Finite element based optimization study on hydroformed stepped tube

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Abstract. Tube hydroforming process is an advanced manufacturing process in which tube is placed in between the dies and deformed with the help of hydraulic pressure. A sound tube hydroformed part depends upon die conditions, material properties and process conditions. In this work, a finite element study, along with response surface methodology (RSM) for designing the simulation, has been used to construct models with loading path, friction, anisotropic index, strain hardening exponent and tube thickness. The responses studied are the die corner radius filling and strain non-uniformity index (SNI) chosen in each step of the tube with maximum 30% thinning as stopping criteria. The factors effect and their interactions on each response were determined and analysed.

1. Introduction

The hydroforming process is widely used to form light weight, high strength and complex parts. In tube hydroforming, tube blanks are formed into a die cavity of desired shape by means of simultaneous application of hydraulic internal pressure and axial compressive loads. The main application fields have been found in automotive, aircraft and aerospace industry. Manufacturing industries are greatly benefited by this process as it reduces the number of parts per product, long term expenditure and weight [1]. Hydroformed products are mainly in the form of stepped tubes, conical tubes and box shape tubes [2].

A sound hydroformed product depends upon material properties, tube geometry, process parameters and friction. Extensive study of their effect is essential for the success of the process. The effect of material properties on the free expansion of tube was investigated by Carleer et al. [3] on different grades of steel. The effect of coefficient of friction on fracture of tube hydroforming was investigated by Zhang et al.[4] based on Gurson-Tvergaard-Needleman (GTN) ductile damage model. Furthermore, a numerical investigation was made by Alaswad et al. [5] to study the geometrical effect on bi-layered tube hydroforming.

The main aim of this study is to integrate the RSM based Design of Experiment (DoE) to construct an empirical model for corner filling and strain non-uniformity index (SNI) as a function of different
process variables as well as tube thickness for a three stepped shaft to determine their mutual interaction and effect on manufacturing of such a part.

2. Finite element modeling

Finite element model was created for stepped tube hydroforming process as shown in figure 1. The tube diameter of 60 mm was selected as starting material. The model consists of a three-stepped shaft die as in figure 1. According to the dimension of the die, a tube of 60 mm diameter was selected as blank. The mechanical properties of the tube are given in the table 1 and Holloman’s power law hardening model was used as the material model.

![Figure 1. Dimensions of die in mm](image1.png)

![Figure 2. Loading path](image2.png)

3. Simulation design

The simulation methodology adopts the Box-Behnken design which consists of 46 simulation runs with different parameters [5]. Table 2 shows the independent variables and their design levels. On the basis of previous literature, the suitable loading is chosen shown in figure 2 [6]. In this study the response chosen were- (i) Corner radius (CR) - measured from die corner to tube corner and (ii) Strain Non-uniformity Index (SNI), which is the difference between Peak true thickness strain and average true thickness strain [7]. The objective of this study is to minimise both the responses.

Response Surface Methodology (RSM) was used for analysis of numerical data which was performed using a statistical software, Design Expert 9.0.6. To obtain the regression equation, a second order polynomial was fitted to the numerical data.

\[ Y = b_0 + \sum b_i X_i + \sum b_{ij} X_i^2 + \sum b_{ij} X_i X_j + \varepsilon \]  

(1)

| Table 1. Mechanical properties of tube |
|---------------------------------------|
| Mechanical Properties of the tube     |
| Elastic Modulus, E (GPa)              | 200 |
| Poisson’s ratio                       | 0.3 |
| Yield Stress, \(\sigma_s\) (MPa)      | 380 |
| Strength coefficient K (MPa)          | 891 |

| Table 2. Process variables and design levels used |
|-----------------------------------------------|
| Variable                        | Code | Path1 | Path2 | Path3 |
| Loading path                     | A    | 0.15  | 0.1   | 0.05  |
| Coefficient of friction (\(\mu\))  | B    | 0.14  | 0.18  | 0.05  |
| Strain hardening exponent (n)     | C    | 1.2   | 1.6   | 1.05  |
| Anisotropic factor(r)             | D    | 1.5   | 2     | 1.5   |
| Tube thickness (t) (mm)           | E    | 2     | 2.5   | 2.0   |
4. Results and discussion

The simulation was carried out using FEM based PAM-STAMP-2G© implementing to the Box-Behnken design matrix. 30% thinning was selected as the stopping criteria for all the 46 combinations of simulation. The analyses of the measured responses were carried out by using design expert software. It was found that the trend followed by each responses for all the three steps are comparatively closer and therefore the response for only one step will be discussed in this paper. The final mathematical models of each response in terms of coded factors (refer table 2) are mentioned below:

Corner radius \( CR \) = \( 5.51 - 0.2A + 1.45B - 0.71D + 0.27E - 0.017AB - 0.1AC + 0.18BD - 0.12BE + 0.047CD + 0.12A^2 + 0.14B^2 + 0.14D^2 \) (2)

\( SNI \) = \( 0.17 - 0.000584A + 0.016B - 0.00937C - 0.00174D + 0.014E + 0.012AD - 0.00221BC + 0.011BD + 0.005075BE - 0.00225CD + 0.00475CE - 0.00474B^2 - 0.00392C^2 - 0.0055E^2 \) (3)

4.1. Effect of variables on corner radius filling (CR)

Perturbation plot for CR is shown in figure 3 and contour plot depicting the mutual interaction between \( \mu \) and \( r \) on CR is shown in figure 4. Corner radius is plotted by varying only one factor in its range while maintaining other variables constant at the midpoint value of all the factors. It was found that friction is the major factor which is affecting the corner radius. As the higher friction forces resist the metal flow resulting in high corner radius, while larger anisotropic value and strain hardening exponent means easier forming and leads to low corner radius. Smaller corner radius can be produced when using advance feed type loading path (path3) since this will allow more material being pushed through the die at low pressure. However as thickness increases, corner radius found to be higher due to lesser bulge height at higher thicknesses. From figure 4 it can be noticed that smaller corner radius can be obtained at low value of friction and high value of anisotropic factor.

![Figure 3. Perturbation of CR](image)

![Figure 4. Contour graph of \( \mu \) and \( r \) on CR](image)

4.2. Effect of variables on Strain Non-uniformity Index (SNI)

It can be observed from the perturbation plot of SNI as shown in figure 5 that SNI increases with the increase in coefficient of friction as well as tube thickness. This is because the material flow through the die is reduced which leads to non-uniformity in strain in the thickness direction. However, high value of anisotropic factor and strain hardening exponent will generate low value of SNI. The different types of loading paths in this study have not shown any significant effect on SNI. It is evident from the
contour plot shown in figure 6 that low value of SNI is obtained at higher strain hardening exponent and lower friction coefficient.

Figure 5. Perturbation of SNI

Figure 6. Contour graph of μ and n on SNI

5. Conclusion

It was found that the coefficient of friction has a very significant impact on both corner filling as well as SNI. CR and SNI have an inverse relationship on the co-efficient of friction. Material properties like anisotropic factor and strain hardening exponent have positive impact on both the responses. Furthermore, tube thickness has more impact on SNI than corner filling. But loading path does not have much impact on SNI, although it does have an influence on CR. Table 3 shows the effect of each independent variable on both responses in the descending order from left to right.

Table 3. Effect of each variable on response in descending order

| Variables (highest to lowest) | Corner radius | Coefficient of friction(μ) | Anisotropic factor(r) | Strain hardening exponent (n) | Loading path | Tube thickness (t) |
|------------------------------|---------------|---------------------------|----------------------|-------------------------------|-------------|-------------------|
| SNI                          | Coefficient of friction(μ) | Tube thickness(t) | Strain hardening exponent (n) | Anisotropic factor(r) | Loading path |

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