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Multi Level Optimization of Tube Hydroforming Process

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Abstract

In tube hydroforming, the loading path that is the relationship between axial feeding displacement and the internal fluid pressure is major significance. Researchers have employed various optimization approaches to find a better loading path. In this research a statistical method based on finite element analysis has been used. An accurate FEA has been used to simulate the process and find the response of the process to the loadings. The Response Surface Method (RSM) has been used to model the responses from the finite element analysis. The behaviour of the process can be predicted using this model. The optimization of the process is then applied to the model. The thickness variance has been considered as the objective function and the bulge height as the constraint. The optimum loading path found which satisfactory results.

Keywords*:* Tube hydroforming, optimization, response surface method, finite element, metal forming

1 Introduction

Application of hydroforming process in industry dates back to 1990's. The hydroforming process is an excellent method for low cost automobile parts manufacturing. The process is a single step process in which the tube is converted to nearly final product. The advantages of hydroformed parts over the welded and pressed parts are lower weight and higher strength. [1]

In many metal forming processes the achieved strain depend on the loading path and the boundary conditions, which means the formability of the parts in the process is a function of the loading path. Since the stress depends on the strain, in processes such as hydroforming, in which multiple loadings are applied, the amount and the sequence of each load affect the property of the produced part. [2] To obtain the desired shape and properties such as minimum thickness, minimum residual stress and maximum formability, a proper loading path must be established. Trial and error practice is time consuming and expensive.

The combination of optimization approaches, design of experiment, and finite element methods has provided a powerful tool to obtain a final product with the desired properties, amongst which the uniform thickness and maximum formability are the most important properties.

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In recent years many research work have carried out to find the optimum loading path for the tube hydroforming processes [3-8]. Aydemir et. al. [3] have achieved optimum loading path by applying the adaptive simulation approach. Their approach was based on the prediction of wrinkling and bursting, so they selected wrinkling and bursting predicting parameters. In the first step a loading path was selected and both the pressure and axial displacement were applied with a constant slope relative to the time. On occurrence of the wrinkling the slope of the pressure was increased and the axial displacement slope was reduced and vice versa in the case of the bursting. They used fuzzy knowledge based controller for their work and the slope of the loading curves at any time were obtained based on the process condition. Imaninejad et.al. [4] obtained the optimum loading path for the aluminium T shape tube hydroforming using optimization approach and the finite element method. The pressure was increased linearly and the optimization was applied on the axial displacement. The objective function in their optimization approach was minimum thickness variation while the maximum effective stress during the forming process was kept below the material ultimate stress. Ray and Mac Donald [5,6] have used LS-DYNA finite element code to simulate the T and X shape tube hydroforming process along with a fuzzy logic algorithm. The optimum loading path found avoids the failure of the tube during forming process. Koc and Coworkers [7] used a new design of experiment methodology called low cost response surface method to establish guidelines for designing hydroformed parts. They considered the protrusion height as optimization objective subjected to the thinning of wall thickness at the protrusion area. They presented a set of optimum geometrical parameters, such as tube length, die radius and protrusion diameter, for tube hydroforming process.

In this paper the finite element simulation along with Response Surface Methodology (RSM) for design of experiment have been used to construct a model for wall thickness variations and protrusion height as a function of pressure-displacement curve for the T shape tube hydroforming process. The model has been established to predict and to optimize the loading path of a steel T shape tube hydroforming.

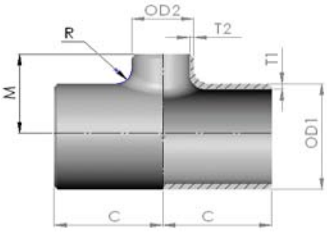
2 The experimental work

The specimen was cut out from a tube with outer diameter is 30mm and its wall thickness is 3.91mm, the length of the specimen was 216 mm. Then the endings were CNC machined. The mechanical properties were obtained and are given in the next section.

The specimen was placed on the hydroforming machine. Axial movement of axial pistons provided the oil-tight sealing after which pressurized fluid and axial feeding were applied.

Fig1*: 2 inches T- shape tube before and after final cutting*

The formed part then was shut blasted and the protrusion was cut in an appropriate height. Fig.1 shows two faultless T shape tubes before and after cutting. The dimensions of die and T shape joint are shown in fig. 2.



The Size (inch)	*Type*	*Dimensions (mm)*				
		C	*M*	*OD1*	*OD2*	*R*
2x2	*Equal*	*64*	*64*	*60*	*60*	*15*

***Fig2:** Dimensions of T shape joint*

3 Finite element modelling

To evaluate a metal forming process, it can be numerically modelled using finite element analysis. A virtual solution for metal forming can be obtained using the finite element modelling, hence reducing the need for large number of experimental tests. The nonlinear dynamic-explicit finite element method (FEM) commercial code, ABAQUS/EXPLICIT 6.4, was used in this study.

The FEM model has been constructed based on T shape tube dimensions in fig.2. The model has been created for three parts, 1) raw tube, 2) rigid die and 3) rigid counterpunch. The study took advantage of part symmetry and ¼ of the T shape die and tube has been modelled. The die has been modelled using ECFM method as presented in [8].

The three dimensional (3D) solid element C3D8R, which is suitable for metal forming and large deformation problems, has been used for tube modelling. The die and the punches have been modelled with rigid element R3D4. The adaptive meshing has been used so it prevents the element distortion. The constructed FE model is shown in fig. 3.

The contact between the tube and the die and punches has been utilized using surface to surface contact algorithm, and it is based on coulomb friction law. In practice nylon is used between tube and the die, therefore the coefficient of friction is set to 0.04 but for the area which the contact is direct the coefficient has been set to 0.1.

The tube material is ASTM A106 steel which is used in gas pipelines and joints. The material has been tested using 600kN ZWIK tensile test machine, the engineering stress-strain curve is illustrated in fig. 4.

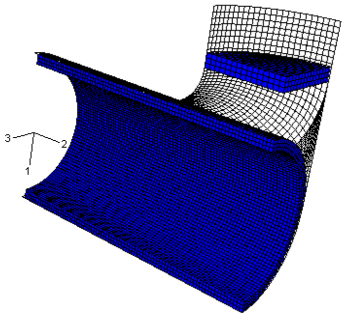


***Fig 3:** FEM simulation of T shape joint*

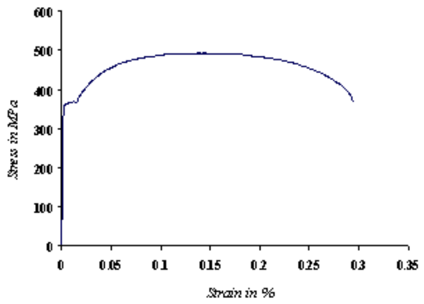


***Fig 4**: The engineering stress-strain curve*

The true stress-strain curve has been obtained and used in FEM simulations. The

Young modulus and Poisson's ratio which have been obtained from the tensile test are 195.5 GPa and 0.31 respectively.

The flow stress of the tube material was obtained by the mentioned tensile test and is expressed by power law as, $\sigma = K\varepsilon^n$ where K= 794.48 MPa is the strength coefficient and n = 0.1711 is the strain hardening exponent.

The loading path was based on the actual production process. The most important loads are the internal pressure and axial feeding of the two ends. The loading path for the process is shown in fig.5. The process time is assumed to be 5 second.

The explicit solution of this problem with fine meshes increases the solution time. The mass scaling technique has been employed to reduce the solution time. In this technique to increase the critical time step, the element density is increased virtually, thus the analysis has been done in less time steps. The nature of the process is quasi static and the inertial or dynamic forces will not affect the process due to the mass scaling. The modelled T shape tube is shown in fig.6.

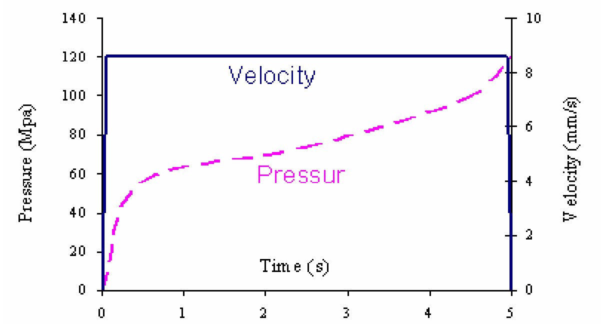


***Fig5:** pistons Pressure and velocity vs. time*

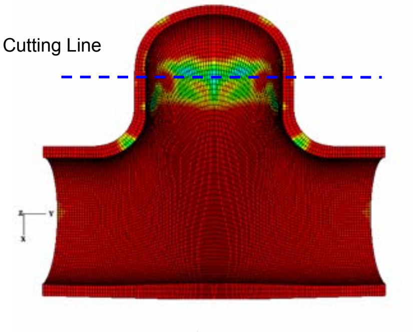
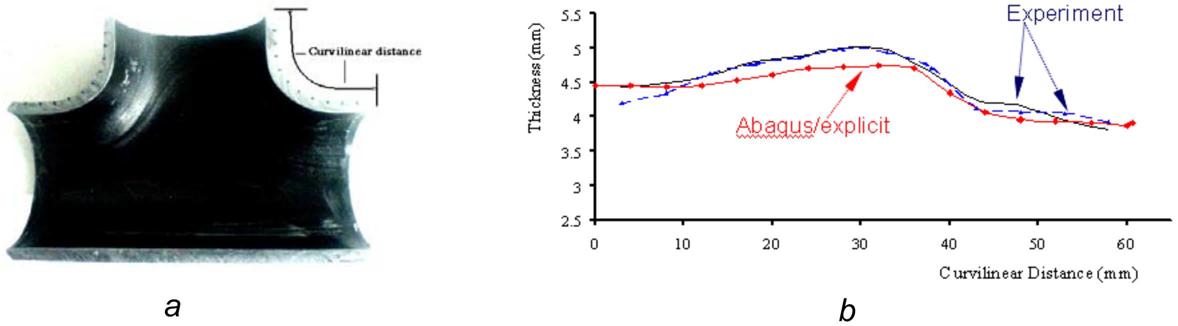


***Fig 6:** Deformed T joint*

To evaluate the solution, the wall thickness and protrusion height have been compared with the product which has been produced with the simulation condition in the Toos Peyvand Company. The T shape tube has been cut through the plane of symmetric as shown in fig. 7a and in eleven points the thickness has been measured. The wall thickness of the T shape tube and the FEM simulation has been compared and are shown in Fig. 7b.



a

b

***Fig7:** a) Cut away part, b) Comparison of the wall thickness in simulation and T shape tube*

4 Optimization and RSM modelling

For any optimization problem an objective function must be defined, which the extreme value (minimum or maximum) of this function has to be found. The most effective parameters which are involved in the objective function are selected as design variables. Sometimes in the metal forming two part quality are in compete with each other, two part quality can not be (or is difficult to) optimize at the same time. [9] As an example, in the hydroforming process of this research, it has been found that the part must have the most uniform thickness variation and maximum formability. Achieving both goals at the same time is possible just by using multiple objective functions where its convergence is difficult. In practice the uniform thickness variation is obtained by applying pressure gradually, but it cause reduction in the protrusion height, In these kinds of situations the most important one are considered as objective function and the others as constraints. Operational research is a branch of mathematics which applies the mathematical and statistical methods in decision making problems and finds the optimum solution. In this research the response surface method (RSM) which is a statistical method has been used.

4.1 The response surface method

The response surface method is a set of mathematical and statistical technique which are useful for modelling of problems with several variables which are influencing the response and the objective is to optimize the response. In this method the responses are obtained experimentally or numerically. [10]

In the design optimization using the RSM, the first step is to specify the model, which can be achieved by finding the objective function and the most important variables which influence the objective function.

4.2 RSM Model

In RSM the responses of the finite element analysis to the inputs are used and the regression analysis is employed to find a model for the data. Assume y to be the observed value of a response variable which depends upon the levels x_1, $x_2,\ldots,x_k$ of some k quantitative factors. The response function is then written as:

$$y = f(x_1, x_2, \ldots, x_k) + \varepsilon \tag{1}$$

Where ε represents the error observed in the response y. If we denote the expected response by $E(y) = f(x_1, x_{2,} \ldots, x_k) = \eta$**,** then the surface represented by $\eta = f(x_1, x_{2,} \ldots, x_k)$ is called a **response surface.**

In most RSM problems, the form of the relationship between the response and the independent variables is unknown. Thus, the first step in RSM is to find a suitable approximation for the true functional relationship between y and the set of independent variables.

If the response is well modeled by a linear function of the independent variables, then the approximating function is the **first-order model.** If there is curvature in the system, then a polynomial of higher degree must be used, such as the **second-order model.** [11]General polynomial response surface models can be written in matrix form as following:

$$\begin{aligned} y &= \boldsymbol{x}\boldsymbol{b}^T + \varepsilon \\ \boldsymbol{x} &= [1, x_1, x_2, \ldots, x_k],\;\; \boldsymbol{b} = [\beta_0, \beta_2, \ldots, \beta_i] \end{aligned} \tag{2}$$

Where *x* is the data matrix and *b* is the parameter vector. To estimate the unknown parameters, a set of data *x* and their responses *y* are provided. Supposing Y and X are the sets of responses and the data matrix, the least square method is used to estimate the unknown parameters as:

$$b = (X^T X)^{-1} X^T Y \tag{3}$$

The response surface analysis is then performed using the fitted surface. If the fitted surface is an adequate approximation of the true response function, then analysis of the fitted surface will be approximately equivalent to analysis of the actual system. Designs for fitting surfaces are called **response surface designs.**

5 Loading path optimization using RSM

In this paper the response surface method have been used to predict T shape responses to the different load path. Loading path is considered as one of the most important parameters that influence the final part properties, such as thickness variation. in this research, in the first step the responses have been modelled by first and second order model. In order to decrease the number of design variable, model was built based on pressure-displacement diagram that is independent of the time. In second step, a multi level response has used to achieve a better result.

5.1 The design of experiments

The design variables in this research are a set of control points on pressure-displacement diagram. In fact these diagrams have been approximated by multi lines curve. Smaller range of variables will results in a better estimation of the optimum point. But it may lead to local optimization, and do not take into account the global optimum point.

5.2 Modelling

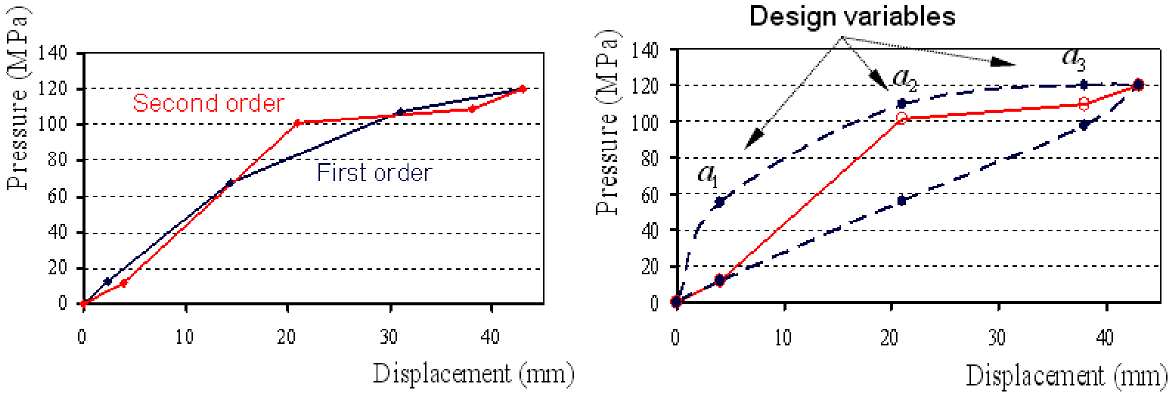
The responses of the finite element simulation to each set of input data (design variables) have been collected. These responses and associated design variables have been used to find the parameter vector using equation (3). Then for both the thickness variation and the bulge height estimated functions have been obtained. For the design of experiments, data collection Matlab/mbc-Model tool box has been employed. The estimated functions for the thickness variation $Var_{est}(x)$, and bulge height, $H_{est}(x)$ are presented for the first order and second order model as followings:

$$\begin{aligned} Var_{est}(x) &= 0.10651 + 0.02186a_1 + 0.03046a_2 + 0.00921a_3 \\ H_{est}(x) &= 87.0308 + 1.67861a_1 + 2.90454a_2 + 0.797463a_3 \end{aligned} \tag{4}$$

$$\begin{aligned} Var_{est}(x) &= 0.060262 + 0.019314a_1 + 0.01415a_2 + 0.0058083a_3 + 0.0050442a_1^2 + \\ &0.012303a_1a_2 + 0.0012335a_1a_3 + 0.016837a_2^2 + 0.0027846a_2a_3 + 0.002246a_3^2 \\ H_{est}(x) &= 82.2376 + 2.27731a_1 + 3.43772a_2 + 0.940528a_3 + 0.0780611a_1^2 + \\ &0.123933a_1a_2 + 0.0320083a_1a_3 + 0.381811a_2^2 + 0.156075a_2a_3 + 0.0825278a_3^2 \end{aligned} \tag{5}$$

5.3 Optimization of the model

The mentioned estimated functions (4) and (5) have been used to find the optimum point for the model. The thickness variation (Var_{est}) has been considered as objective function for the optimization process. The bulg height (H_{est}) that must be bigger than H_{min} and the range of design variables [$a_{i\min}$, $a_{i\max}$] has been used as constraints. MsExcel/Solver has been used to minimise the objective function subjected to the constraints. The optimum loading paths have been presented in Fig. 8a. Fig. 8b has presented the optimum loading path of second order and compared with the ranges of the design variable.



a

b

Fig8: *a) The design variables and their ranges b) predicted loading path*

One can see that the first control point is on the lower boundary and therefore it tends to be lower than the obtained value. Hence another level of optimization has been applied and the ranges of the design variables have been adjusted to find a better estimation for the loading path. Based on the new ranges of the design variable, the RSM has been applied to the problem. In the second level optimization, the RSM model is built as a second order, so 27 simulation test is needed. The following equations indicate response surfaces for the thickness variation and the bulge height. Fig. 9a, also shows compare the optimum loading path for the second level with the design of variable ranges.

$$\begin{aligned}
&Var_{est}(x) = 0.05126 + 0.003808a_1 + 0.004828a_2 + 0.002302a_3 + 0.0009339a_1^2 + \\
&0.0008917a_1a_2 \ -0.0001142a_1a_3 + 0.0006254a_2^2 - 6.5748\text{e-}0.005a_2a_3 + 0.0005249a_3^2 \\
&H_{est}(x) = 82.2 + 0.44078a_1 + 0.5699a_2 + 0.2537a_3 + 0.0007554a_1^2 + \\
&0.02273a_1a_2 + 0.01798a_1a_3 + 0.05066a_2^2 + 0.01236a_2a_3 + 0.01749a_3^2
\end{aligned} \tag{6}$$

6 Conclusion

By comparing the two optimum loading paths in first level optimization, fig. 8a, it can be conclude that the obtained optimum points are the global point, since the paths are close to each other. In order to improve the accuracy of the optimum model, in this research multi level RSM have been employed for second order model, which has been discussed in the section 5.3.

To verify the predicted models, FEM simulation has been applied using the optimum loading paths. The percentage of difference for the thickness variations between RSM models prediction and the FEM simulations are 4.75% for first order, 3.30% for second order and 0.02% for multi level RSM. The bulge height has the same trend as mentioned above. As it can be seen the results have been improved by using the second order model, since the nonlinear surface has been used. The second level RSM improved the prediction since the ranges of the design variable has been smaller.

The influences of the optimum loading paths on the thickness variance have been shown in fig 9b. As can be seen the wall thickness variations has improved from 0.153 for real part to 0.053 for the predicted optimum loading path obtained from the second level. The optimization process can be continued for another level, but since the optimum curve locate in the variables ranges, and differences between the thickness variation for the last two levels is less than 0.001mm, one can conclude that the optimum loading path is obtained.

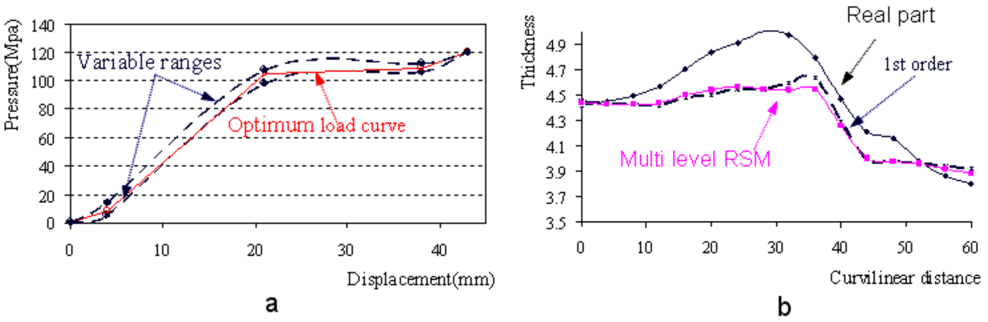


Fig9: *a) Final optimum loading path for 2nd level b) Thickness variation for RSM models*

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