Optimization of Tube Hydroforming Process Using Simulated Annealing Algorithm

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Abstract

In this paper, forming parameters of tube hydroforming (THF) process are investigated and optimized using Simulated Annealing optimization algorithm linked with a finite element commercial code. The goal of this research is to obtain the maximum formability of two dimensional (2D) axisymmetric tubes under a failure criteria based on material’s forming limit diagram (FLD). The initial approximated pressure loading path is determined by proved theoretical equations. Then the Simulated Annealing algorithm written in Matlab software is combined with a nonlinear structural finite element code ANSYS/ LS-DYNA in order to optimize internal hydraulic pressure. The results are compared by experimental observations and a good agreement was observed between them.

Keywords: Tube Hydroforming Process, Optimization, Simulated Annealing, Finite Element Analysis;

1. Introduction

Application of tube hydroforming (THF) process in industry, especially automotive industry, is outstanding, and is widely spread because of its enormous advantages against similar forming processes such as stamping, deep drawing and roll forming.

These years, many investigations have been performed in order to study and analyze the process to understand the vague aspects of THF [1-5]. Therefore, different optimization methods have been proposed by researchers to optimize the loading paths conditions in THF. Fann and Hsiao (2003) used the conjugate gradient optimization method to optimize a T-shaped tube using LS-DYNA [6]. Bing Li et al. (2005) used a multi-objective optimization method and studied the effects of forming parameters on tube hydroforming process by finite element analysis and Taguchi method [7]. Imaninejad et al. (2005) used LS-DYNA and the optimization software LS-OPT to optimize the internal pressure and axial feed loading paths for a T-joint design in which the minimum thickness variation was chosen as design objective to hold the effective stress below the materials ultimate stress [8]. Manabe et al. (2006) studied the optimization process of tube hydroforming using a virtual-database-assisted fuzzy control system to determine the forming parameters [9]. Also, Jansson et al. (2007) proposed an adaptive optimization method based on the use of response surface methods [10]. In addition, Abedrabbo et al. (2009) used genetic algorithm (GA) search methods using optimization software HEEDS in combination with the nonlinear structural finite element code LS-DYNA to optimize
the process parameters and determine the best loading paths for tube hydroforming process. They used FLSD as the failure criterion [11]. In current research, simulated annealing (SA) algorithm written in MATLAB software is directly combined with the nonlinear finite element code ANSYS/LS-DYNA [12] in order to optimize the pressure loading path in THF process. In this paper, the maximum deformation of tube to die cavity is considered as the goal function, and a failure criterion based on maximum thinning and von-Misses stress is used to produce a non-defective product.

1.1. Prediction of loading path

Traditionally, loading path diagram of THF process is obtained using trial-and-error method which mainly relies on past experience and simple equations. For example, pressure loading path diagram is estimated by relating three components of pressure; yield pressure $P_{\text{yield}}$, bursting pressure $P_{\text{bursting}}$ and calibration pressure $P_{\text{calibration}}$, as given in Eqs. (1) to (3), respectively [13]:

$$P_{\text{yield}} = \sigma_y \frac{2t_0}{D_0 - t_y}$$  \hspace{1cm} (1)

$$P_{\text{bursting}} = \sigma_y \frac{4t_0}{D_p - t_y}$$  \hspace{1cm} (2)

$$P_{\text{yield}} = \frac{2}{\sqrt{3}} \sigma_y \ln \left[ \frac{r_b}{r_i - t} \right]$$  \hspace{1cm} (3)

Where, $t_0$ is the initial wall thickness, $D_0$ the tube diameter, $D_p$ the protrusion diameter, $r_b$ the smallest die corner radius, $\sigma_f$ the flow stress of the material, $\sigma_y$ the yield strength of the material and $\sigma_u$ the ultimate tensile strength of material.

Constructing a multi-linear curve through these three pressures may be used as an initial guess for internal pressure.

1.2. Finite Element Analysis

Since the finite element run time is very important during the optimization process, a 2-D axis-symmetric element, PLANE162 is used which is shown in Fig 1. Different material properties for die and tube are defined in Table 1. Die is assumed to be perfectly rigid body and tube is assumed to obey power law plasticity material property. Tube material is ASTM C11000 copper alloy with purity of 99.9%. The material is assumed to be isotropic and strain rate is neglected.

![Fig. 1. (a) Finite element model of tube and die in ANSYS/LS-DYNA; (b) Dimension of final tube.](image)
Table 1. Dimension and Material properties of tube

| Item                              | Unit     | Value |
|-----------------------------------|----------|-------|
| Yield Stress, \( \sigma_y \)     | [MPa]    | 130   |
| Ultimate Tensile Stress, \( \sigma_{uts} \) | [MPa] | 285   |
| Maximum Elongation, \( \varepsilon \) | %       | 28    |
| Coefficient of Friction, \( \mu \) |          | 0.05  |
| Young Modulus of Elasticity, \( E \) | [GPa] | 85    |
| Density, \( \rho \)              | [g/cm³]  | 8.9   |
| Poisson Ratio, \( \nu \)         |          | 0.32  |
| Strength Coefficient, \( K \)     | [MPa]    | 365   |
| Strain Hardening Exponent, \( n \) |          | 0.185 |
| Thickness, \( t_0 \)             | [mm]     | 0.63  |
| Outer Diameter, \( D_0 \)        | [mm]     | 15.87 |

1.3. Simulated Annealing Algorithm

In this paper, input variables in optimization of THF are assumed to be gradients of pressure versus time diagram estimated based on Eqs. (1) to (3). As an advantage for such definitions, there will be no limitations on the number of gradients of pressure diagram. It means this method can be used in any problems having multi-linear pressure increase during the forming process.

In fact, it is expected from THF process to produce parts which fully form into the die cavity without any defects or faults. So, maximum formability of tube during the forming process is assumed as a goal function. Such situation will be detected by calculating of the distance between the tube and die nodes resulted from FE post processor. In other words, the gap between nodes of tube and die is assumed as energy defined in SA algorithm. Therefore, in each step, by considering a new set for gradients of pressure diagram as input variables, new energy (new node distance) will be obtained from FEA. So, there will be some optimized pressure gradients in which minimum tube to die node distance is determined with maximum formability. During the process and before the acceptance criterion for SA happens, finite element model (FEM) is checked based on a failure criterion for implementing of non-defect part.

As it is mentioned by the other researchers working on SA optimization, finding optimal parameters such as initial temperature, annealing schedule, the acceptance function parameters and etc., is problem dependent, and it is best accomplished through trial and error [14].

Besides, determination of initial temperature and initial pressure separately has magnificent effect on the total run time of the program. For limitation of search space in order to decrease the total run time, it is required to define upper and lower bands for internal pressure (Eqs. (1) to (3)).

Variable ratio and cooling function are two other important factors which can affect the total optimization time. Therefore, in Table 2, linking of optimization parameters and FEA parameters are clarified. It shows how each of the FEA parameters and SA parameters are equalized in this investigation.

Table 2. Equalizing FEA and optimization parameter

| FEA Parameters                      | SA Parameters          |
|-------------------------------------|------------------------|
| Gradients of Pressure vs. Time Diagram | Input Variables       |
| Distance between Nodes of Tube and Die | Energy               |

In current research, cooling function is defined according to Eq. (4). This definition increases the rate of convergence. Moreover, initial temperature based on the order of magnitude of the inputs and outputs is obtained as \( 5^\circ \text{C} \). Other optimization parameters data are shown in Table 3.

\[
T(t) = \frac{T_0}{1 + \ln(t)} \quad ; t = 1,2,...
\] (4)
Table 3. Optimization parameters

| Optimization Parameters          |
|---------------------------------|
| Markov Chain: 15               |
| Variable Ratio: 1~1.5            |
| Initial Temperature: 5          |

2. Loading Path Optimization

Loading path optimization is performed for two different situations; constraint bulging and free bulging, in which different boundary conditions are considered. Failure criterion based on the combination of von Misses stress and final thickness obtained from Eq. (5) is determined [15].

$$t_f = t_0 \left( \frac{r_1}{r_2} \right) \frac{1 + \alpha}{\alpha - 2}$$  \hspace{1cm} (5)

Where, $t_f$ is final thickness, $t_0$ is initial thickness, $r_1$ and $r_0$ are final and initial radius of tube respectively, and $\alpha$ is stress ratio. According to current data, final thickness can be calculated, and maximum thinning of 30% is considered as a failure criterion for the FEM. It means, necking as a irreversible fault will be happened in the FE model when maximum thinning resulted from FEA is more than 30%. Moreover, maximum von Missed stress resulted from FEA is compared with ultimate strength of material, and if it will be more than ultimate strength of material, bursting failure will be happened in tube.

2.1. Constraint bulging

For implying the constraint bulging condition, all of the nodes of the two end sides of the tube are fixed in axial direction. Optimization results are shown in Fig 2. It is observed that after approximately 100 true simulations, distance of tube’s nodes to die’s nodes is converging to 0.9 mm. It means that according to the considered failure criterion, there is a little gap between the tube and die and 90% of tube is deformed into die shape. In Fig 3, tube deformation during the process is illustrated in five different time steps and for optimized pressure resulted from FEA.

Fig. 2. Goal function vs. iteration for constraint bulging condition
2.2. Free bulging

Similar results are obtained for free bulging conditions in which it is permitted to tube to contact the die surface. Optimization results are shown in Fig 4. Tube deformation under optimized pressure path is illustrated in Fig 5. It is shown that tube completely matched to the die shape (with 0.2 mm distance between tube and die nodes). In the first steps of simulation, initial distance of nodes of tube and die are more than 1 mm. It means, in initial stage of analysis, most of variable are permitted in optimization algorithm, however when the algorithm grows for producing the new variables, strict conditions will be considered for acceptance of the new ones. It must be mentioned that initial distance between tube and die is 2.8 mm and in initial stages of simulation predicted pressures are not sufficient even to yield the tube. Moreover, following results show that for filling the fillet section of die, it is required to use axial feed.
In Table 4, optimized pressure for constraint and free bulging are compared with each other. For each of them, two different situations are considered in that numbers of stages for forming process differ. Total run time of the process for both of them are similar which is 20 ms, but for cases which are consisted of two stages for simulation, total run time of first stage is 80% of second stage. Theoretical pressure calculated in this table is the minimum pressure required to make plastic deformation in tube.

Table 4. Optimization parameters

| Case Study         | Optimized Pressure [MPa] | Goal Function [mm] | % Maximum thinning | Theoretical Relation [MPa] |
|--------------------|--------------------------|--------------------|--------------------|--------------------------|
| Constraint Bulging - 1 stage | 20.84                    | 0.9                | 30                 | 15.63                    |
| Constraint Bulging- 2 stages | 12.59 - 21.01           | 0.8                | 30                 | -                        |
| Free Bulging- 1 stage     | 20.33                    | 0.8                | 28                 | 17.4                     |
| Free Bulging- 2 stages     | 19.45 - 21.45           | 0.02               | 28                 | -                        |

2.3. Comparison of FEA and experiment

According to optimized pressure obtained from FEM and SA procedure, some experimental tests are performed for producing a perfect product. Experimental conditions are closed to the constraint bulging condition in finite element model. For comparison of FEA and experiments, thinning percentage is shown in Fig 6. Upper section in Fig 6 shows half of a deformed tube. By using a micrometer, final thickness of tube after THF process can be determined. According to initial and final thicknesses, thinning variation in tube length can be calculated. As it is shown in Fig 6, two graphs have similar trends in which maximum thinning will happen in the middle of the tube where the maximum tube bulging is existed. Amount of the maximum thinning obtained from two methods is about 29%. It shows good agreement between two methods in maximum bulge area of the tube. However, thinning resulted from experiment differs with FEM result in two sides of the tube. One of the most important reasons for differentiation of two graphs is different friction coefficients. Another reason for such a difference is that in experiments two sides of the tube are fixed by means of mechanical jacks used for sealing. While in FEA, it is assumed that two-side constraint is applied on tube ends. For clarifying of these differences, distribution of thickness is shown along the tube in Fig 7 and compared with initial thickness of tube. Minimum thickness resulted from experiment in two sides of tube is about 0.54 mm while FEM result in this section is about 0.59 mm. It shows error in instrument devices and measuring is another factor which may have an influence on diversity of results.
3. Conclusion

Based on the procedure provided in this paper, following conclusions can be obtained:

1- Application of simulated annealing in optimization of tube hydro forming process is considered. As a heuristic method, SA procedure can be used in optimization of THF process through the presented method.

2- Giving exact results from optimization for internal pressure makes it more precise than similar optimization methods. In that, it needs complicated, high quality, high developed, and accurate control system for experiments.

3- This procedure is mainly depends on the failure criteria which is chosen in algorithm. So, using more accurate criterion made more precise approximation for the results. However, this method can also be used as a rough estimation in design of forming parameters in THF process.

4- The presented method can be used for optimization of forming processes which are similar to THF process such as sheet forming process. So, in each circumstance where there is a combination of FEA and any optimization algorithm, this method can be used as a powerful tool that may help researchers.
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