CHAPTER-1

INTRODUCTION

1. Tube Hydroforming Process

The tube hydroforming process (THF) has drawn the attention of designers because tubular hydroformed structures have a greater stiffness to weight ratio. Parts are formed with an evolution of pressure applied internally and axial feed or axial movement by applying compressive forces to the ends of the tube (commonly known as end feed). This combination is denoted as the loading path. Although a variety of hydroforming processes have been proposed to produce automotive parts, the determination of the optimum loading path remains a challenge with regard to maximizing formability and minimizing manufacturing costs. The aim of the present investigation is to get the optimized loading path for tubular hydroforming that will generate a quality part using multi-objective optimization methods.

1.1. Introduction

Tube hydroforming (THF) is one of the new forming techniques for forming of tubular hollow parts with variable diameter by applying internal hydrostatic pressure along with end axial feed or axial movement to a straight or preformed tube. THF is relatively advanced technology than conventional forming processes, which has been technologically developed in recent years and is now became popular for forming of tubular components in various field such as automotive, aerospace and household applications. Few of typical applications include forming of tubes into ‘X’ shape, ‘Y’ shape and ‘T’ shape components. And other applications are engine cradles, stepped hollow shafts, exhaust manifolds etc. The tube hydroforming process having many distinct advantages over routine manufacturing process via deep drawing, stamping and welding process such as:

a) Weight reduction of the part due to part consolidation
b) Minimum tooling cost and scrap rate
Enhanced structural strength and improved stiffness

Lesser secondary operations

Better dimensional accuracy

Significant reduction in spring back effects

The success of the tube hydroforming process depends on the proper selection of loading path and proper control of the process parameters. In tube hydroforming, the axial feed at two ends of the tube and internal pressure has to be synchronized and properly controlled. However, this THFP has recently become popular and used for manufacture of various automotive parts and household tubular components. A robust analytical theory is not available to describe the deformation mechanisms of the process, due to the fact that the process is very much shape dependent.

Finite element analysis (FEA) of tube hydroforming with experimental validation is one of the better ways to understand and analyze the process. When the geometry is complex, the validation of the tube hydroforming process experimentally becomes too costly. In such case, FEM simulation alone can deliver a valuable insight and understanding of the process. In this investigation free bulge hydroforming test was conducted for the given load paths; subsequently the processes are simulated using DEFORM-3D and compared with the experimental values.

1.2. Theoretical Background

1.2.1. Hydroforming

Hydroforming (HF) is a process in which hydrostatic pressure is used to deform the components into desired shape and dimension. The hydroforming process has been employed in many applications such as bicycle components, piping joints etc. In addition to that, the hydroforming has become popular in the automobile industry to manufacture of several automotive components. Basically, hydroforming can be classified sheet hydroforming and tube hydroforming. In sheet hydroforming, sheets are placed on the die, clamped in proper manner and then applied pressure to deform the sheet to required shape. The classification of hydroforming process is shown in the Fig. 1.1.
1.2.2. Tube Hydroforming (THF):

Tube hydroforming process having many distinct names in various countries and depends on the time it was investigated. T-joints are the first application by the tube hydroforming process in the duration of 1960s. The THF became most popular in the year of 1980s as the automotive industry kept attention on the process mainly lightweight metal forming applications. In the present investigation, tube hydroforming termed as the metal forming process by this, annealed Inconel 600 tubular blanks are deformed freely called as free bulge tube hydroforming using internal hydraulic pressure produced by various means such as hydraulic, viscous medium, elastomers, polyurethane, etc. with the combination of axial force in terms of axial movement.
Fig. 1.2 Basic working principle of tube hydroforming.

Fig. 1.2. illustrates the basic process principle of THFP. In the initial stage, straight or preformed tubular blank is inserted between two halves of the dies, the geometry of the die is corresponding to the final part geometry to be produced, and the die is closed by the application of the clamping force with the help of ram. Once the die is closed properly, two axial cylinders or axial punches are engaged at two ends of the tube with proper sealing force. Axial punches move along the tube axis. In general, the sealing force which is applied at the two ends of the tube at least equal to product of tube internal area and internal pressure applied. However, in may applications the axial forces may be increased more than the sealing force to force the additional material into forming zone if necessary.
Fig. 1.3. Most common failures and limits in tube hydroforming.

Fig. 1.3. illustrate the common failure occurs in tube hydroforming process caused by plastic instabilities. The failures include buckling, folding and bursting. The risk of buckling of the tube may occur at the initial stage of the process due to application of excess axial force on the tube. The risk of buckling is avoided by minimizing the unsupported tube length with increasing in the section modulus of the tube cross section through the simultaneous expansion of the tube wall. Due to high axial force causes the formation of the folds, theses folds are symmetrical to the longitudinal axis. These folds are controlled by applying little more internal pressure during the expansion phase of the process.

Another limitation of the tube hydroforming process is bursting. The risk of bursting is due to the application of too high internal pressure, this causes initiation of the local necking of the tube wall. Local necking of the tube depends on the initial thickness of the tube blank. The bursting risk can be controlled by proper selection of the loading path and it must be ensured that the tube wall needs to be contact with the die wall at the final stage of the process.

1.2.3. Working Principle of Tube Hydroforming

The working steps of tube hydroforming process are illustrated in Fig. 1.4. After placing of the tube in the tool die cavity, the tool must be closed with proper clamping force. The tube is then filled with a liquid emulsion of a water-soluble material
(concentration < 5%). Then the tube is deformed to corresponding shape of the internal contour of the die by application of an internal hydrostatic pressure and axial force.

There are two different cases can be observed in tube hydroforming process. In the first case or in some applications, the internal pressure is only enough to deform the tube into required shape. Here, the axial forces are used only for sealing the tube to control the leakages. In this case, no additional material can be fed into the expansion zone by axial force.

In the other case, axial cylinders force the additional material into the expansion zone. Here, tube is deformed to the required shape due to simultaneous application of pressure and axial forces.

There is another classification of tube hydroforming such as force controlled tube hydroforming and stroke controlled tube hydroforming. In force-controlled, the axial forces are varied with the internal pressure and in case of the stroke-controlled, the stroke of the axial cylinders is varied with the internal pressure.

![Diagram of tube hydroforming](image)

**Fig. 1.4.** The working principle of tube hydroforming
Fig. 1.5. Common failures (buckling, wrinkling and bursting) in the tube hydroforming.

The common failures of the THF are shown in Fig. 1.5. The risk of buckling is one of the failure in tube hydroforming may occur in the initial stage of the process, particularly when excess axial force is applied to feed the additional material in to the expansion zone. Once the buckling occurs, it cannot possible to control and continue the process. The risk of this failure is depends on the free tube length ($l_f$), initial diameter of the tube ($d_0$), and initial tube wall thickness ($t_0$) illustrated in Fig. 1.6.

Fig. 1.6. The rules should be followed during tool design to avoid buckling.
The free tube length $l_f$ is not permitted to exceed $2d_0$, if $20 \leq d_0/t_0 \leq 45$. However, if diameter to thickness ratio is greater than 45, it indicates that tube wall is very thin, so that the risk of buckling is very high. Therefore, free tube length $l_f$ is very less than $2d_0$. If $d_0/t_0$ less than 20 means that the thickness of the tube is very high, then the risk of buckling is very small. Therefore, the $l_f$ can be permitted to exceed $2d_0$, Fig. 1.6.

The axial forces acting on the tube ends Fig. 1.4. must exceed a certain level to prevent leakage. This limit (Sealing) is also shown in Fig. 1.7. The deformation during hydroforming comprises elastic and a plastic portion. The limit at which yielding occurs is, therefore, of great important. The yielding limit is also shown in Fig. 1.7.

Once these limits (wrinkling, fracture, yielding and sealing) are determined, the working range can be established, Fig. 1.7. This working range is depends upon both tube material and tool parameters.

Assume that the tool shape is kept constant, while the tube material is changed. For example, soft steel exhibits a large working range, while the working range is small for extra high strength steel.

The hydroforming operation can be divided into two stages as shown in Fig. 1.8. The first stage is name as free forming stage and the second stage is the calibration stage. In the first stage of tube hydroforming called free forming, the tube expands freely without contact of the tool. The second stage of the tube hydroforming called calibration starts when the contact is established between the tube and tool. The two stage free forming and calibration is illustrated in Fig. 1.8.
Fig. 1.7. The limits and the working range in tube hydroforming.

Fig. 1.8. Free forming and calibration stages in tube hydroforming. The present investigation deals only with free forming.

In the calibration stage, no material is forced into the forming or expansion zone by the axial force, by application of internal pressure only the tube is forced to conform to the inner contour of the tool. From the Fig. 1.8., it can be observed that, the loading path (loading path describes, the variation of the axial force is along with the internal pressure) during calibration is parallel to the sealing limit.
During the free forming stage, in Fig. 1.9., it can be observed that the formation of the wrinkles at the intake regions of the expansion zone, if the pure-shear path is selected. These wrinkles are quite common and are rectified in the calibration stage.

In the pure-shear, more additional material is fed into the expansion zone by the more axial force during the free forming. There is in more material in the expansion zone in calibration stage starts, this material will compensate the thing of the tube wall in the calibration stage, so that less reduction in the thickness. Therefore, during the free forming, pure-shear loading path is recommended to control and minimize the wall thinning. Uniaxial-tension lies between the plane strain and pure-shear loading path, Fig.1.9.

One of the aims of present investigation is to selection and optimization of a loading path to minimize the wall thickness reduction along with maximum bulge.

Fig. 1.9. Types of loading paths in tube hydroforming.
1.2.4. Multi-Objective Optimization

It is well known, the manufacturing operations needs to deals with non-linear, multi-objective and conflicting multi-objective objectives. For the present research of tube hydroforming process considered two conflict multi-objectives such as the minimum thinning in term of thinning ratio, while achieving maximum bulge in terms of bulge ratio and maintaining a reasonably uniform thickness distribution throughout the component. This establishes a problem of multiple objectives.

Optimizing the process with different conflicting multi objectives (e.g., maximizing bulge ratio and minimizing thinning ratio in the present case) is one of the difficult tasks. However, conversation of the multi objectives problem to single objective problem is the one of common practice. As a result, multiple goals are redefined as a weighted sum objective function, to provide an equivalent cost, thereby artificially converting multi conflicting objectives into a single objective. However, the correlation between objectives is usually rather complex and dependent on the alternatives available. Moreover, the different objectives are typically conflicting, so it is difficult to aggregate them into one synthetic objective function (where the objective function is used to compute the objective value). As a consequence, it may be very difficult to combine dissimilar goals into a single objective function a priori, that is, before alternatives are known.

1.2.5. Design of Tube Hydroforming:

Proper design of the tube hydroforming system play most important role in tube hydroforming process as the system includes high hydraulic pressures and complex shaped parts involved. The tube hydroforming system involves the followings

- Proper clamping devices to provide the sufficient clamping forces on the dies
- Tooling, it includes dies, inserts, sealing system etc.
- High pressure controlling system includes intensifier
• Hydraulic axial cylinders for sealing the tube to prevent the leakages and to apply the axial force to feed the additional material into expansion zone.

1.2.6. Tooling:

THF tooling includes the die holders, dies, axial cylinders, counter punches, sealing systems to control the leakages. In tube hydroforming process, involves high-pressure to deform the tube, so that robust tooling is compulsory to diminish die deflection and part tolerance deviations. Hence, tool steel is used for manufacturing of inserts, whereas for the die material 1045 steel is used. To minimize the die wear and to minimize the friction, generally inserts are hardened and polished to get the high finished surface. For structural parts, diagonal positioning is one ways of balancing the die deflection between vertical and horizontal directions of the part.

1.3. Problem Statement

Currently, the development of tube hydroforming processes is greatly delayed from very long time, which result from many iterations of either trial-and-error based finite element (FE) simulations or expensive changes to prototype tooling. Moreover, many numbers of process parameters such as physical and mechanical properties of the material, geometry of the tubular blank, complex die-tube interface phenomena, and process parameters (i.e. internal pressure, axial feed and loading paths) influences on the hydroformability of the tubular parts. Consequently, more advanced design tools are required to assist engineers for design of better products, robust processes and to minimize the manufacturing lead time and cost. As a result, the goals of the proposed work are to:

1. To determine the forming severity indicator for tubular parts produced using hydroforming process and also to establish the mathematical form of equations for THF.
2. To conduct the experiments as per the design matrix which is developed using the Design of experiments approach.

3. To investigate the effects between the output responses (i.e. bulge ratio and thinning ratio) and the input control variables (internal pressure, axial movement and length of the tube) by plotting the graphs using Design Expert software.

4. To model the THF process, Response surface methodology is used to derive the empirical relationships between the input control variable and the output responses.

5. The THF process is optimized using the Genetic Algorithms.

6. Validating the results

1.4. Description of the Problem

1.4.1. Identification of the Problem

Tube hydroforming has a history of more than 100 years; however it was introduced in the automotive industry only in the past two decades. Typical applications of the tubular components found in the engine and exhaust systems. In addition to that numerous structural parts of the chassis, body and closings such as doors, hoods, etc. are also hydroformed. The main advantage that the process offers is the ability to optimize the structure for weight and strength.

Tube hydroforming having many applications in different areas; however automotive and aero industries are keeping attention on tube hydroforming process since THFP having capability to deform the complex tubular parts in single phase with improved mechanical and structural properties. The parts which are deformed by THFP are structurally good. Through the THFP, it is able to manufacture complex geometrical components with lightweight and fewer welds than conventional metal forming process. The main advantage of tube hydroforming is to reduce the welds in the component. The other benefits with THFP than conventional metal forming technique are low product
cost, tooling cost, reduction in weight, proper utilization of material, less number of operations, and better part quality, enhanced structural stability and stiffness.

The working principle of THF is relatively simple (see Fig. 1.1). The process starts with placing a thin-walled tube inside a die cavity (corresponding to the final shape to be produce). Then, the two ends of the tube sealed with suitable actuators and axial cylinders to apply sealing and axial forces. The tube is then inflated internally with high pressure and thus it deformed and conforms to the internal counter shape of the die. Generally, water along with anticorrosion additives are used as pressurizing medium.

In tube hydroforming, proper combination of internal pressure and axial load selection is the most important phase as the success of the process depends on this loading path. In order to select proper loading path and other process parameters, trial-and-error technique is one of the usual methods in industries. Due to the trial-and-error method is having disadvantages such as high material wastage, consuming of too much time and loss of other resources taking place in the manufacturing industries. Moreover, there is no any specific methodology is available to select the process parameters in the tube hydroforming, due to this reason, the operator as well as the process engineers are not able to understand clearly about the tube hydroforming process (THFP) to obtain the desired quality of the hydroformed component.

Detailed investigation on selection of process parameters is needed to achieve the maximum bulge with minimum thickness variation at maximum bulge point. It would be helpful to understand the process for the operators and process engineers, if tailor-made solutions are defined. The customized solutions serve as a ready reckoner to operate the hydroforming machine with better conditions achieve the specified requirements.

To optimize the tube hydroforming process, the optimal settings of the process parameters such as internal pressure, axial movement or axial feed, tube length and other parameters need to be found. This raises the need of application of appropriate optimization method is to be applied to the hydroforming process.

To understand the THFP, to finalize the process parameters, and to find the lacuna, the trail experiments were conducted on Inconel 600 tubes.
Consequently, investigate the effect of various process parameters on output responses of tube hydroforming, analyze the tube hydroforming, and appropriate methodology is to be suggested for optimizing the process parameters.

1.5. Proposed Methodology to Solve the Problem

The emphasis of present investigation is to find the optimum process parameters for tube hydroforming process. In order to optimize, the performance measures are to be expressed in terms of the process control variables as the performance measures are governed by the process control variables. Since the theoretical modeling of the process is not possible, empirical modeling is carried out for the output parameters. However, while developing the empirical models, a reasonable set of process control variables is to be selected. A set with a less number of input variables would yield a simple model for a particular process. However, it may not represent the process properly. At the same time, a large number of input variables yield a complicated model but it would be a model with more accurate predictive power.

Due to various process parameters such as axial load, internal pressure, friction coefficient and geometrical parameters like tube thickness, tube length, corner radius of the die, free length are involved during the process, the industries are facing complexity to run the process. The selection of loading path (combination of axial force and pressure) is one of the most important step during the process. And also the thicken or thinning of the hydroformed component depends on this loading path.

From the literature and based on number of trial experiments conducted on test samples of Inconel 600 tubes and determined the most effecting variables on tube hydroformed component quality are internal pressure, axial movement and tube length. Hence these are chosen as process control variables in the present work.
These three control variables are defined in the following sections.

1.5.1. **Internal Pressure**

After placing the tube between the two half dies or in the die cavity, both the ends of tube are closed by the axial plungers and the pressure was applied internally to deform the tubular material to conform the shape of the die. Internal pressure is one of the most influencing factors on the hydroforming process. To achieve the maximum deformation or maximum bulge, the internal pressure is increased to above the yielding strength of the material. The pressure which was applied internally is amplified till the expansion of the tube comes into contact with the inner surface of the die. Improper application of pressure leads to failure of the process.

The possibility of bursting failure is due to application of high pressure or improper control of internal pressure. The bursting is initiated by a local necking in the tube wall. The local necking of the tube was majorly depending on the initial thickness of the tube. To avoid the bursting, it must be ensured that the tube wall briefly comes into contact with internal surface of the die at the latest before the necking initiated.

1.5.2. **Axial Movement**

Two axial cylinders are attached at both ends of the tube to apply axial load. The axial cylinders are to be moved simultaneously to apply axial loads on both ends of the tubular blank to feed the tube material into the expansion zone. The load applied on two end of the tube for sealing and to prevent the leakage which is essential at least equivalent to the force calculated from the product internal area of the tube and the pressure applied. However, the axial forces may be amplified to a greater value if the forming job requires it. Then additional material of the tube is forced into the die cavity. The excess axial movement during the hydroforming process causes formation of wrinkles on the tube. Hence, it is essential the proper control of the axial movement.
1.5.3. Length of The Tube

Koc and Altan (2002) studied the influence of the geometrical parameters and other process factors in tube hydro forming using 2D finite element method. They concluded that the internal pressure and tube length are the two major influencing parameters on the maximum bulge of an axis-symmetric component.

The risk of buckling is majorly dependent upon free tube length. The risk of buckling is illustrated in Fig. 1.6 and explained in the section 1.2.3.

Hence, it is necessary to study the influence of tube length on output responses such as the maximum bulge in terms of bulge ratio and minimum thickness variation in terms of thinning ratio. Hence, considered tube length is one of the process parameter.

1.6. Reasons for Selecting Bulge Ratio and Thinning Ratio

- The maximum bulge indicates that the maximum possibility to deform the material to conform the required shape as per the die without failure like bursting. The maximum bulge in tube hydroforming process depends on various factors. The investigation required to know the relation between the process parameter and maximum bulge.

- Thickness control of components during the process is one of the major requirements in tube hydroforming. Thickness of the tubular component during the process majorly depends on the axial force, internal pressure and tube length. The effects of mentioned process parameter on thickness variation have to be investigated during hydroforming.

- From literature, it is noticed that, there is no investigation on the development of numerical relation between process parameters (internal pressure, axial movement and tube length) and output responses (bulging and thinning). The main objective of the current research is to develop the numerical relation between the process parameter and output responses of tube hydroforming.
The selection of the optimum process condition is another critical task in hydroforming. Due to this, the process becoming complex. The optimization of tube hydroforming with multi objectives has to be done to make ease during the selection of optimum process conditions.

The complete plan of the projected methodology is illustrated in Fig. 1.10 and the subsequent sections describes about various steps involved.

As many of the process parameters are involved in THFP, the majorly effected process parameters are found based on the trial experiments and the previous research work, and the consideration of insignificant variables are excessively increases the computational complexity of the models.

Fig. 1.10. Overall schematic of the proposed methodology

In order to reduce the costs of the material and process, Design of Experiments will be used to minimize the number of experiments required without affecting the accuracy and the precision of the analysis.
Once the experiments are conducted, then the tubes are longitudinally sectioned for the measurement of output responses. The maximum bulge diameter and thickness of the tube at maximum bulge point are measured accurately. From them, bulge ratio and thinning ratios are calculated.

The data obtained from simulation and experimentation is utilized to predict the empirical models which are best suits to the problem. Response surface methodology (RSM), the most efficient evolutionary algorithm is applied to get the empirical models for bulge ratio and thinning ratio in terms of process control variables. Once the best-fit models are developed for a particular output response, then it is tested for the adequacy using statistical techniques. And from the empirical models which are developed, the individual effects of THF parameters and their interactions on bulge ratio and thinning ratios also be analyzed.

It is desirable in a tube hydroforming process to have maximum bulge ratio within their feasible limits in order to get a maximum deforming of the tube to conform the required shape. Moreover, minimum process cost and maximum production rate are also required to make the process economical. Therefore, in the present work, minimum thinning is considered as constraint and the maximum bulge ratio is considered as the objective function.

The bulge diameter is maximized, subject to the feasible process variables. The feasible intervals of the process parameters are recognized with a view to have defect-free tube hydroforming components. Once the optimization problem (objective function) is defined, it can be solved by Genetic Algorithm (GA) to get the optimal set of process variables. In turn, the tube hydroforming process can be automated depends on the results obtained.
1.7. **Scope & Organization of the Thesis**

Sheet metal forming is a relevant process for inexpensive manufacturing and allows important cost reduction compare to other methods such as machining. For the manufacture of thin walled parts (either sheet or tube), several metal forming methods are available. The most common method is deep drawing. Deep drawing is one of the compression-tension metal forming techniques in which a sheet metal blank is drawn into a forming die by mechanical action of a punch [1]. This process is well established but has some limitations such as a non-uniform thickness distribution because of the punch-sheet-die contact or undesirable long process chains with stamping and welding. In order to overcome some of these disadvantages, forming methods with fluids media have been established.

Tube hydroforming (THF) is a forming process that uses a pressurized fluid to plastically deform a given tube into a desired shape. Fig. 1.11. shows a typical tube hydroforming operation for a simple part. The first stage is to place an original tube between the upper and lower dies and then dies are closed. Then, the ends of the tube are sealed with two plungers and the fluid is pressurized inside the tube to expand it to take the shape of the die cavity. Usually water with an anticorrosion additive is used as pressurizing medium. A typical process cycle is of 10-15 seconds. Finally, the dies are opened and a hydroformed part is obtained. This process presents many advantages: a lower weight/rigidity ratio as well as reducing the number of welds in an assembly which allows a considerable weight reduction. Moreover, hydroforming provides higher strength and quality in a part with complex shape. This process is also reduces tooling and assembly costs. Finally, hydroforming is recognized as an attractive manufacturing process in many fields, notably in the aerospace industry. The tube hydroforming process is one of best suitable processes to manufacture thin structural components of intricate cross sections and variable lengths. The hydro-formed components having good structural strength and stiffness, these are show the major difference with other conventional forming technique.
Tube hydroforming process (THFP) is becoming most popular forming technique in the automobile industry for manufacture of variety tubular components with structurally sound and stiff than routine forming techniques. By comparing the THFP with the conventional forming processes, the THF offers low piece and tool cost, reduction in weight, improving structural stability, integrity, strength and stiffness for many applications [2].

Successful tubular hydroforming depends on the proper selection of loading path. Loading path is the combination of internal pressure and axial feed at the tube ends. Proper combination of axial feed and pressure is most important step in tube hydroforming process. Bursting is of the failure in THFP and this is due to high internal pressure and insufficient axial feed, similarly buckling is another failure in THFP, this failure occurs when excessive axial feed and insufficient pressure is applied. Optimum loading path selection is one of the time-consuming and expensive processes by trial and error experimentations. The other alternate and accurate method to find the optimum loading path and also to investigate the various process parameters of tube hydroforming process is finite element method (FEM). The results obtained by the FEM are used to
investigate and optimize the forming parameters such as internal pressure, tube length, and axial feed.

The automotive, aeronautic and other industries are show attentions on THF because of its enormous advantages over the conventional forming technique. The various application of tube hydroforming in automotive industry includes engine cradles, radiator supports, roof side rails, exhaust instrument support panels [3]. The range of applications of THF is increasing day to day in automotive industry.

Inconel 600 is a nickel based super alloy having superior properties like corrosive resistant, resistant to oxidation, high tensile strength and good creep properties. Inconel 600 alloy having may application in manufacturing of gas turbines, rocket motors, space craft, nuclear reactors pumps and tooling.

In present investigation cold drawn Inconel 600 seamless pipes are taken, and annealed to improve workability of the pipes asper ASTM standards. Annealed pipes are then being used for conducting free bulge hydroforming experimentation. The proposed work is all about conducting the experiments to investigate the effect of process parameters on bulge, thinning of the tube and optimize the tube hydroforming process.

By trial and error experimentation method, to find the effect of the process parameter such as internal pressure, axial movement on the maximum bulge and minimum thinning is become more expensive. In economical point of view to minimize the number of experiments without affecting quality of the analysis, Taguchi method was applied.

In the present investigation, Taguchi L9 experimental design was selected for experimentation of tube hydroforming process to analyze the effect of process parameters. Taguchi L27 experimental design was selected for simulation of tube hydroforming process to study the effect of process parameters. Then using the experimental and simulation data response surface methodology (RSM) was applied for development of empirical modeling of the process. The developed empirical models are
then used to predict and to optimize the hydroforming process. And also, the mathematical models are being used to select the optimum combination of input variables for the desired hydro-formed product quality and to automate the THFP through the development of a computer program.

1.7.1. Scope of the Work

Automation of a manufacturing process has become more important in industries in order to get maximum production rates and high quality of finished components. However, in order to automate a process, it is essential to find the optimum values of process variables. In turn, this requires the establishment of precise numerical relationships between the process control variables and the chosen output responses. The scope of the proposed work is intended to develop such relationships for the chosen responses in terms of input variables and utilizes those developed relations to find the optimal set of process variables in tube hydroforming process. Once the optimal values are found, then the process could be automated based on them there by reducing failure rate, increase in production rate with high quality products.

To achieve these objectives, the current investigation and study was planned to be carried out in the following steps [4]:

1. Identifying the most influence process parameters in tube hydroforming process.
2. Finding the limits (higher and lower limits) of the process control variables, viz. internal pressure, axial movement or axial feed and length of the tube.
3. Selection and developing of the design experiment matrix for experimentation and simulation.
4. Applying of the FEM simulation as per the design matrix and then noted the output responses, viz. bulge ratio and thinning ratio.
5. Conducting the experiments as per the design matrix and then noted the output responses, viz. bulge ratio and thinning ratio.
6. Development of mathematical models for both experimental and simulation results and then calculating the coefficients of the polynomials.
7. Checking the adequacy of the models developed for experimental and simulation results.

8. Verifying the significance of the regression coefficients, recalculating the value of the significant coefficients and development of final mathematical models, which involves selection of the objective function, along with one or several constraints with limits. This facilitates the optimization process.

9. Presenting the main effects and the significant interaction effects of the process parameters on the responses in two and three dimensional (contour) graphical form.

10. Optimization of objective function using Genetic algorithm, which includes the actual minimization or maximization of the objective function, subject to the constraints already specified.

11. Analysis of results.

1.8. Organization of the Thesis

The contents of the thesis are organized in different chapters. Chapter 1 describes the introduction, working Principle of operation, components, types, applications, capabilities and uses of tube hydroforming process, description of the problem, and scope of the problem. Chapter 2 reviews the relevant literature and presents a critique on the literature. Chapter 3 deals with the response surface methodology which is used to establish the relationship between process variables and performance measures, describes the principles and the advantages of genetic algorithm. Chapter 4 discusses the selection of the material, applications, and experiments to found the properties of the material and its results and discussions. Chapter 5 includes the simulation study of the tube hydroforming, proposed methodology and its results and discussions. Details about the experimentation and the proposed methodology are given in chapter 6. Finally, conclusions drawn from the proposed methodology are furnished in chapter 7.