719	1.287	0.9784	0.971	1.03	0.9784	0.157	1.233