An Investigation into the Optimization of Loading Path in T-shape of Tube Hydroforming

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Abstract. This paper addressed the modeling and optimization of loading path in T-shape hydroforming of tubes using Simulated Annealing (SA) algorithm. Analysis of variance shows that some of pre-selected parameters in loading paths have not significant effect on the deformed tube. Hence, some of optimized parameters found initially, are replaced with their own fixed optimum values in order to seek for the other parameters in more detail by the Simulated Annealing (SA) algorithm. According to the intensity of effectiveness on the deformation, six more important parameters are chosen and their minimum and maximum limitation values are determined. In this case, sixty four different tests for different loading paths are designed by Design of Experiment (DOE) and full factorial method. By using mathematical modeling all required loading parameters are obtained. Proposed models of formability embedded into Simulated Annealing algorithm and optimum value for loading parameters and optimal load paths are found. The obtained results show that more accurate loading path may be found for T-shape of tube hydroforming.

Keywords: Hydroforming, Loading path, DOE, Full Factorial, Regression, Optimization, Simulated Annealing.
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INTRODUCTION

In order to reduce the weight of structures without reduction in their strength, hollow parts have been widely used especially in the automotive and aerospace industries. Hence, hydroforming of thin-walled structures is attractive for manufacturing of hollow shape. The advantages of hydroforming compared with classical manufacturing processes include improved part quality, dimensional accuracy the possibility of design of complex cross section. However, the hydroforming technology is still new and it suffers some drawbacks such as lack of knowledge base, slow cycle time and expensive equipment. Production of a product with high quality depends on some factors such as loading path, material formability and lubrication conditions. The loading path here, however, has a more significant roll. There are three loading paths in this process include, internal pressure, axial feeding and counter punch displacement versus time. Appling proper loading parameters in this process has a main role on the formability and can prevent typically defects such as wrinkling, thinning or bursting. Adjusting the loading conditions in tube hydroforming is known as design of load paths and many researchers have tried to find the ways to make the products by optimal loading curves. Koc [1] generated simple design rules on geometrical and process parameters in tube hydroforming process. Kang [2] studied forming limit diagrams in tube hydroforming under combination of internal pressure and axial feeding. Narasimhan [3] investigated the effect of loading conditions on stress and strain histories on tubular hydroforming. Zhang [4] proposed a new method combining genetic algorithm with finite element simulation to obtain the optimal forming parameters. Abedrabbo [5] used an optimization method linked with a finite element method to develop loading parameters in tube hydroforming process. In this study, the optimum conditions of loading parameters were investigated by using of design of experiment (DOE) with combination of finite element simulation.

In this paper, firstly all loading parameters in T-shape hydroforming are determined. Then using Analysis of Variance (ANOVA) loading parameters with lower effect are eliminated. After that, sixty four load paths based on Full Factorial method are designed. For each set of loading path the tube hydroforming process is simulated in Abaqus/Explicit. Finally, the formability of tube versus loading parameters is estimated by a proper mathematical model in statistical software and with the aid of these models, optimum values for each parameter are determined by Simulated Annealing (SA) algorithm.

FINITE ELEMENT SIMULATION

Abaqus/Explicit software is used to simulate T-shape tube hydroforming and to investigate the effects of different loading conditions. To verify the results of simulation model, they are compared with experimental data found by Hwang [6]. Half of the used model is shown in Fig. 1.

The material parameters (AA6063-T5) are chosen for simulation and it is considered to be anisotropic. The material model assumed to be as $\overline{\sigma} = 181.09\overline{\varepsilon}^{0.318}$ MPa and the Hill anisotropy model is used for considering of tube anisotropy. The simulation conditions are the same as experimental model used by Ref. [6]. Both ends of tube and axial punches can only move in axial direction. Die is fixed in all degree of freedom and the counter punch can move perpendicular to tube axis. Shell element (S4R) and rigid element (R3D4) are used for meshing the tube and tools, respectively. The comparison between the obtained results and the experiment data showed a good agreement; hence this model was selected for further investigation for the effects of loading path.

PROBLEM STATEMENT

Three pre-assumed load paths for internal pressure, axial punches and counter punch are selected to be applied for T-shape tube hydroforming [7] as are shown in Figs 2-4.

There are five possible variables inside the internal pressure curve which can be optimized potentially. These parameters are, yield pressure (P_{yield}), time interval of yield pressure (T_{yield}), expansion pressure ($P_{expansion}$), time interval of expansion pressure ($T_{expansion}$) and final pressure (P_{final}). However, further studies showed the yield pressure can be fixed at a specific value. In the current study it is taken equal to 2.5 MPa.

Figure 3 shows that three parameters can be chosen for further investigations in the axial punch load path including displacement of first stage (S_{middle}), time interval of first stage (T_{middle}) and final displacement (S_{final}).

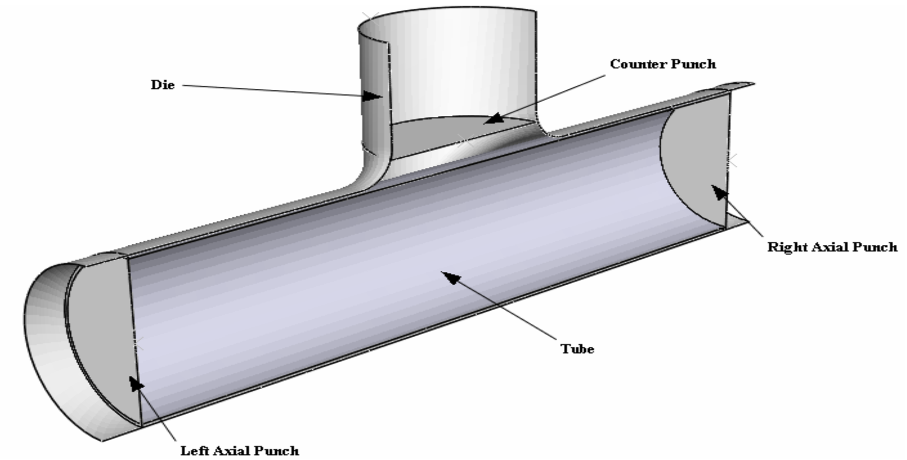

FIGURE 1. Half of finite element model.

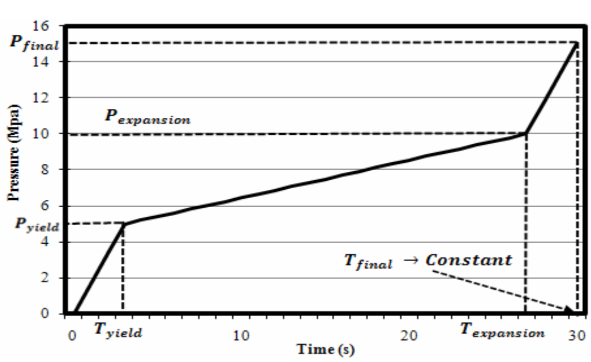

FIGURE 2. Internal pressure path with five variables.

Finally, based on Fig. 4 the potential variables for counter punch may be introduced as starting time (T_{start}), first place of counter punch (CP_s), stopping time (T_{stop}) and final place of counter punch (CP_f).

Based on these three diagrams 11 different variables can be selected for optimization process. Moreover, for each variable a lower and upper bound can be found based on experience data as shown in Table 1 [7]. It must be noticed that, there are totally 2^{11} possible load paths which is unrealistic to be investigated. Hence, the design of experiment method (DOE) may be applied to design the minimum required proper experiments. Using this method, 32 load paths are designed based on Taguchi and 2 level experiments method. From the applied thirty two different paths, four sample paths of internal pressure are shown in Fig. 5.

In order to investigate the tube formability, the minimum tube thickness and maximum height of T-branch are considered as indicators. Using these load paths in Abaqus/Explicit and analyzing the process will give the results for minimum thickness and maximum height as they are already reported by the authors [7]. The percentage effects of all aforementioned variables are examined for the minimum thickness and maximum height of T-branch in Figs.6 and 7, respectively. Based on Analysis of Variance (ANOVA) it is found that some loading variables have not so significant effect on the outputs. To optimize the process more effectively, those variables are replaced with their optimum values [7].

Five insignificant variables are eliminated and the other six more important variables with their bounds are listed in Table 1.

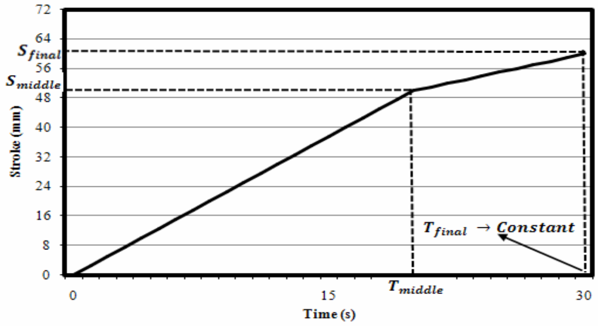

Figure 3. Axial punch path with three variables.

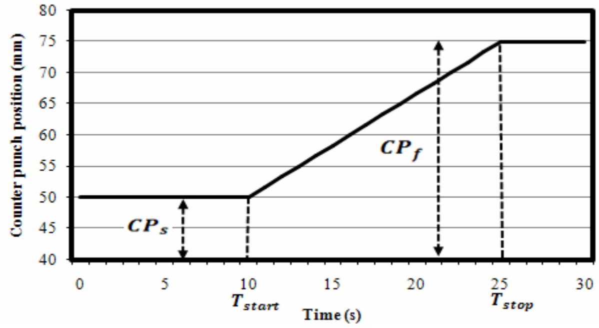

Figure 4. Counter punch path with four variables.

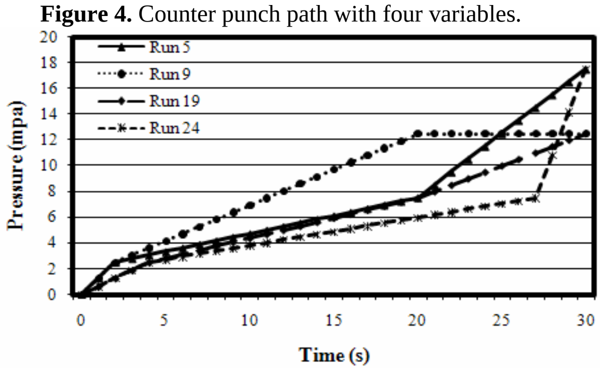

Figure 5. Four sample paths of internal pressure designed by Taguchi method.

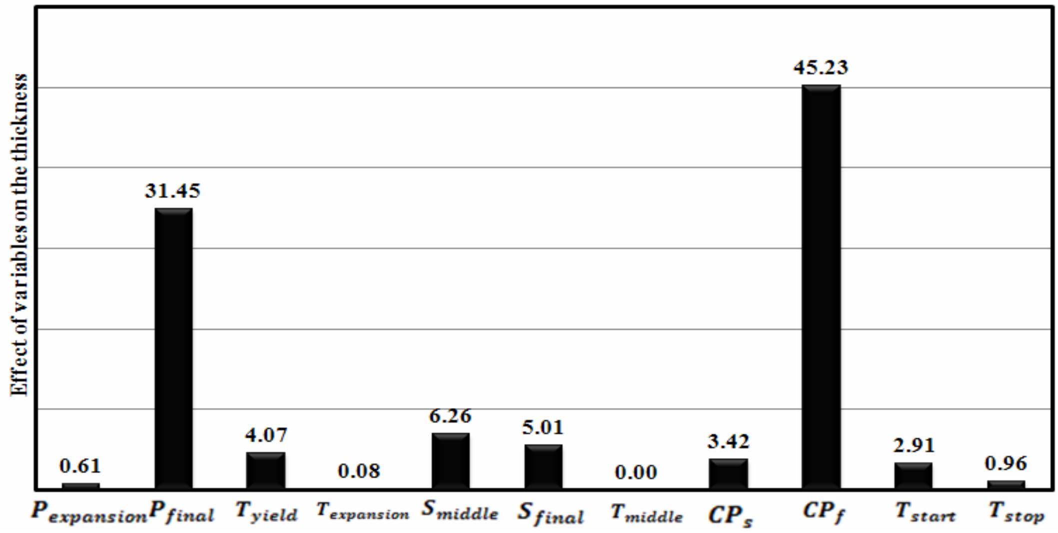

Figure 6. The percentage of effect of different parameters on minimum thickness.

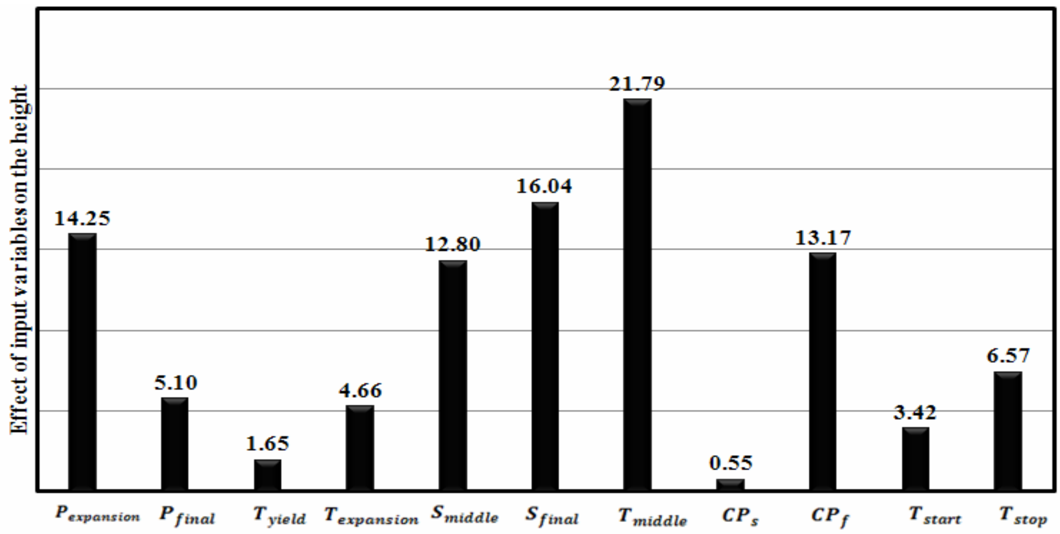

Figure 7. The percentage of effect of different parameters on maximum height.

Table 1. Selected loading variables for further investigation for optimal design of load paths.

No	Factor	Unit	Notation	Minimum Level (-)	Maximum Level (+)
1	Expansion pressure	Mpa	P_{expan}	7.5	11
2	Final pressure	Mpa	P_{final}	12	14
3	Initial axial punch displacement	mm	S_{middle}	50	56
4	Final axial punch displacement	mm	S_{final}	61	65
5	Time step of axial punch	s	T_{middle}	23	27
6	Final place for counter punch	mm	CP_f	74	80

DOE BASED ON FULL FACTORIAL METHOD

Because there are now only six effective variables, it would be possible to consider all conditions of loading parameters. These conditions are determined by Full Factorial method and 64 load paths are designed. Then, the effect of each load path is simulated by Abaqus/Explicit and the values for minimum thickness and maximum height are calculated, Table 2.

REGRESSION MODELS

In order to evaluate the tube formability for the different loading variables, it is required to find a relation between the minimum thickness and maximum height and six loading parameters. Each output can be expressed by a function of linear, curvilinear, stepwise or logarithmic forms. Choosing a model to optimize the loading variables properly depend on the nature of problem and the required accuracy. In the current study, the regression technique and the linear and curvilinear functions in Minitab software are used to fit the data in Table 2. These models for each output can be stated as follows;

Linear models

Thickness = $3.28 - 0.00638\, P_{expan} - 0.00898\, P_{final} + 0.00180\, S_{middle} + 0.00605\, S_{final} - 0.00535\, T_{middle} - 0.0121\, CP_f$ (1)

Height = $-24.3 + 0.440\, P_{expan} + 0.136\, P_{final} - 0.160\, S_{middle} + 0.477\, S_{final} + 0.289\, T_{middle} + 0.394\, CP_f$ (2)

Curvilinear models

Thickness = $11.6 - 0.191\, P_{expan} + 0.0555\, P_{final} - 0.0357\, S_{middle} - 0.123\, S_{final} - 0.0412\, T_{middle} - 0.0727\, CP_f + .00237\, P_{expan} P_{final} + 0.000074\, P_{expan} S_{middle} - 0.000469\, P_{expan} S_{final} - 0.000558\, P_{expan} T_{middle} + 0.00251\, P_{expan} CP_f + 0.000026\, P_{final} S_{middle} + 0.00184\, P_{final} S_{final} - 0.00020\, P_{final} T_{middle} - 0.00258\, P_{final} CP_f + 0.000820\, S_{middle} S_{final} + 0.00118\, S_{middle} T_{middle} - 0.000582\, S_{middle} CP_f - 0.00131\, S_{final} T_{middle} + 0.00129\, S_{final} CP_f + 0.000820\, T_{middle} CP_f$ (3)

Table 2. Full Factorial table with output results.

No	P_{expan}	P_{final}	S_{middle}	S_{final}	T_{middle}	CP_f	T (mm)	H (mm)
1	+	+	-	-	-	-	2.53	39.18
2	-	-	-	+	+	+	2.51	42.97
3	-	+	-	-	+	-	2.54	39.4
4	-	-	+	+	+	+	2.51	41.83
5	+	+	+	+	+	-	2.53	41.12
6	+	+	-	+	+	+	2.45	45.03
7	+	+	+	-	+	-	2.52	39.03
8	+	+	-	+	+	-	2.5	41.49
.	.	.	.	.	.	.	.	.
58	+	-	+	+	-	+	2.52	42.86
59	-	-	+	+	-	+	2.51	40.75
60	-	-	+	-	+	-	2.58	38.05
61	+	+	+	+	+	+	2.49	44.53
62	+	+	+	+	-	+	2.51	42.57
63	-	-	-	+	-	+	2.53	41.91
64	+	+	+	+	-	-	2.57	40.19

$$\textbf{Height} = 195 - 1.91\,P_{expan} - 1.72\,P_{final} - 0.740\,S_{middle} - .66\,S_{final} - 0.886\,T_{middle} - 2.18\,CP_f - 0.0421\,P_{expan}\,P_{final} + .00298\,P_{expan}\,S_{middle} - 0.0142\,P_{expan}\,S_{final} + 0.00920\,P_{expan}\,T_{middle} + 0.0442\,P_{expan}\,CP_f + 0.0056\,P_{final}\,S_{middle} - 0.0086\,P_{final}\,S_{final} + 0.0170\,P_{final}\,T_{middle} + 0.0268\,P_{final}\,CP_f + 0.0102\,S_{middle}\,S_{final} + 0.00245\,S_{middle}\,T_{middle} - 0.00288\,S_{middle}\,CP_f - 0.00547\,S_{final}\,T_{middle} + 0.0257\,S_{final}\,CP_f + 0.0141\,T_{middle}\,CP_f \quad (4)$$

Determination of proper models for output

As mentioned, the appropriate model is selected based on the better attainable accuracy. First, the requirement of residuals independency is checked and if the distribution of residuals has a specific shape then it means that the selected model is not proper and a higher degree of regression should be used [8]. The distributions of residuals of maximum height for linear and curvilinear models are shown in Figs. 8 and 9. It can be observed that the residuals distribution has a V-shape form for a linear model; however, the residuals distribution has not any specific shape for a non-linear model.

Another way to investigate the accuracy of model is based on the Correlation Factor. This factor is calculated by summation of square of residuals and is evaluated from 100%. As the factor become closer to 100% the accuracy of model is better. The correlation factors for the thickness and height for two regression models listed in Table 3. It can be observed that the curvilinear model is superior to linear model for both outputs. Therefore curvilinear models could predict better behavior formability of tube by application of different loading parameters.

These models provide a relationship between the loading parameters and outputs and can be used to predict the formability of tube under different loading parameters and also to determine the optimum set of loading parameters for a good formability of tube. In this study, the two curvilinear models are used for construction of objective function and calculate the optimum input.

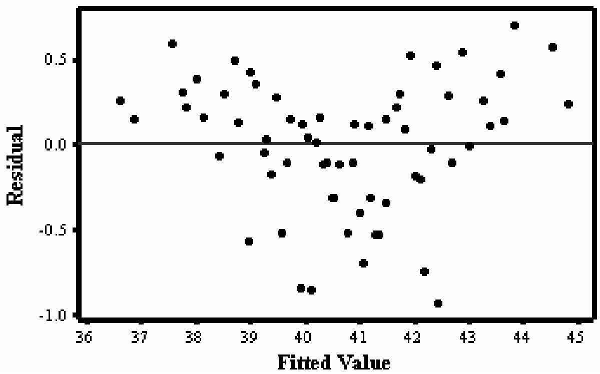

Figure 8. Residuals distribution of height for linear model.

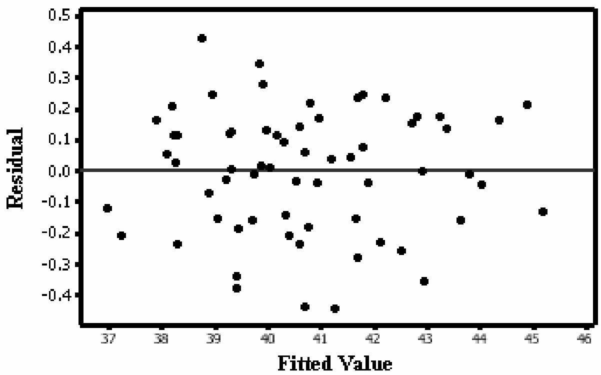

Figure 9. Residuals distribution of height for quadratic model.

Table 3. Correlation factors for proposed models**.**

Model	Thickness	Height
Linear model	72.7%	96.0%
Curvilinear model	92.3%	98.9%

OPTIMIZATION

In practical situation, in order to gain a desired formability for tube in hydroforming process it is required that the loading parameters are adjusted precisely. The mentioned two mathematical models give us a good opportunity to find the optimum set of these variables and in turn a proper load path. To do so, the above non-linear Equations 3 and 4 must be solved simultaneously. The evolutionary algorithms are a powerful optimization technique which can be used for solving these kinds of problems. Simulated Annealing (SA) is one of these algorithms and it is used for optimizing of loading parameters in current study. This algorithm was proposed originally by Kirkpatrick [9] and inspired by metallurgical annealing process. In this algorithm an objective function which has a form of error function is defined. In the current study it is constructed based on two functions as follows;

$$f = \frac{\left(T_{\exp} - T\right)^2}{T_{\exp}} + \frac{\left(H_{\exp} - H\right)^2}{H_{\exp}} \tag{5}$$

Where T_{exp} and H_{exp} are calculated by Equations 3 and 4, respectively and T and H are desired values which are selected by designer.

The proposed SA code is written in Matlab and the obtained convergence rate of the algorithm is shown in Fig. 10. Five sets of optimum parameters are calculated and the best set with the smallest error is selected, Table 4. The obtained optimal loading parameters based on SA and FEA results are compared to each other in Table 5.

The final shape of formed tube gained by the application of optimum load paths is shown in Fig. 11 which is formed by internal pressure of 12 MPa. It is found that the pressure has decreased 20% while the thinning percent improved, simultaneously. For instance, the maximum thinning percent was 14% in the experimental model [6] while it reduced to the 9% after applying the optimum load paths in this study, moreover the height of branch also increased slightly compared to the experimental one (from 41.9 to 42.23mm).

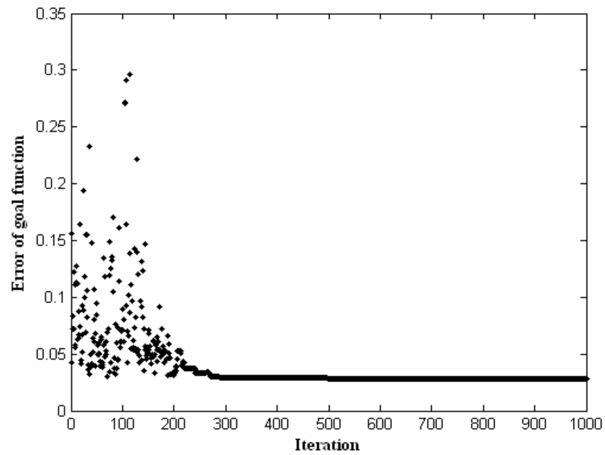

Figure 10. Convergence rates for SA algorithm**.**

Table 4. Optimal loading parameters 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}
9.7	12	2	24.5	50	65	23	56	78	9.5	30

Table 5. Comparison of results between SA and Abaqus**.**

SA		Abaqus	
T (mm)	H (mm)	T (mm)	H (mm)
2.59	42.18	2.545	42.23

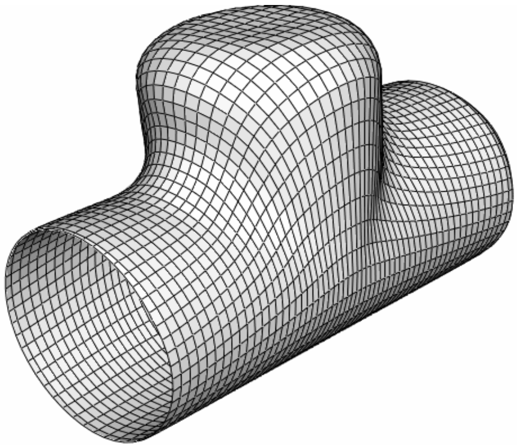

Figure 11. The final shape of formed tube gained by optimal loading paths.

CONCLUSION

A new technique for investigating of optimal load path in T-shape tube hydroforming was presented. First by using of analysis of variance (ANOVA) some loading variables which had not significant effect on the formability were eliminated and replaced with their own fixed optimum values that obtained by Simulated Annealing (SA) algorithm. Based on the intensity of effectiveness on the deformation, six parameters with new bounds were determined. Then, sixty four load paths were designed by DOE and Full Factorial methods. After simulating the process for each load path, the formability of tube was evaluated by mathematical modeling and regression method. Then the proposed models were embedded in SA algorithm to seek for optimum values of each load parameters. Finally, after determination the optimum variables the optimal load paths were designed. The comparison between the formability results of the optimal load path and the experimental results proves the efficiency of this method for determination the optimum load paths in tube hydroforming process.

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