Loading Path Optimization of T-shape Tube Hydroforming Process

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This paper addresses modeling and optimization of loading path in T-shape hydroforming of tubes using analysis of variance technique and Simulated Annealing (SA) algorithm. A set of experimental data has been used to assess the influence of loading process parameters in hydro-formed geometry. The process variables considered here include the yielding and expanding internal pressures and their required times, the calibration pressure, the axial and counter punches movements. The process output characteristics include thickness and height of protrusion. The Taguchi method and regression modeling are used in order to establish the relationships between the input and output parameters. Thirty two different cases for different loading paths are designed. The Abaqus/Explicit is used to calculate the minimum thickness and maximum height of protrusion. The adequacy of the model is evaluated using analysis of variance (ANOVA) technique. The proposed model is embedded into a Simulated Annealing (SA) algorithm to optimize the loading process parameters and to find the best input variables. Computational results prove the effectiveness of the proposed model and optimization procedure.

Keywords: Hydroforming, T-shape, Loading path, Design of experiment, Taguchi, Regression, Optimization, Simulated annealing

Introduction

With the current drive for decreasing air pollution and fuel consumption, the increasing demands on vehicle body structures in safety, lightweight and cost efficiency call for new manufacturing processes. Therefore hollow products are increasingly employed for automobile parts and the hydroforming of tubes is attractive in automobile industry as a forming process of hollow products. The major advantages of tubular hydroforming include: weight reduction in component, superior structural strength and stiffness, fewer secondary operations, etc. However, tube hydrofroming is a complex process and products can be affected by many factors including: loading conditions, die geometry, lubrications conditions and etc. In hydroforming process variation of internal pressure, axial material feed and counter punch displacement versus time usually referred to as load-curves. Due to inappropriate selection of loading paths, the various forming defects such as, wrinkling, thinning and bursting often occur. Considerable researches have been conducted to investigate optimization of loading trajectories for different tubes hydroforming processes. Fan [1] optimized loading conditions for tube hydrofroming by using conjugate gradient method with finite element method. Subhash [2] used finite element simulation and optimization software to optimize the loading paths for closed-die T-branch tube hydroforming. In the current study, a new approach to optimize the loading parameters is presented. It would firstly attempt to relate the loading parameters to process output characteristics, through developing empirical regression models. Hence, thirty two different loading paths are designed by DOE method. Output characteristics including minimum thickness and maximum height of protrusion of formed tube are calculated by finite element simulation for each load paths. Abaqus/Explicit [3] is used to simulate the process and to calculate the desired outputs. When the best relation between the loading parameters and outputs are found, the proposed model is implemented into a simulated annealing (SA) optimization procedure to identify proper set of loading parameters.

Analysis of T-Shape Hydroforming by Abaqus/Explicit

The hydroforming process is simulated using the commercial finite element software, Abaqus/Explicit6.7. Before investigating different loading parameters, simulation process must be verified with an available experiment data. Hence, an experimental model that has been studied by Hwang [4] is selected and simulated here. The tube has a diameter, wall thickness and length of 72mm 298.5 and 2.8mm, respectively. Two axial punches and one counter punch are used for this process. The material of tube is Aluminum alloy 6063-T5. To consider the anisotropy of the material, the Hill's anisotropic plasticity model is assumed in the simulation. The shell element (S4R) is used for the tube analysis and the die and punches are modeled as being rigid entities. Loading curves used in simulation are according to [4]. The model was analyzed with those specifications and the obtained thickness distribution calculated from simulation model is compared with those from Ref. [4]. It was found that there is a good agreement between them.

Design of Experiment and Mathematical Modeling

Problem Statement. In tube hydroforming for T-branch usually the intent is to produce the part with maximum protrusion while minimize the tube wall thickness variation. Lin [5] used the finite element method in conjunction with abductive network to predict an acceptable product with a minimum wall thickness and the maximum protrusion height on the T-shape tube. Subhash [2] considered both thickness deviation and branch height as the objective function for optimized loading paths. In the current study also the minimum thickness and maximum T-branch height are selected as outputs functions. They are calculated by the FE simulation when different load paths are applied. These two functions are named as the objective or cost functions in the next parts.

Definition of Internal Pressure Path and Determination of Lower and Upper Bounds. The effect of internal pressure has been studied by many researchers. They have focused on choosing an appropriate pressure curve versus time in tube hydroforming. Cherouat [6] investigated the effect of three different load curves for pressure and reported a successful forming by using a multiple stages pressure curve. Hwang [4] has also used a similar form of pressure curve with 3 stages contain yield, expansion and calibration phases. In the current study, the total time experiment is assumed to be fixed value and therefore five variables are sufficient to design the internal pressure curve. They are the yielding, expanding and calibration pressures and their required times. These five variables are shown as **Figure 1**. Based on some experimental data, the minimum and maximum limitation values are selected for each variable as shown in **Table 1** in rows 1-4. By iinvestigating the results from some more simulations it can be shown that the amount of yield pressure may be fixed at 2.5 MPa. Hence, in order to design the pressure curve four variables should be found.

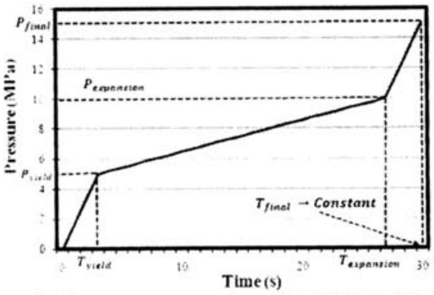

Figure 1. Pressure curve versus time with considering design variables.

Axial Punch Displacement Path. Axial punch displacement curve is very similar in many researches and usually consists of two stages. In this study similar to what assumed by Fan [1] and Altan [7], a two stages path is used for axial punch. Because of the symmetry, the axial punch path consists of two variables for displacement and the time of first variable, **Figure 2**. They are as specified in Table 1 (rows 5-7) with their minimum and maximum bounds.

Counter Punch Displacement Path. The counter punch is used to control the branch height and avoid over thinning at the branch in hydroforming process. It also controls the evolution of thickness at the top of protrusion. Gelin [8] used this parameter for T-shape hydroforming process. Teng [9] also investigated hydroforming of a 45 degree Y-shape tube and used the counter punch for preventing of excessive thinning. The counter punch displacement path is usually simple and the involved variables are the amount of displacement and the starting and stopping times. Moreover, two variables are needed to determine the amount of displacement which are the initial and final places of counter punch. **Figure 3**. The difference between these two variables will show the movement of counter punch. The minimum and maximum bounds for the counter punch variables are shown in **Table 1** (rows 7-11).

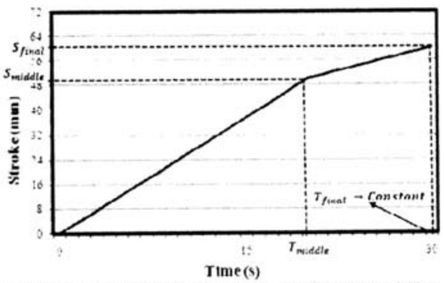

Figure 2. Axial punch feeding versus time and its design variables.

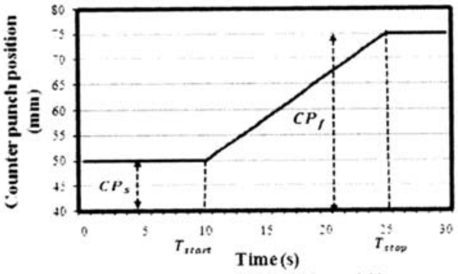

Figure 3. Counter punch path and its design variables.

Design of Experiments. To develop the mathematical model with the minimum number of trail experiment a test design matrix is constructed. There are eleven loading parameters and each of them has two levels as shown in Table 1. Hence and according to Taguchi L_{32} design of experiments matrix, thirty two combinations of the input parameters have to be considered, **Table 2**. The last two columns of this table show the calculated results from finite element simulation. These data can be used to assess the mathematical models.

Mathematical Modeling. Different regression functions such as linear, stepwise and curvilinear can be fitted to the above data and the coefficients values may be calculated using regression analysis. In the current study, the regression analysis is achieved by linear and stepwise functions. General form of linear regression is as follows;

$$Y=\alpha_0+\sum_{i=1}^{n}\alpha_i X_i, \qquad i=1,2,......,n \tag{1}$$

where Y is the output parameter such as thickness. X_i are input or loading parameter and α_i are coefficients which have to be calculated by regression analysis. The stepwise elimination process removes the insignificant terms to adjust the fitted linear model. Using regression technique, in Minitab Software, two types of mathematical functions contain linear and stepwise have been fitted to the experimental data. The models representing the relationship between loading parameters and outputs are calculated as follows;

Thickness = $3.89 - 0.00341\ P_{expan} - 0.0244\ P_{final} - 0.0219\ T_{yield} - 0.00087\ T_{expan} - 0.00544\ S_{middle} + 0.0122\ S_{final} + 0.00019\ T_{middle} + 0.00671\ CP_s - 0.0244\ CP_f + 0.00742\ T_{start} + 0.00213\ T_{stop}$ (2)

Height = $-15.5 + 0.387\ P_{expan} + 0.231\ P_{final} - 0.329\ T_{yield} - 0.158\ T_{expan} - 0.183\ S_{middle} + 0.513\ S_{final} + 0.342\ T_{middle} + 0.0636\ CP_s + 0.310\ CP_f - 0.190\ T_{start} - 0.131\ T_{stop}$ (3)

Stepwise linear regression model for thickness and height:

Thickness = $3.895 - 0.0244\ P_{final} - 0.0219\ T_{yield} - 0.0054\ S_{middle} + 0.0122\ S_{final} + 0.0067\ CP_s - 0.0244\ CP_f + 0.0074\ T_{start}$ (4)

Height = $-12.14 + 0.387\ P_{expan} + 0.231\ P_{final} - 0.33\ T_{yield} - 0.158\ T_{expan} - 0.183\ S_{middle} + 0.513\ S_{final} + 0.342\ T_{middle} + 0.310\ CP_f - 0.190\ T_{start} - 0.131\ T_{stop}$ (5)

The adequacies of various functions have been evaluated using analysis of variance (ANOVA) technique. A significant criterion for adequacy of model is correlation factor (R^2). This factor evaluates from 100% and if in a regression analysis its amount approach 100%, that illustrates the better accuracy of the model. Correlation factors for above regression models are tabulated in **Table 6**. Based on ANOVA, the values R^2 in linear model are over 85% for two outputs. This means that the model provide a good representation of the actual process in terms of Thickness and Height response.

For illustrative purpose, the distributions of real data (simulation results) around regression lines for linear model are shown in **Figure 4** for Thickness response. This figure demonstrates a good conformability of the developed models with the real process.

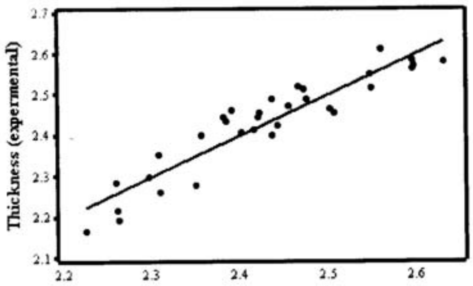

Figure 4. Predicted values for thickness versus actual values.

Optimization

To determine proper values of loading parameters, a set of equations must be solved simultaneously. Analytical and numerical methods may be used to solve these kinds of problems. For instance, evolutionary algorithms which are powerful optimization techniques widely used for solving combinational problems. One of these algorithms called, simulated annealing (SA), is used in this study to seek out the best amount of parameters. Kirkpatrick [10] employed it as a powerful optimization method in his studies. This model of optimization is established based on metallurgical annealing process. In order to use the SA technique for estimation the values based on outputs a suitable objective function should be defined. This function is in the form of error function and is defined as a squared error function given below;

$$F = \frac{\left(T_{exp} - T\right)^2}{T_{exp}} + \frac{\left(H_{exp} - H\right)^2}{H_{exp}} = 0 \qquad (6)$$

In this function, T_{exp} and H_{exp} are calculated by relations 2 and 3, respectively, and T and H are desired values which are selected by designer. A proposed algorithm code of SA was written in MATLAB programming software. By running the code of SA, the optimum set of input variables in **Table 3** is seek out based on the minimum error of the outputs and the obtained results are shown in **Table 4**. By comparison between the obtained results and the experimental data given by Hwang [4], it can be found out that despite 15% reduction in final pressure, percentage of thinning decreases from 15% to 9% while the height of protrusion has no significant change. The convergence curve for one of the calculation is shown in **Figure 5**. This curve illustrates that the convergence of proposed SA algorithm is satisfactory and the desire input are obtained after about 300 iterations.

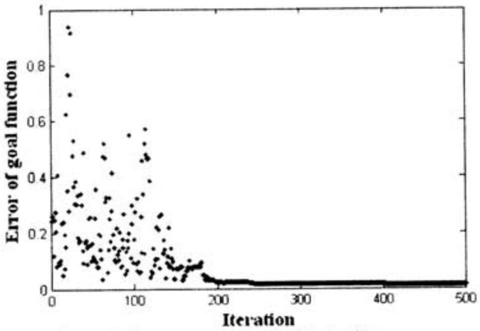

Figure 5. Convergence rates for SA algorithm.

The obtained formed tube by using the optimum loading parameters confirms that the final shape of tube is almost without any defects in its T-branch part, **Figure 6.**

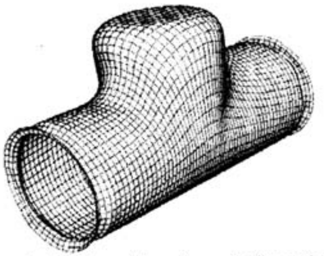

Figure 6. Tube formed by optimum loading paths.

Conclusions

T-shape tube hydrofroming was studied and the optimization of loading parameters was investigated in detail using a proposed approach. By using design of experiment method thirty two loading paths upon Taguchi method based on two levels experiment were designed. All cases were simulated by using finite element method and the desired outputs contain the minimum Thickness and maximum Height of protrusion were calculated. Mathematical models for two objective functions are established by using analysis of variance technique and regression. Simulated annealing (SA) algorithm was used to optimize objective functions versus desired loading parameters. The comparison between the obtained results using the optimized loading paths and the experimental data showed that, despite reduction of final required pressure, formability of the tube was improved.

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Table 1. Loading variables with upper and lower bound.

No	Factor	Unit	Notation	Minimum (-)	Maximum (+)
1	Expansion pressure	MPa	P_{expan}	7.5	12.5
2	Final pressure	MPa	P_{final}	12.5	17.5
3	Yielding time	s	T_{yield}	2	4
4	Expansion time	s	T_{expan}	20	27
5	Initial displacement of axial punch	mm	S_{middle}	50	60
6	Final displacement of axial punch	mm	S_{final}	60	64
7	Time of initial displacement	s	T_{middle}	20	27
8	Initial place of counter punch	mm	CP_s	50	56
9	Final place of counter punch	mm	CP_f	75	81
10	Starting time of counter punch movement	s	T_{start}	5	10
11	Stopping time counter punch movement	s	T_{stop}	20	30

Table 2. The matrix of DOE for loading parameters and the FE simulation results.

No	P_{expan}	P_{final}	T_{yield}	T_{expan}	S_{middle}	S_{final}	T_{middle}	CP_s	CP_f	T_{start}	T_{stop}	T (mm)	H (mm)
1	-	-	-	-	-	-	-	-	-	-	-	2.51	38.23
2	-	-	-	+	-	-	-	-	+	+	+	2.47	36.36
.	.	.	.	.	.	.	.	.	.	.	.	.	.
31	+	+	+	-	+	+	+	+	-	-	-	2.41	42.15
32	+	+	+	+	+	+	+	+	+	+	+	2.35	42.34

Table 3. Optimum variables calculated by SA.

P_{expan}	P_{final}	T_{yield}	T_{expan}	S_{middle}	S_{final}	T_{middle}	CP_s	CP_f	T_{start}	T_{stop}
9.5	12.5	2	24.5	50	63.5	25.5	56	75.5	9.5	30

Table 4. Comparison between the results of SA and Abaqus.

SA		Abaqus	
T (mm)	H (mm)	T (mm)	H (mm)
2.66	39.91	2.55	40.8