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DOE Approach for THF Process to Reduce Number of FEA Simulations through LCRSM

L.Dattatreya[*1], K.Vishali[2], Parthasarathy Garre[3]
[*1,2] B.Tech Student, Aeronautical Department, MLRIT, Hyderabad, India
[3] Associate Professor, Aeronautical Department, MLRIT, Hyderabad, India
gps.mlrit@gmail.com

Abstract

The manufacturing process of hydro formed parts is in direct relevance to engineers attempting to build some aircraft and automobile parts. A newly proposed design of experiments technique was presented to predict the protrusion height of "Tee-shaped" hydroformed parts. Low Cost Response Surface Method (LCRSM) was utilized to facilitate the economical prediction and optimization of this height as a function of geometrical parameters subject to thinning of the wall thickness at the protrusion region. The same methodology is also proposed for the economical investigation of other geometries and conditions. As a result of this study, not only were known and expected trends of effect of parameters verified, but also numerical values within a practical range of parameters at certain conditions were obtained. In addition, interactions between factors were also revealed as predicted. Moreover, this information was gained from a substantially reduced number of finite element analysis simulations through low cost response surface method compared to standard response surface method or factorial techniques, avoiding costly physical experimentation.

Keywords: DOE, FEA, LCRSM, THF.

Introduction

Tube hydroforming (THF), is the application of internal fluid pressure to force the tube that has been cut or formed to fit the die cavity into the deformation zone with or without end feeding, is a relatively new technology for making lighter and stronger products [1]. Tube hydroforming is a process of forming closed section; hollow parts with different cross sections by applying an internal hydraulic pressure in conjunction with end axial feed to a straight or preformed tube. It is a relatively new technology among metal forming processes, which has been developed for a few years and is now being widely used for manufacture of tubular parts of different configurations for automotive, aerospace and household applications [2]. Since THF processes involve so many variables, process planning and tool design is much more difficult compared with that for conventional metal processes. For complicated deformation analysis, FEM is a very useful tool, both for process optimization and for remedial work [3]. FEM used to analyze the plastic deformation of tubes inside a simple sectional die during tube hydroforming and to discuss the effects of stress ratio, friction coefficient, n-value, and anisotropic parameter r-values upon the wall thickness distribution and the fracture location of the formed tube during hydroforming using combined axial load and internal pressure [4]. Design of experiments (DOE) has become an important methodology that maximizes the knowledge gained for experimental data by using a smart positioning of points in the space. The methodology provides a strong tool to design and analyze experiments; it eliminates redundancy observations and reduces the time and resources to make experiments. DOE is a statistical technique useful in complex physical processes, such as determination of geometrical dimensions, shapes, selection of material combination in many design processes [5]. It is quite expensive to experimentally validate THF process and thus finite element simulation alone can provide a valuable insight, after conducting simulation for the process, DOE was selected to determine the optimum branch height of the copper tubehydroforming [6]. The optimization of process parameters for any process can be investigated using response surface methodology (RSM). Choosing relevant parameters from the previous study of THF, the experimental data were fitted into a quadratic polynomial model using

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multiple regression analysis. The optimum process conditions can be determined by analyzing response surface three-dimensional surface plot and contour plot and by solving the regression model equation with Design Expert software [7]. The low cost response surface methods (LCRSM) is which typically require half the experimental runs of standard response surface methods based on central composite and Box Behnken designs but yield comparable or lower modeling errors under realistic assumptions. In addition, the LCRSM methods have substantially lower modeling errors and greater expected savings compared with alternatives with comparable numbers of runs, including small composite designs and computer-generated designs based on popular criteria such as D-optimality. Therefore, when simulation runs are expensive, low cost response surface methods can be used to create regression meta-models for queuing or other system optimization. The LCRSM procedures are also apparently the first experimental design methods derived as the solution to a simulation optimization problem. For these reasons, we say that LCRSM are “for and from” simulation optimization [8].

THF Process

Tubehydroforming (THF) is a process of forming hollow parts with different cross sections by applying simultaneously an internal hydraulic pressure and axial compressive loads to force a tubular blank to conform to the shape of a given die. Geometry of die and workpiece, initial tube dimension, tube anisotropy, and internal pressure are of the important parameters in this process. With the advancements in computer control and high-pressure hydraulic systems, this process has become a viable method for mass production, especially with the use of internal pressure of up to 6000 bars. Tube hydroforming offers several advantages as compared to conventional manufacturing processes. These advantages include part consolidation, weight reduction through more efficient section design, improved structural strength and stiffness, lower tooling cost due to fewer parts, fewer secondary operations (no welding of sections required and holes may be pierced during hydroforming), and tight dimensional tolerances. Despite several benefits over stamping process, THF technology is still not fully implemented in the aerospace and automotive industry due to its time-consuming part and process development. In THF, compressive stresses occur in regions where the tube material is axially fed, and tensile stresses occur in expansion regions. The main failure modes are buckling, wrinkling and bursting. It is clear that only an appropriate relationship between internal pressure curve versus time, and axial feed curve versus time, so called Loading Paths (LP), guarantees a successful THF process without any of the failures. Hydroformed tubular parts vary over a wide range of shapes. This variety goes from a simple bulged tube to an engine cradle with multiple part features such as bends, protrusions, and complex cross sections. Figure 1 shows some types of parts which are produced in this process.

Figure 1. Tube hydroformed parts: (a) cylindrical stepped tube, (b) conical stepped tube, (c) rectangular stepped tube, (d) bellows

The increasing application of hydroforming techniques in automotive and aerospace industries is due to its advantages over classical processes as stamping or welding. Particularly, tube hydroforming with various cross sectional shapes along the tube axis is a well-known and wide used technology for mass production, due to the improvement in computer controls and high pressure hydraulic systems. For production of low-weight, high-energy absorbent, and cost-effective structural automotive components, hydroforming is now considered the only method in many cases. The principle of tube hydroforming is shown in Figure 2. The hydroforming operation is either force-controlled (the axial forces vary with the internal pressure) or stroke-controlled (the strokes

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vary with the internal pressure). Note that the axial force and the stroke are strongly interrelated (see figure 2). The hydroforming operation comprises two stages: free forming and calibration. The portion of the deformation in which the tube expands without tool contact, is called free forming. As soon as tool contact is established, the calibration starts. During calibration, no additional material is fed into the expansion zone by the axis cylinders. The tube is forced to adopt the tool shape of the increasing internal pressure only.

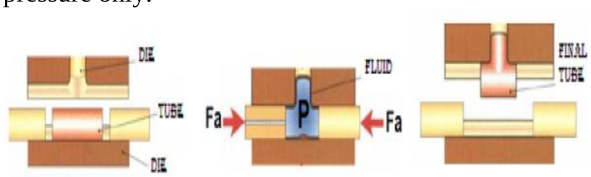

Figure 2. The principle of tube hydroforming: original tube shape and final tube shape (before unloading).

Some typical applications are manufacture of angled X- and T-branches and connectors, stepped hollow shafts, exhaust manifolds, automobile cross members, axle tubes, engine cradles, roof headers, radiator supports, metal bellows, missile cones, nozzles etc. Due to various distinct advantages of the process over conventional manufacturing processes, the use of this technology has increased drastically over recent years. The process provides a number of advantages in comparison with conventional manufacturing via stamping and welding such as: (a) part consolidation resulting in weight reduction of the component, (b) weight reduction through more efficient section design and tailoring of the wall thickness, (c) reduced tooling cost, (d) improved structural strength and stiffness, (e) less number of secondary operations, (f) reduced dimensional variation, (g) significant reduction in spring back effects and, (h) reduced scrap rate.

FEA Simulations

Finite element analysis (FEA) has been commonly used in numerical simulation of hydroforming. Even during the experimental prototyping phase, FEA is used to optimize the process design. Necessary modifications of the dies can also be investigated by “virtual manufacturing”. This enables the saving of time and costs for the whole product development cycle. Successful prototyping showing the part’s feasibility and process reliability is followed by the design, manufacture and try-out of the series production tooling. To ensure adequate tooling life time and a constant part quality, the FEA is used in this stage to determine the stresses and elastic deformation acting on the tool elements due to the forming loads. In the context of the above described component and process design, the FEA is used to check the production feasibility of the component, to analyze and optimize the final component quality and expected process reliability and to determine an indication of the required process forces for the die and machine design. The forming possibilities of the hydroforming process are crucial for product development. The tube model passes through the individual forming steps, so that the strains and stresses from each preceding step are considered. For the tube model, four-node shell elements with complete integration over the shell thickness work satisfactorily. In practically all cases, the component curved surfaces are the most critical areas in the hydroforming process. Very good simulation results can be achieved by the detailed reproduction of the bending process. Final dimensions can be calculated with an accuracy variation of less than 2% by such coherent simulation. The forming limit curve (FLC) of the aluminium material was used to estimate the process feasibility with the FEA during the component and process design. This was done on the assumption that the ratio of maximum to minimum strain is almost constant during the forming. Besides other boundary conditions, the choice of the friction law and friction coefficients is important for the accuracy of the simulation results. For most if the simulations, Coulomb’s law of friction was used. A modified friction test, working with pressurized tubes, enables the determination of suitable values for the friction coefficient. In this example the first execution of the pre-forming operation resulted in wrinkles on a bent area of the part. It was not possible to flatten those wrinkles with the internal pressure by the subsequent hydroforming operation. To remove this potential failure, different variants of pre-forming die shapes were investigated by FEA and the most suitable one was translated into the new die cavity. A saving of time and costs of about 70% was achieved with the aid of FEA in comparison to an experimental try-out. Wide spreading of the HF has been limited by a kind of secrecy on knowledge bases and the lack of specific material specifications for incoming shapes and tubes. Hence, new component applications cause many problems that usually must be solved individually. Excellent example can be hydroformed X and T-joint. Experimental results of X and T-joint hydroforming have been compared by many researchers with the results of extensive FEA simulations in order to find a method of failure prediction.

With the aid of FEA simulation, the part quality control, and the design of the tubehydroforming process can be easily implemented and monitored. FEA simulations provide insights on the necessary process parameters/ loading paths (i.e. internal pressure and axial feed), part geometry, and part formability by analyzing the thinning, thickening, and strain distribution in the deformed tube.

Low Cost Response Surface Methodology

Many engineers and scientists use design of experiments techniques to construct empirical regression or .response surface models. An important application of response surface models is meta-models for optimizing a simulated system. When simulation runs are expensive, e.g., if a system with a large number of queues is being modeled with a high degree of realism, response surface methods (RSM) permit the user to develop an inexpensive surrogate or meta-model. Literature provides applications of RSM to simulation meta-modeling. Popular choices for experimental designs include box central composite and small central composite designs. These designs have several important justifications but are only available for numbers of experimental runs that may, for many relevant applications, be considered too large. In the common situation in which the experimenter has only a fixed budget, he or she must simply drop factors until the corresponding number of runs meets the budget. Because these procedures clearly can result in models of limited scope and poor engineering results, there has been considerable interest in alternative methods with fewer runs for a given number of factors.

The application of low cost response surface methods (LCRSM) is very similar to that of ordinary response surface methods except multiple models are fit instead of one and the diagnostic test is different. The four major steps in the application of any response surface methodology are experimental setup and testing, modeling, diagnosing whether the model is sufficiently accurate and additional testing, if needed. We use the application of LCRSM to aid in decision-making aimed at increasing profits and reducing customer lead-times of a fictitious facility to illustrate the methods.

Design of Experiments

A designed experiment is the simultaneous evaluation of two or more factors for their ability to affect the resultant average or variability of particular product or process characteristics. To accomplish this in a n effective and statistically proper fashion, the levels of the factors are varied in a strategic manner, the results of the particular test combination are observed, and the complete set of results is analyzed to determine the influential factors and the preferred levels, and whether increases or decreases of those levels will potentially leads to further improvement.

The DOE process is divided into three main phases, which encompass all experimentation approaches. The three phases are planning phase, Conducting phase and Analysis phase. The planning phase is the foremost important phase for the experiment to provide the expected information. The second most important phase is the conducting phase when test results are actually collected. if the experiments are well planned and conducted, the analysis is actually much easier and more likely to yield positive information about factors and levels. The analysis phase is when the positive or negative information concerning the selected factors and levels is generated based on the previous two phases. The analysis phase is least important in terms of whether the experiment will yield positive results. This phase, however, is the most statistical in nature of the three phases of DOE by wide margin. As it has heavier involvement in statistics, the analysis phase is typically the least understood by the product or process expert.

Steps involved in DOE are state the problems or the area of concern, state the objective of the experiment, select the quality characteristics and measurement systems, select the factors that may influence the selected quality characteristics, identify control and noise factors, select the levels of factors, select the appropriate orthogonal array, select interaction that may influence and selected quality characteristics or go back to step4, assign factors to OA and locate interactions, conduct tests described by trails in OA, analyze and interpret results of the experimental trails and conduct confirmation experiment.

Methods and Discussions

The increased interest stems in part from the fact that, through the THF process, manufacturers are able to produce complex shaped parts with lightweight and fewer welds than through alternative metal forming techniques. The main objectives of this study were to report design guidelines related to maximizing part expansion for a common type of geometry, namely Tee-shaped joints shown in figure 3, to be used at the beginning phases of part, tool and process design, and to illustrate how the necessary data can be derived economically for other geometries using finite element analysis (FEA) and low cost response surface methods (LCRSM), proposed. The design guidelines are selected to achieve maximum protrusion height with an acceptable level of wall thinning. Finite element analysis (FEA) was used in order to avoid the

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cost and limitations of compiling a database of real world parts. FEA permits arbitrary combinations of input parameters including design parameters and process conditions to be investigated with limited expense. Based on the verification of FEA with experimental data through many case studies performed by various authors and other institutes, FEA can be considered to be a viable way of developing simple guidelines for parts and features commonly encountered in the tube hydroforming market. Additional FEA simulations are planned to further enlarge the knowledge base about particular parts using predetermined parameters varied over practical ranges.

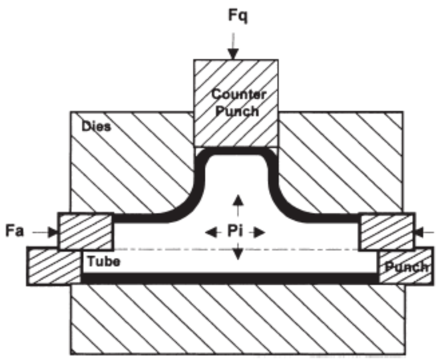


Figure 3. Hydroforming of a typical Tee-shaped part. (*P*i) is pressure, (*F*a) is axial, and (*F*q) is counter force.

The Tee-shaped part geometry was chosen for analysis because it is one of the most common features on tube hydroforming products. It is also interesting because it is perhaps the simplest part that involves a non-axisymmetric expansion region, which characterizes many of the most relevant design geometries. The generally acknowledged most desirable feature of a hydroformed part is high expansion, which corresponds to the protrusion height (Hp) on a T-shaped part. Thus, the protrusion height (Hp) is selected for modeling as a function of process inputs.

Even though FEA experiments are less expensive than physical experiments, they still require substantial preparation and execution time. For this reason, there has been considerable interest in developing and applying design of experiments methods to permit surrogate prediction or "response surface models" to be constructed using small numbers of FEA runs. These prediction models can then be used in decision-making related to optimization of the systems modeled using FEA. In our case, we were particularly interested in using design of experiments methods requiring few runs because we were proposing methods to be repeated for the exploration of a large number of different part geometries and sets of boundary conditions.

Therefore, in order to develop prediction models with acceptable accuracy by running a small number of simulations, we selected the recently proposed LCRSM procedures. These methods are based on linear regression and can be applied using standard spreadsheet or statistical software. LCRSM methods were derived as solutions to optimization problems that have only recently become possible to solve because of advances in computer speeds. LCRSM allowed us to identify important interactions between the input factors with only a fraction of the cost of standard experimental methods.

FEA simulations were taken from literature using the same conditions applied in an experimental work for a Tee-shaped part as reported by earlier researchers order to compare FEA predictions with experimental results. Figure 4 shows the modeling of tube hydroforming a Tee-shaped part. Table 1 tabulates geometrical, material and process parameters utilized in our FEA simulations and experimental work reported in previous researches.

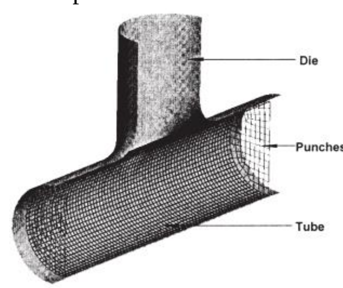


Figure 4. FEA model for the Tee-shaped part used in computer simulations.

Table 1
Geometrical, material, and process conditions obtained from literature and used in the simulations.

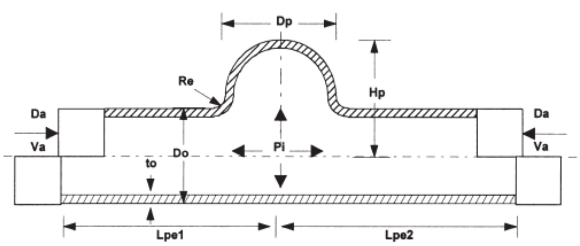
Geometrical Parameters	**Dimensions**	**Material Properties (Low Carbon Steels)**	
Do	89mm	E	207GPa
To	4mm	K	460MPa
Dp	89mm	n	0.19
Re	25mm	**Process Parameters**	
Lpe1	142.5mm	Maximum Pressure	32MPa
Lpe2	142.5mm	Total Axial Feeding	53.8mm
Hp	Response	Coulomb Friction	0.05

		Coefficien t	

We begin here by reviewing LCRSM procedures. Then, we describe the test methodology and the application of LCRSM to modeling the protrusion height (Hp) on a Tee-shaped hydroformed part.

The application of low cost response surface methods (LCRSM) is very similar to that of ordinary response surface methods, except multiple models are fit instead of one and the diagnostic test is different. It is crucial to understand all the effects and interactions of all these parameters and quadratic curvatures on the formability in order to successfully produce a tube hydroformed part. With this knowledge, engineers would be able to design manufacturable hydroformed parts with a minimum number of modifications and trials. Low cost response surface methods (LCRSM) permit these interactions and curvatures to be investigated with minimum experimental cost.

Geometrical parameters of interest can be the length between a feature (protrusion or bulge) and the edge (L_{pe}), protrusion diameter (D_p) or bulge width (w), and fillet radius (R_e) as shown in figure 5. The geometrical parameters that are anticipated to have significant effects on the response are identified as follows: distance between protrusion and edge (*L*pe1 and *L*pe2), fillet radius (*R*e), and protrusion diameter (*D*p).



Hp	Height of Feature
Lpe1	Distance between Feature and Edge
Lpe2	Distance between Feature and Edge
Do	Initial Outer Diameter of Tube
Dp	Outer Diameter of the Feature (i.e., protrusion)
Re	Fillet (Entry) Radius of Feature
to	Initial Tube Wall Thickness

Fig. 4. Geometrical parameters for a Tee-shaped part in hydroforming process.

Five levels of each factor were determined within a wide range of typical dimensions of T-shaped parts. In a novel application of experimental design, one might imagine applying a "full factorial" design requiring 5^4=625 runs. However, several options exist that offer far greater efficiency, in the sense of prediction accuracy per run, based on a relatively small numbers of runs. In general, LCRSM procedures can be expected to offer comparable or superior model accuracy with approximately half the runs of methods based on CCDs, which are the most widely used response surface procedures.

LCRSM was applied using the four-step process described in literature as follows:

Step 1:

(Setup and Experimentation) The factors in Table 2 were chosen, and FEA simulations were set up by scaling the design in Table 3 using the ranges in Table 2. The scaled inputs are in millimeters as shown in Table 4. FEA simulations were performed according to the set-up in Table 4. For each run, values of the measured protrusion height (Hp) were recorded as tabulated in Table 4. In the array, there were 3 repeated runs, which we interspersed with the other runs to evaluate the variability in the modeling, meshing, and analysis procedure.

Table 2
Response, factor and factor levels used in the simulations

Response					
Hp	Protrusion height at the final forming step (mm)				
Factors	Levels				
	-1	-0.5	0	0.5	1
	Ranges (mm)				
Lpe1	100	200	300	400	500
Lpe2	100	200	300	400	500
Re	6	9	12	15	18
Dp	25	30	35	40	45

Table 3
(a) The start up design in scaled (-1,1) units, (b) the model forms and (c) the follow up runs, which the diagnostic in step 3 may suggest are needed to meet the accuracy goals:

(a)				
Run	A	B	C	D
1	-0.5	-1	-0.5	1
2	1	1	-1	1
3	-1	1	1	1
4	1	-1	-0.5	-0.5
5	0	0	-1	0
6	0	1	0	0
7	-0.5	-1	1	-0.5
8	-1	0	0	0

9	1	1	1	-1
10	-1	1	-1	-1
11	0	0	0	-1
12	0.5	-0.5	0.5	0.5
13	0.5	-0.5	0.5	0.5
14	0.5	-0.5	0.5	0.5
(b)				
Form 1	β_o+ β_AA+ β_BB+ β_CC+ β_DD+ β_A2A^2+ β_B2B^2+ β_C2C^2+ β_{AB}AB+ β_{AC}AC+ β_{BC}BC			
Form 2	β_o+ β_AA+ β_BB+ β_CC+ β_DD+ β_A2A^2+ β_B2B^2+ β_C2D^2+ β_{AD}AD+ β_{AD}AD+ β_{BD}BD			
Form 3	β_o+ β_AA+ β_BB+ β_CC+ β_DD+ β_A2A^2+ β_D2D^2+ β_C2C^2+ β_{AC}AC+ β_{AD}AD+ β_{CD}CD			
Form 4	β_o+ β_AA+ β_BB+ β_CC+ β_DD+ β_D2D^2+ β_B2B^2+ β_C2C^2+ β_{CD}CD+ β_{CD}CD+ β_{BC}BC			
(c)				
Runs	A	B	C	D
A1	-1	-1	-1	1
A2	-1	-1	-1	-1
A3	-1	1	1	-1
A4	1	1	-1	-1

Table 4
The input settings and output Hp values from the simulation study and the actual run order

Run Order	Lpe1	Lpe2	Re	Dp	Hp
(a)					
1	400	300	6	35	25.5
2	200	500	6	40	28.9
14	300	400	12	25	24.5
4	100	400	18	30	31.4
5	100	200	12	35	33.3
6	400	300	18	40	28.8
7	500	200	15	25	26.0
8	200	400	12	45	32.1
9	200	100	6	25	29.2
10	300	100	15	35	33.3
11	400	100	9	45	34.5
12	500	500	12	40	25.4
13	500	500	12	40	25.7
3	500	500	12	40	26.3
(b)					
15	100	100	18	45	41.6
16	100	200	18	25	31.5
17	100	400	6	25	29.0
18	200	100	6	45	34.0

Step 2:

(Model Selection) Regression models of each response were generated by fitting the model forms shown in Table 3. The fit model with the lowest sum of squares error (highest R2) was selected, giving rise to the following tentative model to predict the (Hp) as a function of the inputs:

$$Y_{est} = 28.2-2.87A-2.74B+1.21C+2.86D+0.91A^2+1.94B^2-0.56C^2-1.08AB-0.49AC+0.11BC \quad (1)$$

Note that the primary justification of these choices of fit models given in literature relates to the pragmatic need to keep the number of candidate models small in order to maintain reasonable computation times for the practitioners during analysis. While LCRSM procedures have so far only been characterized formally for the specific sets of models described in the table(s), we have used linear combinations of fit models and other approaches for prediction following engineering judgment in specific cases.

Step 3:

(The Least Squares Coefficient Based Diagnostic) In order to determine whether additional runs were needed, the following was calculated:

$$\beta_{q,est} = (\Sigma\beta^2_{i,est})^{1/2}\ (q-1)^{-1/2} \quad (2)$$

where $\beta_{q,est}$ were the least squares estimates of the q^6 second order coefficients in the model chosen in Step 2. These included coefficients of terms like A^2 and BC, but not first order terms such as A and D. The calculated value was $\beta_{q,est}$=1.12 mm. It was determined that the maximum acceptable standard error of prediction or "plus or minus" accuracy goal, $\sigma_{prediction}$, was to equal 1 mm. Since $\beta_{q,est}>\sigma_{prediction}$, it was needed to perform the additional runs as described in Step 4 in order to meet our model accuracy goal. Otherwise, only 14 runs would have been enough.

Also, the standard deviation of the (H_p) for the repeated runs equaled 0.45. Multiplying this by the standard statistical correction factor of 1.12, confirms that the tests were repeatable to within σ_{repeat}=0.50mm. Therefore, our estimated errors when we stopped equaled approximately $2\sigma_{repeat}$, which indicates that

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LCRSM would have obtained comparable model accuracy to other more expensive methods in this case.

Step 4:

(Additional runs, if necessary) Since it was determined that additional runs were needed to achieve our accuracy goals in step 3, additional experimental runs were performed as specified in Table 2. After the experiment, a full quadratic polynomial regression model was fit as in ordinary response surface methods (RSM). The resulting model is expected to have comparable errors as if a central composite design had been applied based on 27 runs. The final prediction model was:

$$Y_{est} = 27.6-2.86A-2.76B+1.02C+2.91D+1.66A^2+2.03B^2-0.37C^2+0.43D^2-1.33AB-0.57AC+0.18AD-0.43BC-0.48BD+0.70CD \quad (3)$$

with the inputs expressed in coded [-1,1] units (useful for comparing with the tentative model) or with the inputs expressed in engineering units (useful for engineering decision-making):

$$H_{pest}=33.22-0.0266L_{pe1}-0.0216L_{pe2}+0.264R_e-0.1046D_p+0.000042L^2_{pe1}+0.000051L^2_{pe2}-0.0105R^2_e+0.0043D^2_p-0.000033L_{pe1}L_{pe2}-0.00048L_{pe1}R_e+0.000089L_{pe1}D_p-0.00036L_{pe2}R_e-0.00024L_{pe2}R_e+0.0117R_eD_p \quad (4)$$

This model was used to study the effects of the input factors and to create the response plots below. In this section, we describe in detail the choices of the geometrical parameters, material properties, and process parameters that determine the boundary conditions in the FEA simulations that generated the *H*p values in Table 4. A summary of the fixed geometrical parameters is shown in Table 5. In order to determine the loading curves necessary to hydroform a part, simple analytical models such as in equation 5 used to obtain some of the initial values of the curves.

$$P_u =(2\sigma_u t_o/D_o-t_o);\ P_y =(2\sigma_y t_o/D_o-t_o) \quad (5)$$

where (P_u) is the highest value before bursting pressure, (P_y) is the pressure to start deformation,

Table 5
Geometrical, material and process conditions used in the simulations

Geometrical Parameters	Dimensions	Material Properties (Low Carbon Steels)		
Do	45mm		E	200GPa
to	2mm		K	484MPa
Dp	Factor		n	0.19
Re	Factor	**Process Parameters**		
Lpe1	Factor	Maximum Pressure		44MPa
Lpe2	Factor	Total Axial Feeding		15mm
Hp	Response	Coulomb Friction Coefficient		0.05

D_0 is the initial tube diameter, t_0 is the initial tube thickness, σ is the yield and tensile strength of the material. However, these values are not obtained within the time domain. Hence, two FE simulations are usually run to refine the loading paths. A combination of the geometrical factor ranges is selected for a preliminary simulation to determine the loading curves, which would be applied for all of the simulations. The combination of L_{pe1} and L_{pe2} 300 mm, R_e 12 mm and D_p 45 mm is selected as representative of the entire combination set. Figure 5 and Table 5 show the loading paths applied for all of the simulations.

To summarize, it has been observed that the length between feature and edge is the most influential factor affecting the desired expansion regions. It is also known that friction is in fact the driving factor that makes this effect become prominent. Longer tube distance from the edge to feature is influenced more by friction, and thus less metal flowing into the expansion zone. However, it can be seen that when one side of the tube is very long while the other side is short, the protrusion height obtained is still satisfactorily high, L_{pe1} 100 mm and L_{pe2} 300 mm. This is an indication of the rule of thumb in hydroforming that a feature that requires large expansion should be located near the ends of the tube as much as possible so that material feeding via axial punches may help postpone the bursting while increasing the possibility of reaching high expansion degrees.

Conclusion

In this paper, we have derived and presented models of the part expansion of T-shaped joints as a function of geometrical parameters for a non-axisymmetric expansion. The derived models predict the effects of distances between features such as protrusion, bulging, bending and feeding end on the protrusion height. The models predict that the part distances, L_{pe1} and L_{pe2}, have the greatest influence on protrusion height or expansion ratio. We feel that these models are of direct interest to designers attempting to gain the cost and other benefits of hydroforming. Results of investigating the derived models include that for parts having crucial expansions or protrusions, it is recommended that these expansion regions are located in the regions close to the feeding end. Hence, this reduces the effect of friction on moving material from the ends towards the expansion area. It is also shown that a combination of FEA and DOE techniques can generate useful information about many unknowns in a THF process, particularly for a new technology for which only limited expertise has been gained. Via use of LCRSM, intuitive but precise information about the main effects of geometric parameters was successfully obtained with a reduced number of FEA runs, effort, and cost. It is also demonstrated that interactions are clearly revealed with fewer simulations than would be required by standard response surface methods, including those based on the widely used central composite designs.

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