International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 12 (2017) pp. 3416-3425
© Research India Publications. http://www.ripublication.com

Development of Empirical Model for Tube Hydroforming Process using RSM

Bathina Sreenivasulu[1]
Assistant Professor, Department of Mechanical Engineering,
Madanapalle Institute of Technology and Science, Madanapalle. Andhra Pradesh., India.

Dr. G. Prasanthi[2]
Professor, Department of Mechanical Engineering, JNTUA College of Engineering,
Anantapuramu, Andhra Pradesh., India.

[1]ORCID: 0000-0002-5995-9908, Researcher ID: O-5166-2016, Scopus Author ID: 56297245800

Abstract

Tube hydroforming Process (THP) is a new forming technology to produce complex tubular components in minimum number of phases. In this process the pressurized fluid and axial feed by axial plungers is used to produce the required geometry. The components which are developed by the tube hydroforming technique are structurally superior and stiff.

The present study is to establish an empirical model for tube hydroforming process using simulation and experimental results. And also investigated and analyzed the effect of the various input parameters on the output responses. Annealed Inconel600 tubes with the diameter of 57.15mm and thickness 1.45mm are deformed to investigate the control variable. Tubes are simulated using DEFORM-3D FEM tool.

Many number of control variable are involved in tube hydroforming process. From the previous research study and pilot experiments, it has been noticed that the internal pressure (IP), axial feed (AF) &Tube Length (TL) has predominant effect on the process. Hence, IP, AF & TL are considered as input and influencing parameters. After various pilot experiments on annealed Inconel 600 tubes, the ranges and level of each process parameter are noted.

To minimize the expenditure on process, material and to minimize the time, FEM tool DEFORM -3D is used to analyze the effect of various parameters on tube hydroforming. Taguchi L27 orthogonal array is selected to minimize the number of simulation to analyze the process variables with same accuracy.

After successful simulation runs, the RSM (Response Surface Methodology) is applied to develop a numerical model to the responses. Further, the developed mathematical models are further for further to optimization the THP.

Keywords: Tube Hydro forming process, FEM simulation, annealed Inconel 600, Response surface methodology.

INTRODUCTION

Global wise Tube hydroforming process is becoming more popular forming technique due to its capabilities to form various tubular components with high strength. Now a days, all manufacturing industries are showing attention on THP as the process having ability to manufacture the difficult tubular products in single phase with better mechanical and structural properties.

THP is an advanced forming process, in this process, deforms different hollow tubular cross-sections to a predefined shape of section of using hydraulic pressure and axial force. Stepped hollow shafts, metallic bellows, automobile chassis components and radiator supports are some of the application of the tube hydroforming.

[1] Many advantages find in THP than routine manufacturing process like welding, machining, and stamping process such as: (i) Weight reduction, (ii) Controlled wall thinning, (iii) Low tool cost, (iv) Better structural strength and stiffness, (v) minimizing secondary phase operations, (vi) better dimensional accuracy, and (viii) low wastage.

Figure 1. illustrates the working principle of THP. Annealed Inconel 600 tubes are inserted in between the two half of free bulge test die and the two ends of the tube are sealed by two axial plungers moving along the tube axis. Initial axial load applied on the ends of the tube for sealing of the tube as applied high pressure liquid is supplied inside the tube. The internal pressure is applied inside the tube to deform the tube. This hydraulic pressure is applied uniformly throughout internal side of the tube. The axial forces increase further to achieve better thickness control.

University Grant Commission (UGC-India) for provided financial support through minor research project grant (Proposal N0. 6099/15.

Internal pressure is increased in THP until the tube expands to required shape or wall meets the inner surface of the die cavity. The process steps in THP are illustrated in the figure no 1. In this, the tub is place in between the die. By controlling the input factors, it is possible to produce quality products by the THP by avoiding various failures such as buckling, wrinkling, or bursting.

To minimize the difficulties during the tube hydroforming process, it requires, the analysis of various process parameters and its effect on the output response of tube hydroforming to judge the quality of the process. Due to this reason, selected this process for further investigation.

The quality of components which are produced by THP depends selection loading path i.e. combination of internal pressure and axial movement. The present research includes that the exploration of the effect of input parameters on the formability.

Free bulge test THP is conducted using FEM tool DEFORM 3D, different simulation run was conducted to study and analyze the effect of input process parameters on the output responses.

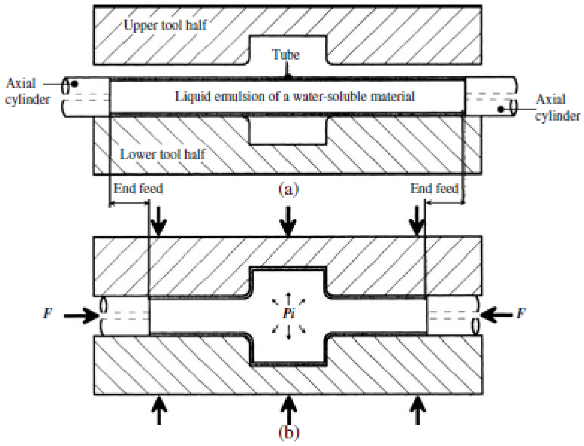


Figure 1: Tube Hydroforming Process (THP)

The main aim of the free bulge hydroforming is to test the hydro-formability of the tubular material. For this investigation, maximum bulge ratio without any failure is taken as one of the output response. Along with the above objective, another objective has considered as minimum thinning ratio.

The proposed methodology for the current investigation is to develop a numerical relation using FEM simulation using DEFORM 3D and Design Expert 10. This empirical model can be used further for development of objective functions.

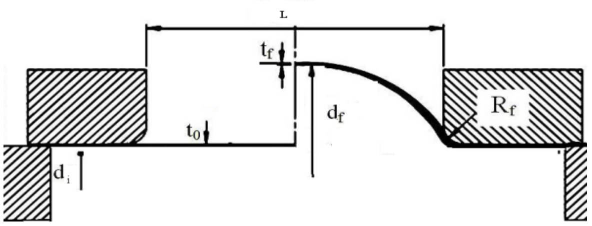


Figure 2: Free Bulge Tube Hydroforming process.

To perform the tube hydroforming operation correctly and accurately, it is necessary to investigate the relation of process parameters, geometrical dimensions and material properties to output response. Since, there is no explicit relationship between forming severity and load path, it is very difficult to perform a sensitivity analysis by analytical methods [2].Due to the high expanse for experimentation and to save the time numerical simulations are applied as it is an effective tool and less expensive to analyze the effect of process parameters on the tube hydro-formability.

Asnafi [3] and Asnafi and Skogsgardh [4] was established an analytical model to investigate the sensitivity of the tube hydroforming process with respect to material properties, geometrical and process parameters during free forming stage. Chen and Ngaile [5], the effect of pressure on the formed shape, thinning of the tube and corner filling was studied and analyzed and developed an analytical model with bending effect.

Manabe and Amino [6] numerical simulation was carried using a FEM tool out to investigate the influence of process parameters and material properties on THP. Number investigator are studied on THP and developed various method for THP to simplify the tube hydroforming process for suitable to industry. Honggang [7] et al, developed a method and defined the optimum process parameter for the square cross section die.

Carleer et al. [8] investigate the anisotropy and hardening exponent influence on hydroformed tubes and concluded the above two parameters having considerable effect on expansion of the tube in THP. Using Finite Element Method, Boudeau et al. [9] used FEM to investigate the influence of material properties, process parameter success of the process and also concentrated on the failure analysis.

Die geometry is one of the major factor, it effects the quality of the THP. Ko and Altan [10] investigated the effect of geometry of the die on the quality of THP using 2D FEM tool and concluded that the internal pressure and tube length having more effect on the bulge of an axisymmetric tube.

Yang et al. [11] studied the effect of pressure and axial load on tube hydroforming process and defined a mathematical relation between input factors and output responses. Performing more number of trail experiments or simulation to study the process parameter effect on the THP is not suggestible as THP is more expansive and time consuming and it is not economically justified. Taguchi method is one of the alternative method to minimize the number of experiments to study the effect of the process parameters on the THP without affecting the quality of the analysis. Taguchi method was applied to metal forming area [12–16].

In current research, L27 Taguchi orthogonal array is selected for analysis of tube hydroforming process. DEFORM 3D explicit FEM tool to simulate the tube hydroforming process at 27 distinguished conditions. After successful simulation runs the output response are noted. Further, these simulation data are used for modeling of the tube hydroforming process. Using RSM (Response Surface Methodology), the THP was modeled. The adequacy of the obtained model was tested using Analysis of variance (ANOVA). Regression Coefficient (R2) is used to the adequacy of the predicted model. After confirm the adequacy of the model, these models will be used for further optimization of the THP. The effect of internal pressure, tube length and axial feed on the output responses such as bulge ratio and thinning ratio are analyzed and plotted using Design Expert 10 software. In the present investigation die, axial plungers and tube are modeled using AutoCAD 16 and exported to DEFORM 3D and tube material is selected as Inconel 600 and properties of the material is given as annealed INCONEL600. The dimensions of the die, axial plunger and tube are match with the dimension of the experimental setup at the IIT Mumbai, India.

The novelty in this research is that only a very few researchers worked on the super alloys hydroforming applications and comparisons has made between simulation and experimentation.

SIMULATION PROCESS

FEM simulation of tube hydroforming process using DEFORM 3D includes various steps. First step, solid modeling of various components such as upper and lower die, axial plungers and the tubular blank. The geometry of the all components are matched with geometry of experimental setup which is located at Indian Institute Technology, Bombay, India to verify the experimental and simulation results. In the present investigation all solid models and the tooling assembly structure are created using Auto CAD 2016. All of solid models are then converted in to the suitable formats such that the simulation solver should understand [1]. CAE engineers need to create the simulation-related models for the given deformation system like physical model, mathematical model and numerical model. The boundary and initial conditions, geometry constraints have to be predefined. The type of elements, mesh density and solution parameters are describes by numerical model.

Computer aided engineering (FEM based) simulation process includes four steps

(a) Preprocessing: create or import the geometry, definition of material, meshing, finalizing the boundary conditions, declaration of the number of steps, stopping criteria, providing input parameters et.,

(b) Simulation process: The solver runs the simulation to execute the FEA.

(c) Post processing: After completion of simulation is display in the post processor.

(d) Results analysis and evaluation: All the results received from the post processor, are analyzed and evaluated.

The simulation results received from the DEFORM 3D are compared with the experimental data. The results which are received from the simulation are not acceptable, then appropriate modifications have to be made in terms of part design and modeling, tool geometry and design, process conditions, material and its properties, and re-simulate the process are agreed with experimental results.

Solid Modelling:

Various parts such as upper and lower die, two axial plungers and tubular blanks with three different lengths are modelled with dimensions same as the experimental setup using AutoCAD 16 and are shown in below figures 3-6. Geometrical details of the die and tube are given in table 1.

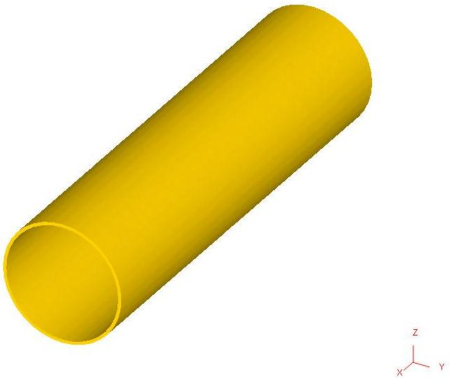
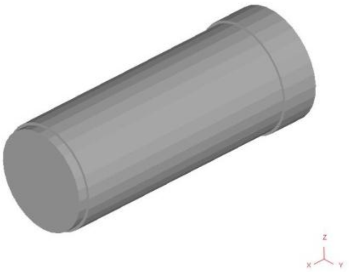
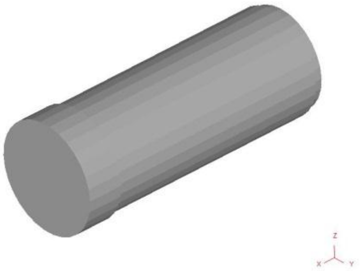


Figure 3: Tube blank CAD model

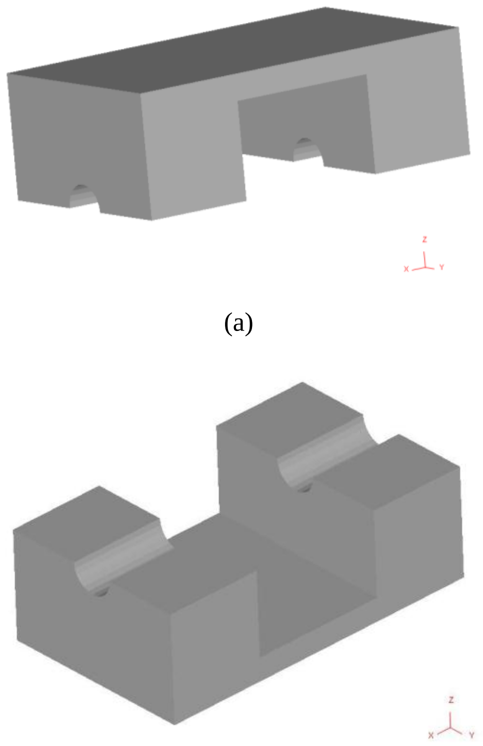


(a)



(b)

Figure 4: (a) Right and (b) Left axial plunger CAD models



(a)

(b)

Figure 5: (a) Upper and (b) Lower die CAD Models

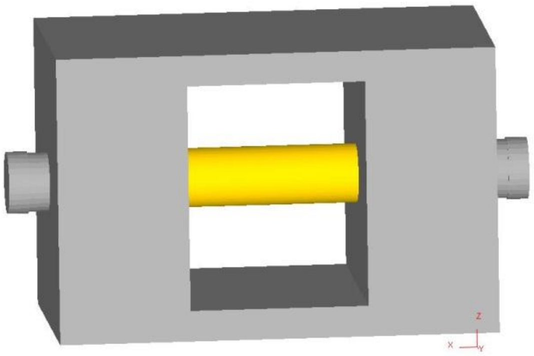


Figure 6: Assembly of die along with axial plunger and tube

TABLE 1. GEOMETRICAL DETAILS OF DIE AND TUBE

Die Geometrical Details	
Total length of the die	L_d
(Die length parallel to the tube axis)	
Total Width of the die	b
(width perpendicular to the tube axis)	
Radius of the corner at forming zone	R
Free Length of the Die	L_f
Tube Geometrical Details	
Tube External Diameter	di
Tube Length	L_1, L_2, L_3
Tube Thickness	T_i

All dimensions of the die and axial plungers are same as the experimental die setup shown in figure 7. The simulations for the free bulge test of a straight tube is performed using DEFORM 3D and the simulation runs has conducted at various conditions as per the Taguchi's L27orthogonal array on the INCONEL 600 tube.

Presently, INCONEL 600is considered as the tube material. This material having superior properties like resistant to corrosion, heat and oxidation since it is a nickel based super alloy. This material exhibits high tensile strength and good creep properties.

Figure 7. Experimental die setup

Detail of the chemical composition of the stated material are noted in table 2. Table 3 illustrated the mechanical properties of the tubular material.

TABLE 2. CHEMICAL COMPOSITION OF ANNEALED INCONEL 600

Element	Ni	Cr	Fe	Mn	Cu	Si	S	C
Percentage	72.31	16.54	9.90	0.14	0.017	0.4	0.001	0.012

TABLE 3. TENSILE PROPERTIES OF THE TUBE MATERIAL

0.2% proof load(KN)	Ultimate load(KN)	0.2% proof stress (MPa)	U.T.S (MPa)	Modulus (MPa)	%of elongation
3.02	9.55	174	549	153084	41.64

The aim of free bulging THP is to test the hydro-formability in terms the maximum possible bulge without any defects. To study the bulge, bulge ratio denoted by d_f/d_i is taken output responses. To investigate the variation in the thickness during the bulge, another output response selected is the thinning ratio. The thinning and the bulge ratio are two output responses considered. The thinning ratio is defined by

$$Thinning\ ratio = \frac{t_o - t_f}{t_o}$$

$$Bulge\ ratio = \frac{d_f}{d_i}$$

Where t_o and t_f are the original and final thicknesses before and after the THP, d_i *and* d_f are the initial and final diameters of the before and after bulge tube hydroforming as shown in Fig. 2.

From literature study, internal pressure, axial movement and tube length are most effecting input parameters on the bulge and thinning ratio. Due to this reason, the above parameters are taken as the decision variables and trial experiments were conducted to find the working range of input parameters. Two levels such as maximum and minimum levels are coded with +1 and -1. The middle level of each factor is coded with '0' and calculated using following expression (1).

$$X_i = \frac{2[2X - (X_U + X_L)]}{(X_U - X_L)} \qquad (1)$$

Here, X_L X_U represents the minimum level and X_U represents the maximum level. X_i denotes is intermediate level coded value of each parameter X. X is a value between X_L to X_U of each process parameter. For the current investigation all process parameter, its ranges and units are shown in the table 4.

TABLE 4. RANGES AND LEVELS PROCESS PARAMETERS OF TUBE HYDROFORMING

Process parameters	Units	Notation	Low level (-1)	Centre level (0)	High level (+1)
Internal Pressure (P)	Bar	x_1	230	250	270
Axial Movement (AM)	mm/sec	x_2	0.2	0.35	0.5
Length of the Tube (L)	mm	x_3	195	210	225

FEM simulation has done at 27 different process conditions as per Taguchi L27 orthogonal array. The 27 different process conditions are showing in table 5.

TABLE 5. L27 ORTHOGONAL ARRAY FOR SIMULATION TUBE HYDROFORMING

Run	X_1:Internal pressure	X_2:Axial force	X_3:Length
1	230	0.2	195
2	230	0.2	210
3	230	0.2	225
4	230	0.35	195
5	230	0.35	210
6	230	0.35	225
7	230	0.5	195
8	230	0.5	210
9	230	0.5	225
10	250	0.2	195
11	250	0.2	210
12	250	0.2	225
13	250	0.35	195
14	250	0.35	210
15	250	0.35	225
16	250	0.5	195
17	250	0.5	210
18	250	0.5	225
19	270	0.2	195
20	270	0.2	210
21	270	0.2	225
22	270	0.35	195
23	270	0.35	210
24	270	0.35	225
25	270	0.5	195
26	270	0.5	210
27	270	0.5	225

METHODOLOGY

Figure. 8 explains that the current methodology and discussed about various steps of the proposed methodology in further sections. Many number of variables are effects the hydroforming process. Among these variables, the significant variables are determined by the literature and from the trail experiments. To minimize the computational difficulty, only significant process parameters are considered for the analysis

[17]. DOE is used to minimize the time, material and cost for the process. Using DOE, Taguchi L27 simulation runs are selected to analyze the process without effecting accuracy

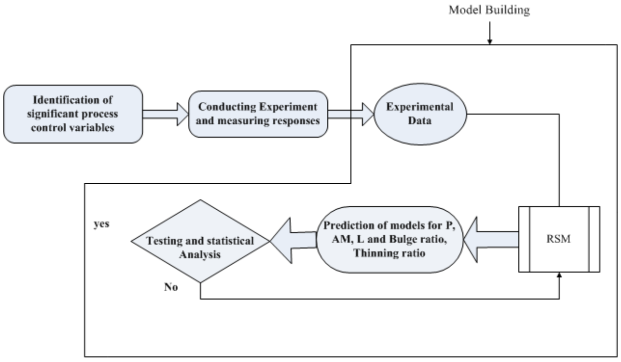


Figure 8. The flow chart of the proposed methodology.

Response Surface Methodology (RSM):

The RSM is a mathematical tool to investigate the relationships between input factor of the tube hydroforming process to process responses. By applying the regression analysis on the experimental results, it produces a model of output responses to some individual factors.

All the independent input parameters of the process are denoted in quantitative form as shown in the following equation

$$Y = f(X_1, X_2, X_3 ....X_n) \pm \varepsilon \quad (2)$$

Here X_1, X_2,X_3, ……X_n are the independent input parameters, *Y* is the output response and *f is* its function. The main aim of RSM is to approximating the function *f* using appropriate lower order polynomial in some region of the independent input parameters. If the outcome is well defined by a linear model of the input parameters, the expression (2) can be rewrite as the linear model (2):

$$Y = C_0 + C_1 X_1 + C_2 X_2 + ...C_n X_n \pm \varepsilon \quad (3)$$

However, if a curvature appears in the system, then a higher order polynomial such as the quadratic model may be used and expressed as follows (4)

$$Y = C_0 + \sum_{i=1}^{n} C_i X_n + \sum_{i=1}^{n} d_i X_i^2 \pm \varepsilon \quad (4)$$

The goal of the RSM is to explore the responses within the limits of process parameters and also to find the province of interest where the out responses reaches its optimum or near optimal value [1].

Response Surface methodology Procedural steps:

Various sequential steps of RSM are described below [18-22]:

1. The initial step involved in RSM is establishment of design of experiments to conduct appropriate experiments or simulations to found reliable responses.
2. Development of a numerical model of the second order response surface with the best fittings.
3. Locating the optimal set of experimental or simulation tube hydroforming process parameters that provides the high or low value of output response.
4. Represent the influence of the input factor on the response both directly and the interactively using2 dimensional and 3 dimensional graphs.

Design of Experiments (DOE):

The initial and important step in RSM is DOE after finalizing the problem statement. As per the previous research, number of experimental designs are existed such are Full Factorial Designs, Fractional Factorial Designs, Latin-square Designs, Box-Behnken Designs, Central Composite Designs (CCD),V-Optimal Designs, A-Optimal Designs, G-Optimal Designs, D-Optimal Designs.

From the above experimental designs, one among them has to be selected based on the requirements and constraints. For the present research work, Central Composite Designs (CCD) is chosen to finish the experiments and simulation runs.

Central Composite Design (CCD)

One of the popular experimental design for response surface methodology is central composite design.

The CCD has3 sets of design points and are listed below

- Factorial points,
- Star or axial points,
- Center points.

All points in CCD are defined in terms of coded values like -1, 0, 1 are shown in the figure 9. CCD are intended to approximate the coefficients of a quadratic model.

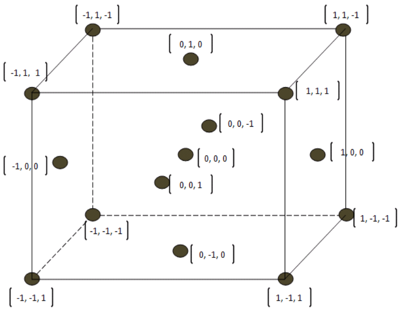


Figure 9. Illustration of Points in central composite design

Factorial Points :

In 3 level and 3 factor experimental design, all levels of the factors are code with -1, 0, and 1. Here '-1' represent the low level of the factor and '1' or '+1' represent the high level of the factor and '0' the intermediate value. All possible combinations of the levels (coded values -1, 0 and 1) o each factors are included in three level factorial design. All corners of the cube in the figure represent factorial points. There are eight factorial design points possible for a 3-factor case in central composite design as shown in figure 9. Following are the eight combinations of this design.

(1, 1, -1) (1, -1, -1) (-1, -1, -1) (-1, 1, -1) (1, 1, 1) (1, -1, 1) (-1, -1, 1) (-1, 1, 1)

Star or Axial Points:

Star points or axial points are found at center of each face of the cube and are showing in figure 9. The other name for this design is face centered CCD. Following are the 6 possible combinations of this design.

(0, 1, 0) (0, 0, -1) (1, 0, 0) (-1, 0, 0) (0, 0, 1) (0, -1, 0)

Center Points :

Center points represent the points when all level of each factors are set to 0 that is intermediate point of each factor. This is represented as (0, 0, 0) shown in figure 9.

RESULTS & DISCUSSION

Bulge and thickness are measured and calculated bulge and thinning ratios from the bulge and thinning ratio expressions after successful simulation runs at different conditions and are noted in table 6.

TABLE 6. TUBE HYDROFORMING RESPONSES AT DIFFERENT CONDITIONS.

Run	Internal pressure	Axial force	C:Length	D_f/D_i	$(T_i-T_f)/T_i$
1	230	0.2	195	1.125	0.2335
2	230	0.2	210	1.1556	0.2361
3	230	0.2	225	1.1054	0.2343
4	230	0.35	195	1.2416	0.21874
5	230	0.35	210	1.2182	0.2242
6	230	0.35	225	1.2216	0.2305
7	230	0.5	195	1.2904	0.2172
8	230	0.5	210	1.2871	0.2325
9	230	0.5	225	1.2225	0.23071
10	250	0.2	195	1.3265	0.2456
11	250	0.2	210	1.3242	0.2642
12	250	0.2	225	1.3273	0.2746
13	250	0.35	195	1.3513	0.2462
14	250	0.35	210	1.3352	0.2584
15	250	0.35	225	1.3046	0.2692
16	250	0.5	195	1.3352	0.2285
17	250	0.5	210	1.3145	0.2425
18	250	0.5	225	1.3526	0.24242
19	270	0.2	195	1.5865	0.27069
20	270	0.2	210	1.4597	0.2846
21	270	0.2	225	1.4389	0.3015
22	270	0.35	195	1.4697	0.2495
23	270	0.35	210	1.4521	0.2643
24	270	0.35	225	1.4067	0.28168
25	270	0.5	195	1.4524	0.2368
26	270	0.5	210	1.5415	0.2468
27	270	0.5	225	1.5286	0.2719

Development of Empirical models:

After successful completion of simulation runs for tube hydroforming at 27 different conditions, the output responses such as bulge and thinning ratio are collected and used to employed the proposed methodology. The aim the present methodology is to finding the mathematical relationship between out puts to the process parameters is to optimize tube hydroforming.

Design Expert10 V is a statistical analysis tool [15]. Using Design Expert, regression coefficients of the proposed modes are computed.

Analysis of variance (ANOVA):

Using quadratic model, analysis of variance is carried out. The statistical data of analysis of variance for the bulge ratio is noted in table 7 and for thinning ratio is noted in table 8. From previous study, it is noted that the value of "prob. > F" is less than 0.05 then the model which is proposed is treated as significant. From the 7 and 8, it is observed that the values of "prob. > F" are lesser than 0.05. in all instance for the proposed model and this indicate that the proposed models [16] are significant. The obtained equation for the above models are represent in the equation 4 and 5.

$$\frac{d_f}{d_i} = +1.32 + 0.11x_1 - 0.061x_2 - 0.16x_3 + 0.047x_1x_2 + 0.26x_1x_3 - 0.066x_2x_3 - 0.046x_1^2 + 0.066x_2^2 - 0.16x_3^2 \quad (5)$$

$$\frac{t_0 - t_f}{t_o} = +0.20 - 0.020x_1 + 0.0848x_2 + 0.010x_3 - 0.013x_1x_2 + 0.038x_1x_3 + 0.0954x_2x_3 - 0.013x_1^2 + 0.13x_2^2 - 0.037x_3^2 \quad (6)$$

TABLE 7. ANALYSIS OF VARIANCE [PARTIAL SUM OF SQUARES] FOR DF/DI

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	1.80	9	0.20	45.30	< 0.0001*
A-Internal pressure	0.20	1	0.20	45.32	< 0.0001
B-Axial force	0.068	1	0.068	15.33	0.0011
C-Length	0.47	1	0.47	106.61	< 0.0001
AB	0.026	1	0.026	5.99	0.0256
AC	0.80	1	0.80	180.41	< 0.0001
BC	0.052	1	0.052	11.71	0.0033
A2	0.013	1	0.013	2.91	0.1065
B2	0.026	1	0.026	5.95	0.0260
C2	0.15	1	0.15	33.51	< 0.0001
Residual	0.075	17	4.419E-003		
Cor Total	1.88	26			
Std. Dev.	0.066			R-Squared	0.9229
Mean	1.14			Adj R-Squared	0.8821

* - Refers to Significant terms

Acceptability or adequacy test :

The obtained empirical models from the ANOVA are tested for their acceptability

Multiple regression coefficients (R^2):

The acceptability or adequacy test using regression coefficient is one the popular method. R^2 is calculated to authenticate that whether the fitted models actually describe the experimental or simulation data. The quality of the fit for the obtained model is generally expresses in terms of R^2[16].The multiple regression coefficient $R^2$is defined as the ratio of variability given by the model and total variability in the experimental or simulation data. From the literature, if regression coefficient value i.e. R^2 value is nearer to 1, then the obtained model is fits for the experimental or simulation data.

The regression coefficient R^2 in the table 7 for the bulge ratio is obtained 0.9229 which is closer to 1(unity) and which is noticed that the 2nd-order model can illuminate the variation in bulge ratio up to the extent of 92.29%.

From Table 8, it is noticed that regression coefficient $R^2$is 0.8821 for the thinning ratio. This shows, the 2nd–order model can illuminate the variation in thinning ratio up to the extent of 88.21%.

The adjusted R^2 is used to provide opportunity to estimate a further appropriate estimation of R^2 value. Using expression 7, the adjusted R^2 value is to be computed.

$$Adjusted\ R^2 = 1 - \frac{[(1-R^2)(N-1)]}{N-K-1} \quad (7)$$

Here, N stands for number of observations and K stands for total number of predictors. R^2 is depends on N and K. If value *N* is smaller and *K* is larger, then the variation between R^2 and adjusted R^2 is larger (since*(N-1) / (N-K-1)* << 1). In other hand, if value *N* is very large and *K* is small, then the variation between the R^2 and adjusted R^2 is very minimum, that means the value of R^2 is much closer to adjusted R^2 value (since*(N-1) / (N-K-1)* is closer to 1).

It is noticed that form the table 7 for the bulge ratio the R^2 and adjusted R^2 values are 0.9929 and 0.8821 which are closer to each other.

Whereas for the thinning ratio from the table 8

It is observed that the R^2 and adjusted R^2 values are 0.9611 and 0.9405. the variation between R^2 and adjusted R^2 is very minimum.

From the ANOVA statistics of the bulge ratio and thinning ratio, it is observed that the values of R^2 and adjusted R^2 are closer to each other and the variation is minimum. This means that the model which is developed can represent the process adequately.

TABLE 8. ANALYSIS OF VARIANCE [PARTIAL SUM OF SQUARES] FOR (TI-TF)/TI

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	0.15	9	0.016	49.38	< 0.0001*
A-Internal pressure	7.438E-003	1	7.438E-003	22.66	0.0002
B-Axial force	1.297E-003	1	1.297E-003	3.95	0.0632

C-Length	1.932E-003	1	1.932E-003	5.89	0.0267
B	1.971E-003	1	1.971E-003	6.00	0.0254
AC	0.017	1	0.017	51.54	< 0.0001
BC	1.093E-003	1	1.093E-003	3.33	0.0857
A2	1.036E-003	1	1.036E-003	3.16	0.0936
B2	0.11	1	0.11	322.24	< 0.0001
C2	8.425E-003	1	8.425E-003	25.67	< 0.0001
Residual	5.580E-003	17	3.283E-004		
Cor Total	0.15	26			
Std. Dev.	0.018			R-Squared	0.9611
Mean	0.26			Adj R-Squared	0.9405
* - Refers to Significant terms					

Further, the adequacy of the developed model is validated using normal probability plot of residuals. The normal probability plots are plotted to validate where the data is normally distributed and for any assumption is violated. If the all data points are distributed closer to the line in normal probability plot, then it is considered that the normality of the developed model is feasible. If the data points are spattered away from the line, then normality of the developed model is treated as not feasible.

The normal probability plots of the residuals for bulge ratio and thinning ratio are shown in figure 10 and figure 11 respectively. These plots are used to assess the model adequacy.

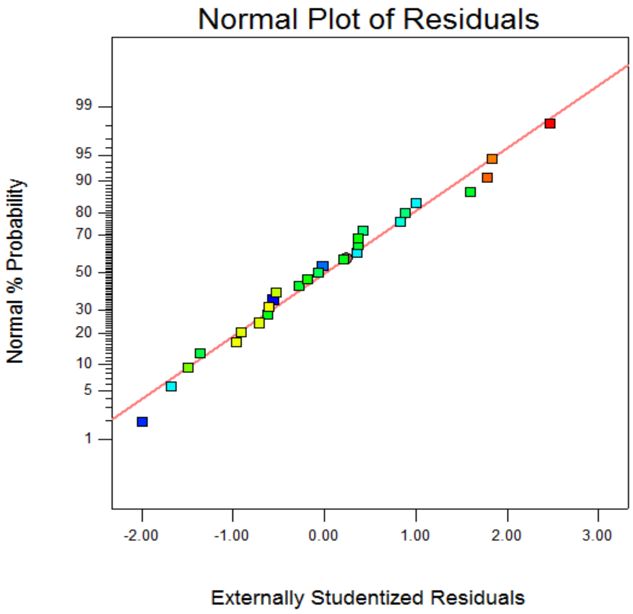


Figure 10: Normal probability plot of residuals for df/di

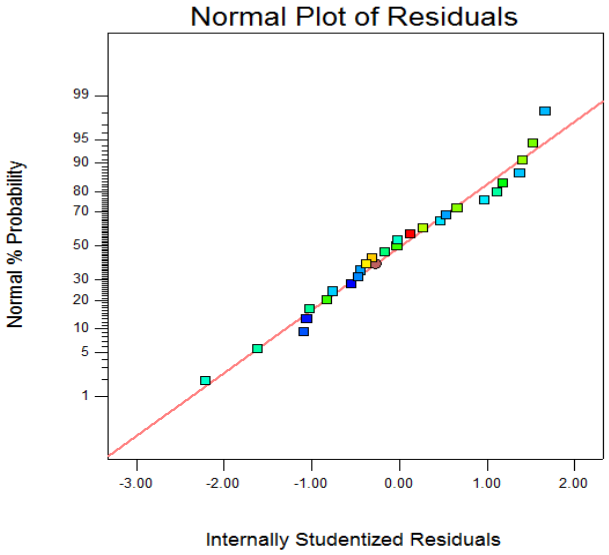


Figure 11: Normal probability plot of residuals for $(to-t_f)/to$

It can be noticed that from Figure 10 and 11, all data points are distributed nearer to line, from this it can be understand that the errors are distributed normally and the normality of the developed model is treated as fishable. Hence, the developed empirical models are considered significant. Hence, these numerical model can be used for further optimization of the hydroforming process parameters.

CONCLUSIONS

Tube hydroforming is one of the advanced forming technique to form difficult tubular components in a single phase. Even many number advantages like structural properties, minimum number of secondary operation etc. with tube hydroforming, but industries still facing the problems to use hydroforming technique like selection of optimum process parameters. In present research bulge ratio and thinning ratio are taken as the quality characteristics to verify the quality of TFP. At initial stage of tube hydroforming, one of the crucial stage is the selection of input factors since these are show a major role to achieve better bulge ratio and thinning ratio.

Therefore, it requires the development of a methodology to find the optimum process parameter. In present investigation internal pressure, axial feed and length of the tube are taken as process parameters to achieve desired product quality as these are more significant. In this research mainly focused on development of empirical models for the input process parameters by using simulation data.

Equation 4 and 5 are the two numerical model which are developed in this investigation. From the table 7 and 8, it observed that the R^2 values for bulge ratio and thinning ratio are found to be 0.9929 and 0.9611 which are very close to 1. That designates that the developed models can be used for further analysis and optimization. The normal probability plots are also plotted between the process parameters and the output responses. Hence, this methodology for tube hydroforming can be used to automated the process.

ACKNOWLEDGMENT

The authors are thankful to the MITS, Madanapalle, AP, India for supporting cooperation for successful completion this research and also thankful to University Grant Commission (UGC) for providing financial support through minor research project grant (Proposal N0. 6099/15).

REFERENCES

[1] G. Santosh Kumar • B. Sreenivasulu, (2012), A Generative CAPP System for Tube Hydro Forming, Journal of The Institution of Engineers (India): Series C (January–March 2012) 93(1):1–25

[2] Honggang An & Daniel E. Green &Jennifer Johrendt (2010), “Multi-objective optimization and sensitivity analysis of tube hydroforming”, Int J Adv Manuf Technol, 50:67–84

[3] Asnafi N(1999), “Analytical modeling of tube hydroforming ”. Thin Walled Struct 34:295–330

[4] Asnafi N, Skogsgardh A (2000), “Theoretical and experimental analysis of stroke-controlled tube hydroforming”. J Mater Sci A279:95– 110

[5] Yang C, Ngaile G (2008), “Analytical model for planar tube hydroforming: prediction of formed shape, corner fill, wall thinning, and forming pressure”. Int J Mech Sci 50:1263–1279.

[6] Manabe K, Amino M (2002),“Effects of process parameters and material properties on deformation process in tube hydroforming”. J Mater Process Technol 123:285–291

[7] Ahmetoglu e Altan, Ahmetoglou, M., Altan, T.,(2000), " Tube hydroforming: state-of-the-art and future trends ", Journal of Materials Processing Technology, vol. 98, 25-33.

[8] An Honggang, D.E. Green, J. Johrendt, (2010), Multi-objective optimization and sensitivity analysis of tube hydroforming simulations, Int.J. Advanced, Manufacturing Technology, DOI: 10.1007/s00170-009-2505-x

[9] Carleer B, Kevie G, Winter L, Veldhuizen B (2000) Analysis of the effect of material properties on the hydroforming process of tubes. J Mater Process Technol 104:158–166

[10] Boudeau N, Lejeune A, Gelin JC (2002) Influence of material and process parameters on the development of necking and bursting in flange and tube hydroforming. J Mater Process Technol 125–126:849–855

[11] Ko M, Altan T (2002) Application of two dimensional (2D) FEA for the tube hydroforming process. Int J Mach Tool Manuf 42:1285–1295

[12] Yang J, Jeon B, Oh S (2001) Design sensitivity analysis and Optimization of the hydroforming process. J Mater Process Technol 113:666–672

[13] Park K, Kim Y (1995) The effect of material and process variables on the stamping formability of sheet materials. J Mater Process Technol 51:64–78

[14] Lee SW (2002) Study on the forming parameters of the metal bellows. J Mater Process Technol 130–131:47–53

[15] Ko D, Kim D, Kim B (1999) Application of artificial neural network and Taguchi method to perform design in metal forming considering workability. Int J Mach Tool& Manuf 39:771–785

[16] Yang HJ, Hwang PJ, Lee SH (2002) A study on shrinkage compensation of the SLS process by using the Taguchi method. Int J Mach Tool Manu 42:1203-1212

[17] B. Sreenivasulu, Dr. G. Prasanthi (2017), “Empirical modeling & Analysis of Tube Hydroforming process of annealed Inconel600 using Response Surface Methodology” Int J of Mechanical and Mechotronics Engineering, vol: 17, 127-133

[18] Jae-Seob Kwak., “Application of Taguchi and response surface methodologies for geometric error in surface grinding process”, Int J of machine Tools & Manufacturing, 45:327–334, 2005.

[19] Box G.E.P., Draper N.R., “Empirical model-building and response surfaces”, New York: John Wiley & Sons, 1987

[20] Myers R.H., Montgomery D.C., “Response surface methodology”, Wiley, New York, 1995.

[21] Montgomery D.C., “Design and analysis of experiments”, 5th edition, John Wiley & Sons, INC, New York, 2003.

[22] Design Expert, 7.1.3v, Stat-Ease Inc., 2021 E. Hennepin Avenue, Suite 480, Minneapolis, 2006.