# INVESTIGATION \& OPTIMIZATION OF PROCESS PARAMETERS OF ROLL BENDING MACHINE IN REALIZING CONICAL SHELLS IN ALUMINIUM MATERIALS 

A Thesis submitted to Gujarat Technological University

For the Award of

Doctor of Philosophy
in
Mechanical Engineering

## By

Nimeshkumar Mahendrabhai Patel
Enrollment no.

179999919037

Under supervision of

Dr. Jeetendra A. Vadher



## GUJARAT TECHNOLOGICAL UNIVERSITY AHMEDABAD

[MARCH - 2024]

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## ABSTRACT

In the current research, For the sheet metal forming by roller bending machine, achieving the accurate geometry of components is the crucial task of many manufacturing industries. This is because of the "Springback" which refers to the elastic recovery of the deformed component. The microstructure and macroscopic mechanical properties of the sheet undergo changes during its forming process which results in inaccurate geometry of the component. These changes are common and inevitable in each phase of the production process. Hence to predict and controlling the Springback as per the geometrical shape requirements is one of the key factors influencing the quality of rolled sheet metal parts. In this research work, the investigation is made on realizing accurate conical shell-shaped components by roller bending machine for the material of construction (MOC) ALUMINIUM 6063. Effects of sheet metal thickness, number of passes, roller pressure, and roller rpm on Springback for ALUMINIUM 6063 are analyzed. After the testing of the spring back analysed with the regression analysis. In the validation work, Select the one input parameter range to develop a abaqus model. This model has been generated on the Abaqus software and after getting the result validate the result. Validation of the work has been compared the analytical work and practical work. Also find the errors between practical and analytical work.

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# List of Abbreviations 

## Symbol Parameter

| OA | Orthogonal Array |
| :---: | :--- |
| DOE | Design Of Experiment |
| FEA | Finite Element Analysis |
| OFAT | One Factor At A Time |
| DF | Degree Of Freedom |
| SS | Sum Of Square |
| MS | Mean Of The Square |
| DOE | Design Of Experiment |
| ANOVA | Analysis Of Variance |
| Seq.SS. | Sequential Sum Of Squares |
| Adj.MS | Adjusted Mean Square |
| Adj. SS | Adjusted Sum Of Square |
| SN | Signal To Noise |

# List of Symbols 

| Symbol | Name |
| :---: | :--- |
| W | Roller Distance From The Center To The Outside |
| $\beta$ | Top Roller And Bottom Roller Angle |
| D | Top Roller Diameter In Mm |
| E | Young's Modulus Of Material N/Mm2 |
| T | Thickness Of Plate In Mm |
| $\Sigma$ | Yield Strength Of Material N/Mm2 |
| N | Number Of Passes |
| K | Curve Fitting Constant |
| A to d | Exponents Of Independent Parameters |
| S | Spring Back |
| G | Acceleration Due To Gravity Of Top Roller |

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## CHAPTER - 1

## Introduction

Today in modern era, man has been continuously striving for converting the natural resources into useful products for industrial revolution human history. The world is totally dependent on science \& technology. Manufacturing plays a vital role in extracting products from natural resources. Manufacturing involves in converting raw material to finished products to be used for useful purpose.

### 1.1 Manufacturing

The word manufacture is derived from two Latin words, manus (hand) and factus (make). As a field of study in the modern era, manufacturing is defined two ways, one technologic and the other economic. Technologically, manufacturing is the application of physical and chemical processes to alter the geometry, properties, and appearance of a given starting material to make parts or products. Manufacturing also includes assembly of different parts to make products. The processes to accomplish manufacturing involve a combination of machinery, tools, power, and labour, as depicted in Figure No. 1.1.


Fig 1.1 Manufacturing System (a) Technical Process (b) Economic Process [71]

Manufacturing is carried out as a sequence of operations. Each operations bring the material closer to the desired final state. Economically, manufacturing is the
transformation of materials into items of greater value by means of one or more processing of assembly operations. The key point is that manufacturing adds value to the material by changing its shape and size by combining processes. The material has been made valuable product through the manufacturing operations performed on material. Some of examples of manufacturing process such as iron ore is converted into steel, sand is transformed into glass, petroleum is refined into plastic, Plastic is moulded into the complex geometry of a patio chair, it is made for valuable products. The words manufacturing and production are often used interchangeably. The author's view is that production has a broader meaning than manufacturing.

Manufacturing may produce many products, meaning individual parts or pieces of parts or it may produce continuous products. Nails, gears, steel balls, beverage cans and engine blocks are example of products. Metal or plastic sheet, wire, hose and pipe are continuous products that may be cut into individual pieces and thereby become discrete products. Because a manufactured item has undergone a number of changes during which raw material has become a useful product, it has added value, defined as monetary worth in terms of price.

### 1.2 Classification of Manufacturing process

Manufacturing process may be classified in two types primary manufacturing process and secondary manufacturing process.

Metal forming is one of the fundamental primary manufacturing processes in which desired shape, size and finish can be achieved without any significant loss of material by plastic deformation of the metal.

### 1.2.1 Primary Manufacturing Processes

These processes are of two types. Some of these finish product to its usable form whereas others do not, and require further working to finish the component to the desired shape and size. The products obtained through this process may or may not be required to undergo further operation; depending upon the function they have to perform. Same in the case with forging than casting. Many operations like cold rolling
die casting, metal spinning and wire drawing etc., lead to the production of directly useful articles. The common operations are:

- Casting
- Forging
- Rolling
- Bending
- Drawing
- Shearing
- Spinning
- Electroforming


### 1.2.2 Secondary Manufacturing Processes

A fairly large number of components are not finished to their usable shapes and sizes through the primary processes. These components are further subjected to one or more of the machining operation called secondary processes, to obtain the desired shape and dimensional accuracy. Thus, the components undergoing these secondary operations are basically the roughly finished products through primary operation. The secondary operations are mainly necessary when a very close dimensional accuracy is required or some such shape is desired to be produced which is not possible through primary operations. These operations require the use of one or more machine tools, various types of cutting tools and cutters, marking and measuring instruments, testing devices and gauges etc. of which a combined application leads to the desired dimensional control. The common machining performed for this purpose are the following:

- Turning
- Threading
- Drilling
- Shaping
- Sawing
- Grinding


### 1.3 Metal Forming

Metal forming includes a large group of manufacturing processes in which plastic deformation is used to change the shape of metal work-pieces. Deformation results from the use of a tool, usually called a die in metal forming, which applies stresses. Stresses applied to plastically deform the metal are usually compressive, stretch, bend, or shear stresses to the metal. To be successfully formed, a metal must possess certain properties. Desirable properties include low yield strength and high ductility. Metal forming processes can be classified into two basic categories: bulk deformation processes and sheet metalworking, and these two categories contain many processes shown in Figure No. 1.2.


Fig. 1.2 Classification of Metal Forming [71]

### 1.3.1 Bulk Deformation

Bulk deformation processes are generally characterized by significant deformations and massive shape changes, and the surface area-to-volume of the work is relatively small. The term bulk describes the work parts that have this low area to- volume ratio.

### 1.3.2 Sheet Metal Working

Sheet metal working processes are forming and cutting operations performed on metal sheets, strips, and coils. The surface area-to-volume ratio of the starting metal is high; thus, this ratio
is a useful means to distinguish bulk deformation from sheet metal processes. Press working is the term often applied to sheet metal operations because the machines used to perform these operations are presses. Sheet metal operations are always performed as cold working processes and are usually accomplished using a set of tools called a punch and die.

### 1.4 Bending Process

Bending is one of the commonly used metal forming process for obtaining the different shapes such as cylindrical, conical and spherical shells. It is very common process for changing sheet and /or plate into channels, drum, tanks etc. V-bending, edge bending, Air bending and three roller bending are most commonly used methods for bending. The use of bending process has increased because of increase of large chemical industries that requires vessels of varying shape \& size. To make shells of cylindrical or conical shape, a sequential V-bending process or a three roller bending process can be used.

The bending can be affected by various parameters viz bend angle/ radius of bending, thickness of plate, die opening/ center distance between the rollers and material characteristics. The success of bending is mainly depending upon correct knowledge of the material properties. The spring back is the vital parameter of control for the successful accurate bending. The spring back control is the function of the material properties selected for the analysis. The accuracy and success of bending depends on control of above parameters. In the industry trial and error method is commonly adopted for manufacturing of cylindrical \&/or conical shell by either three roller bending or V -bending.

### 1.4.1 V Bending

In V-bending a wedge shaped punch forces on metal strip or plate into the wedge shaped die cavity. As the punch descends, the contact forces at the die corner produces a sufficiently large bending moment at the punch corner to produce the necessary deformation. The bending operation is affected by various governing parameters like length of bend part, thickness of sheet, geometry of punch and die, material properties and angle of bend. The spring back and
punch reversal position is function of material behaviour. V- bending process shown in the Figure No. 1.3.


Fig 1.3 V Bending Process [72]

### 1.4.2 Three Roller Bending

The three roller bending process is one aimed at producing materials with various curvatures by a set of three rollers.

In roller bending forces acting on plate, rolls undergo changes in shape during rolling. Just as a straight beam deflects under a transverse load, roll force tend to bend the rolls elastically during rolling. As expected, the higher the elastic modulus of the roll material, the smaller the roll deflection. As a result of roll bending, the rolled strip tends to be thicker at its center than at its edges. The usual method of avoiding this problem is to grind the rolls in such a way that their diameter at the center is slightly larger than at their edges.

In this, plate is fed by two side rollers and bends to a desired curvature by adjusting the position of center top roller in one or several passes. Distance between the bottom rollers can also be varied. In three rollers bending machine desired curvature is function of thickness ( t ), width (b) of plate, material properties, center distance between the two bottom rollers and position of the top roller, roller distance from the center to the outside (w), top roller and bottom roller angle $(\beta)$. The involvement of so many parameters together makes the problem complex and till now experience on the shop-floor is taken as guide lines for a process planning. Any change in shape, material, machine required the similar experience to be developed again before satisfactory production can be obtained. Three roller bending process shown in the Figure No. 1.4 .


Fig 1.4 Three Roller Bending Process [5]

### 1.4.2.1 Advantages of Three Roller Bending

Many potential advantages of three roller bending over the bending process

- One Pass Bending. Due to the design of the machine, finished shells are rolled in one pass
- Very small flat area must be generated
- Product part of various length from the same roll sets
- It is providing better dimensional accuracy
- It is providing tooling allows for high degree of flexibility.
- It is used for all metals can be roll formed


### 1.4.2.2 Disadvantages of Three Roller Bending

The limitations and constraints of the research work is described below

- Higher force is required due to operation
- Higher power consumption
- Strain hardening of the work metal limit the amount of forming that can be done
- Sometimes cold forming- annealing-cold forming cycle should be followed, the work piece is not ductile enough to be cold worked. is the melting point of the work-piece.


### 1.4.2.3 Application of Three Roller Bending

The application of three roller bending research work is as given below

- Power distribution components.
- Warehouse \& data storage
- Commercial food storage
- Solar
- Trains
- Trailers \& trucks
- Guard rails \& sign posts


### 1.5 Design of Experiment

A scientific approach plan the experiments is a necessity for the efficient conduct of experiments. By the statistical design of experiments, the process planning of the experiment is carried out, so that appropriate data will be collected and analyzed by different statistical methods. When a problem involves data being subjected to an experimental error, the statistical methodology is the only objective approach to analysis. There are two aspects of an experimental problem: the design of the experiments and the statistical analysis of the data. These two points are closely related since the methods of analysis depend directly on the design of experiments employed. The advantages of the design of experiment are as follows:

- Reduce the number of trials
- Significant decision variables for process/ product identified.
- Optimal setting of the parameters found.
- Experimental errors have been estimated
- The relationship between the input parameters on output characteristics of the process has been identified.
- Important decision variables that control and improve the performance of the product and the process identified.
- A qualitative estimation of parameters has been made
- Inference regarding the effect of parameters on the characteristics of the process has been made.

DOE is a technique of defining, investing all possible combinations in an experiment involving multiple factors and identifying the best combination. Different factors and their levels are identified. The design of experiments is useful to combine the factors at appropriate levels with respective acceptable ranges to produce the best results and exhibit minimum variation around the optimum results. In a designed experiment, the engineer often makes changes in the input factors. Determines how the output functional performance varies accordingly. It is important to note that not all variables affect the performance in the same manner. Some may have strong influences on the output performance, some may have medium influences, and some do not influence at all. Therefore, the objective of a carefully planned design of experiment is to understand which set of variables in the process affects the performance most and then determine the best levels for these variables to obtain satisfactory output functional performance in the product. The design of experiment is used to develop a layout of the different conditions to be studied. An experiment design must satisfy two objectives:

1. The number of trials must be determined.
2. Conditions for each trial must be specified.

Before designing an experiment, the knowledge of the product/process under their investigation is of prime importance for identifying the factors likely to influence the outcome. This Design of Experiments (DOE) is a method to determine the critical factors in a process, identify and fix the problem in a process, and also identify the possibility of estimating interactions. The methods of Design of experiment such as full factorial method, taguchi method, response surface method.

### 1.5.1 Taguchi Method

The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varies. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations.

The variables selected for this investigation are initial pH , reaction time, current density and coagulant types. In the Taguchi method, if all variable interactions, are taken into consideration, the L27 ( $3^{3}$ ) orthogonal array is the most appropriate experiment plan. The L27 orthogonal array with variables and their interactions have been used for the research work. The input parameters are number of pass, pressure of roller, thickness of sheet, and roller speed. From the above input parameters given a total number of 27 experiments.

## CHAPTER - 2

## Literature Survey

This work is aimed to study the research work related to the roller bending by different researchers and to propose optimal parameters that affect the bending of ALUMINIUM alloys. In bending very recent techniques and very experiments conducted experiments on the studies. Many analytical methods were studied by different researchers such as finite element method, analysis of variance, regression etc. interactions taking place during the process.

### 2.1 Literature Review

In the present work, based on the roller bending, reported in the literature of bending process it may be majorly classified as mentioned.

1. Models on the roller bending plate
2. Review on an optimization of mechanical properties of Friction stir welding
3. Roller bending input parameters
4. Raw material used in the work

Yan Wang et al. (2018) observed the dynamic analysis with four roller machine performed using the Abaqus/ Explicit code. It has been analyzed finite element analysis with multi pass of the rolling banding process. The specific steps are as follows: Firstly, as shown in Fig. 2.1a, the left roll is lifted to align the plates. Subsequently, as shown in Fig. 2.1b, the right roll is lifted to bend the end of the sheet. After pre-bending, the top roll starts and roll the plate firstly, as shown in Fig. 2.1c. In the second rolling process, as shown in Fig. 2.1d, the right roll continues to lift and the top roll rotates in reverse. Then, the right roll is lifted again, the top roll rotates in the forward direction, and the plate is transited to the third rolling process, as shown in Fig. 2.1e. It has been validated result of theoretical as well as practical work. The multi-pass roll forming process, which is a process method that can effectively improve the forming accuracy of work pieces, has been widely used in the industry represent by Figure No. 2.1. Many theories about multi-pass roll forming have been developed.

(a) alignment

(d) second rolling

(b) pre-bend

(e) third rolling

(c) primary rolling

(f) end of rolling

Fig 2.1 Four Roll Bending Forming Process [63]
Gaochao Yu et al. (2019) observed the four roller bending process and its optimum forming process is determined. The stress and deformation of plate between the rollers during each forming stage like, pre-bending, reverse rolling, final bending, positive roll bending, unloading, and spring back also, given in the below Figure No. 2.2. In this paper theoretical analysis, numerical analysis and experiments have been done. In this process ABAQUS software is used for the analysis work. It has been observed the stress strain analysis. It is obtaining ovality of $0.43 \%$ and 1.5 times the thickness of the straight edge, from the experiments less than $5 \%$ and minimum is $1.74 \%$. Researchers have been concluded the physible method of the four roller bending method. It has been concluded that the effect of lower and upper spacing and plate thickness.


Fig 2.2 Main Procedure of the Four Roller Bending Process [66]

Jabbar Gattmah et al. (2019) observed the v bending process with the help of ABAQUAS software to find out the finite element analysis. In this paper punch radius and plate thickness is important parameters for spring back and residual strain. Plate thickness increase so spring back decreased.

Jan SLOTA et al. (2015) observed the spring back phenomena for mild steel material. It has been analysed stamping optimisation with the help of finite element analysis. In this paper different hardening models were used such as isotropic, kinematic, and mixed isotropickinematic. Researchers have been observed the kinematic behaviour of the material more accurate results than others.

Vishwanathan Shrinath et al. (2019) observed the three roller bending process for ALUMINIUM alloy. This paper has been given the information about the work on the numerical model using hyper works and radios solver to influence on the load, distance between forming rollers and thickness and spring-back. Meshed model of the three roller bending shown in the Figure No.
2.3. The amount of spring back increases with an increase in top roller displacement. The amount of spring-back increased with decreased plate thickness. Distance between bottom rollers has a minor influence on the spring back. Below Figure No. 2.4 shows the stress distribution in the plate and Figure No. 2.5 gives the information about the strain distribution on the plate with three roller bending.


Fig 2.3 Meshed of Three Roller Bending [60]
$\mathrm{Max}=1.103 \mathrm{E}+02$
SHEZL 635
Min $=0.880 \mathrm{E}+00$ SHELC゙1693


Fig 2.4 Stress Distribution in Sheet Metal [60]

Contour Plot
Plastic Strain along the thickness(Scalar value, Max)

- $6.053 \mathrm{E}-03$
$-5.380 \mathrm{E}-03$
$-4.708 \mathrm{E}-03$
$-4.035 \mathrm{E}-03$
$-3.363 \mathrm{E}-03$
$-2.690 \mathrm{E}-03$
$-2.018 \mathrm{E}-03$
$-1.345 \mathrm{E}-03$
$-6.725 \mathrm{E}-04$
$-0.000 \mathrm{E}+00$

Max $=6.053 \mathrm{E}-03$
SHELL 433
$\operatorname{Min}=0.000 \mathrm{E}+00$
SHE゚LLA


Fig 2.5 Strain Distribution in Sheet Metal [60]
G. Pradeep Dev et al. (2016) observed bending process on AA 6061 with three-point bend test. Spring back during the unloading has been analysed with finite element analysis. Parametric numerical simulation studied for elastoplastic behaviour. The systematic approach is carried to developing numerical models of three point bending for ALUMINIUM strip. Surface plot the overall correlation can be understood that the residual stress is increased when sample thickness and displacement load is higher for shorter roller distances. The thickness has significant role in the spring-back and residual stress formation. Further for the betterment of component strength these two parameter may be optimized and appropriate optimum parameters can be obtained. Below Figure No. 2.6 gives information about the three roller bending process setup.


Fig. 2.6 Three Roller Bending Setup [20]
Péter Máté et al.(2020) observed the numerical analysis of three roller bending process of thin plate. This method is observed with the help of finite element method for numerical and analytical analysis. It is used simple four nodes quadratic plane. It has been applied first load to peak point of the curvature and after it would be exponentially decreased harmonic function. Figure No. 2.7 represent the structure sketch.


Fig. 2.7 Structure Sketch [39]

Jenan Mohammed Naje (2019) have been observed that some of factors can influence the industry of sheet metal, and the realization of the applicable sheet based on its features and the goal which the sheet has been made for it. However, the physical factors which affected metal forming of the bend angle which has been proportional to the motility of the sheet formation, the width of the sheet which is inversely proportional to the formation of a metal, the bend radius which is directly to the metal formation, and finally the sheet thickness has been inversely proportional to the metal formation. Studies and researches were made in order to optimize the methodology of the metal formation to make it less power and time consuming with better formation and less errors.

Ionel Gavrilescu et al. (2021) has been observed that the application of the three roller bending. In this paper bending machines are designed for the ship building with wide range of the radii and custom basis of the shipyards. It is used for the finite element analysis and regression analysis used for the research. It is also providing the flow chart in the below Figure No. 2.8. Three roller bending simulation was carried out using the Ansys workbench static structure program. It is also shown in the below Figure No. 2.9. It is used for bent bar theory for analytical model analysis work. In this paper S235JR and S275JR steels are used for the naval
industries and it analysis work on the FE analysis. Regression analysis has been used for the relation with parameters. It is main aim to found the setting parameters of the three roller machine. The models take into consideration the plate thickness ( $8-12 \mathrm{~mm}$ ) and vertical displacement of the upper roller (up to 78 mm ). For other values of the yielding stress, the bending force can be obtained by interpolation (because the three-roller bending system has a diameter of 189 mm and the distance between the axis of the lower rollers of the system is 320 mm ).


Fig 2.8 Flow Chart of the Finite Element Analysis [14]


Fig 2.9 (a) Total Deformation at End Stage
Fig 2.9 (b) Points for the Estimation of the Radius [14]
Prafull S et al. (2019) worked on the trial and error method to achieve desired curvature or shape of final products. Mathematical model is developed using dimensional analysis. Developed model is validated with experimental data and mean square error between computed and estimated values are calculated. The absolute index $\pi 3$ value is highest 0.2820 and most influencing. The lowest absolute index $\pi 2$ value is -0.9934 . The sequence of influence of the
other independent pi terms present in the model are $\pi 4, \pi 1$, and $\pi 5$ having absolute indices $-0.5384,-0.7068$, and -0.8016 respectively. Percentage error for top roller displacement is found to be $1.237 \%$. Percentage error obtained is less than $10 \%$. It shows that values obtained from mathematical model are close with actual experimental values. Below Figure No. 2.10 graph shows the independent pi terms influencing the dependent pi term $\pi \mathrm{R}$ in descending order.

## Indices of Pi Terms for $\boldsymbol{\pi}_{\mathrm{R}}$



Fig 2.10 Graph Shows the Independent Pi Terms [55]

Sutasn Thipprakmas et al. (2022) analysed the spring back effect on the bent holed parts in v die bending process. The bending mechanisms and spring-back in the case of bent holed parts were different from those in the case of bent non-holed parts. Vice versa, they were the same in the case of hole located at leg zone. The results were clearly based on the stress distribution analysis. Although the bending characteristics decreased by making hole when the hole was located at bend radius zone, the additional elastic zone was formed on the hole during hole deformation. The amount of spring-back was increased. In addition, it increased as the hole diameter increased. With the hole located next to bend radius zone, in this zone the reversed bending characteristics was formed but there rarely was any distortion of hole. Making hole, this reversed bending characteristics decreased and the amount of spring-back increased. In addition, the amount of spring-back increased as the hole diameter increased.
M.K.Chudasma et al. (2013) observed the cylindrical conical cross section structural parts are widely used in industrial parts. In this process blank sheet are cut in below Figure No. 2.11 shape. It has been given predicted forces are analysed of the work.


Fig 2.11 Schematic Diagram of the Conical Bending Setup [5]
Prafull S. Thakare et al. (2018) analysed the different process parameters in the work such as Top roller radius, Bottom rollers radii, Top and Bottom rollers inclination (for conical bending only), Center distance between bottom rollers, Thickness and width of plate, Material properties of plate ( $\mathrm{E}, \mathrm{K}, \mathrm{n}, \mathrm{v}$ ), Number of passes, Coefficient of friction between rollers and plate material. It has been analysed analytical result models with experimental models.

Xian Feijun et al. (2000) observed the conical roller bending process for advanced precision forming process for producing ring. It has been analysed systematically rigid plastic FEM for effects on process parameters. In the given below Figure No. 2.12 gives the cut section view for the roller bending process and it is helpful to the conical bending process.


Fig 2.12 Cut Section View of the Bending Strip [11]
A.H. Gandhi et al. (2008) observed the empirical model of the top roller position explicitly as a function of desired radius of the curvature with the help of the three roller bending. The below Figure No. 2.13 gives the geometry of the roller bending process. It is observed that the spring back curvature is directly related to the material properties and dimensions. Below Figure No. 2.14 represent the comparison of internal bending moment for different thickness of the plate.


Fig 2.13 Geometry of Roller Bending [3]


| $\square-\mathrm{t}=5 \mathrm{~mm}$ | $-\overrightarrow{\mathrm{m}} \mathrm{t}=8.29 \mathrm{~mm}$ |
| :--- | :--- |
| $\cdots \Delta \cdots \mathrm{t}=12 \mathrm{~mm}$ | $--ヤ-\mathrm{t}=14 \mathrm{~mm}$ |

Fig 2.14 Comparison of Internal Bending Moment for Different Thickness of the Plate. [3]
Z.Q. Hu et al. (2009) Have been observed the continuous flexible forming technology with 3D parts and formulation observe. In this work bendable roller has been developed for the bending process. The experiments show that the transversal spine of 3D part is determined by the bended shape of the bendable rollers, and the longitudinal spine of the 3D part is determined by the relative displacement among the top roller and the two bottom rollers. The technology of forming 3D surface sheet metal using bendable rollers can produce 3D surface parts in a rapid and economical way.
M. Hua et al. (1994) discussed the working principal and mechanism of the continues four roller bending process. The sequence of the processes has been given (i) the process edge setting in, (ii) edge pre-bending in which the RHS, side roll is nominated to perform the bend and is named pre-active side roll while the LHS, side roll used originally for edge setting is termed pre-inactive side roll (iii) steady continuous bending with pre-active side roll operative (iv) steady continuous bending with pre-inactive side roll operative. Below Figure No. 2.15 represent the sequence of roller thin plate bending.



2.

5.

3.
Coses)
6.

Fig 2.15 Sequence of Roller Thin Plate Bending [21]

Vaibhav Suresh Deore et al. (2015) observed the bending machine for the bend of the metal. Layout of the machine and configuration is decided based on analysis. It is used to manufactured a pyramid type plate bending machine. In this paper some of the material selection have required a desire property.

- It should possess modulate strength, toughness in working condition.
- It should sustain vibration caused by rotating parts.
- It should have attractive outlook.
- It should be least in weight.
- Material should retain its strength under loading.
- It should be fulfilling from economical point of view.

Ahmed Ktari et al. (2012) observed the FEA model dynamic analysis of steel sheet bending with three roller bending with abacus software. It has been validating this work with numerical and experimental results. Several maps were then developed, enabling variations in desired ferrule diameters versus positions of the top roller and the distance between the bottom rollers of both 14 and 30 mm sheet thicknesses. Maps made the rolling process easier and faster. Below Figure No. 2.16 represent the Cylindrical rolling process phases: (a) initial bending condition; (b) initial rolling condition; (c) $1 / 4$ of the rolling process; (d) $1 / 2$ of the rolling process; (e) $3 / 4$ of the rolling process and (f) obtained ferrule.

(a) initial bending condition

(b) ) initial rolling condition


Fig 2.16 Spring Back Effect [26]
A Ktari et al. (2021) observed the tube hydroforming process. This work is related to the 3DFE analysis of THF process in a square section die plastic flow and residual stress after the spring back. FE model is validated with the experimental work and found that the thee different zones such as straight wall, transition zone, corner radius were easily visible. It is observed that the transition zone found the smallest thickness. It is evolution the plastic strain on both inner and outer surfaces present the corner zone seems to quasi uniform. The residual stresses are
higher near the inner thickness of corner sections than the outer surface. COF affects significantly the values of the residual stresses particularly near the outer surface of the tube corner zone. In this paper taken a COF $0.05,0.1,0.15,0.2$ and 0.25 . The below Figure No. 2.17 (a) represent the hydro formed tube and Figure No. 2.17 (b) shows the cross section for thickness variation measurements.


Fig 2.17 Hydro Formed Tube and Cross-Section View [25]

A Mercuri et al. (2021) observed the roll bending process of thick metal sheet. In this work three-point roller bending machine with pyramid type machine has two bottom roller and one top roller. This one is used for the industries in oil and gas field, naval field, or automotive field. A Finite Element (FE) 3D model of both the roll-bending machine and the metal sheet is used to simulate the mechanical behaviour of the metal sheet during the forming process, checking for the influence of the spring-back effect and the bending moments from the rolls. This roller bending process has been divided in three phase
(i) Roll-bender and sheet dimensions have been collected together with material properties for the bent sheet.
(ii) key-process parameters during both pre-bending and roll-bending processes have been acquired and thermal video footage of the roll bending process has been recorded.
(iii) final product main geometrical features have been acquired; in particular, thickness, internal diameter, external diameter and length have shown variations along the cylinder length and a deviation of cylinder shape to an hourglass shape have been detected.

In this paper analysis on the axial strain field at the edge located strain and appreciable differences between internal and external edge strain on three roller bending process. Thermal measurements are taken through the Flir A655 thermal camera, which allows both the thermal video record and the numerical temperature local data collection during the whole process. In the below given Figure No. 2.18 gives information about the thermal shooting of roll bending process, which represent the image easily visible that the heating temperature at the curve portion has been shown, hence rolls x-position and y-position units are in mm .


Fig 2.18 Thermal Shooting of Roll Bending Process [1]
Mohammad Zamani Nejada et al. (2014) observed the Failure shear deformation theory (FSDT) and elasticity theory for the analysis work. Multi-layer method (MLM) shows the radial displacement, radial stress, circumferential stress and shear stress. It has been observed that the radial displacement and circumferential stress distribution change with respect to the internal pressure. In this paper FGM used for the levelling radial displacement profile in the axial direction of the truncated cone and reduced stress.

Si-Myung Park et al. (2020) analysed on the surgical bending plate with automated bending apparatus. It is observed that the experimental testing effect of input angle in the proposed bending apparatus revealed that the predicted angle of spring back was very similar. The higher
accuracy of the plate shape and bending process have some advantages for reconstructive surgery is reduce operating times, increase convenience, and improve plate stability.

Jingwen Peng et al. (2017) observed the three roller bending on the ALUMINIUM alloy 2060 T8. The ALUMINIUM-lithium alloy 2060-T8 is widely utilized in the fabrication of future aircrafts. With the application of this high-strength alloy, the severe shape variation after unloading has been challenging the traditional process for forming fuselage skin components. In this work comparison of the different forming curves achieve with different forming curve. This has been work on the different methods used and final configuration achieved. It is compared result with FE simulation and theoretical process. the analytic models produce the precise prediction due to the application of the variable material model. Because of the remarkable benefit of time saving, the theoretical calculation of the three-roller bending is more suitable and favourable in actual fuselage skin fabrications. In this process lower and upper roller ascending and descending process shown in this below Figure No. 2.19.


Fig 2.19 Simulation Process of the Three Roller Bending Process [38]
Prafull. S. Thakare et al. (2019) observed the bending operation on the single and multi-passes. It has been observed that the single pass bending is economical and efficient method but final
dimensions depends on the experience and expertise of operator. It has been revealed that the relationship among with various parameters (top roller diameter, bottom roller diameter span of bottom rollers, yield strength of material, thickness of plate, desired radius, young's modulus) with non-dimensional formulation. Model used for individual as well as interaction effect of various parameters on multi pass cylindrical forming of plate. Validation process has been used with dimensional analysis and experimental data. It is found that the average RMSE to be less than $10 \%$ of applied methodology.

Rameshwar J. Sherepatil et al. (2020) observed the four roller double pinch bending machine, three roller symmetric bending machine, three roller asymmetrical bending machine used. It has been work on the L9 Taguchi method for three different levels in order to determine $\mathrm{S} / \mathrm{N}$ ration. In this work input parameters such as diameter to top roller $(\mathrm{mm})$, diameter of bottom roller ( mm ), span of bottom rollers (mm), type of motor, bending capacity, plate thickness and three materials (E250, E300, E350). It has been found that the significant factors from the ANOVA that the thickness of plate, number of pass, yield strength of material and radius of curvature.

Quan Hoang Tran et al. (2014) observed 3D-dynamic Finite element (FE) model of a roll bending process verified using experiments was developed in this paper. This model allowed the authors to identify the primary processing parameters of the roll bending process and to investigate the influence of these process factors on the precision of the final shape. The influence of several forming parameters, such as plate thickness, final shape radius, and width of final shape, on reaction forces were studied in detail. Furthermore, a new experimental approach for measuring strains with strain gauges to obtain the strain variation left in the formed plate is proposed. This comprehensive analysis will be beneficial in the industrial context for an accurate prediction of the final shape or reaction forces acting on bending rolls to increase the effectiveness. In the given below figure gives information about the time vs. power with regard to the thickness of the plate.


Fig 2.20 Power Vs. Time of the Bending Process [56]
From the above Figure No. 2.20 represent that the thickness increased so apply power increase and time is considered is constant for all plate thickness.

Rameshwar J. Sherepatil et al. (2020) analysed that the roller bending process top roller is responsible for the accuracy in profiles. Bending operation depends on the skill and experience of the workers. It has been observed that the multi-pass bending is good compared to single pass bending.

Rehan Waheed et al. (2021) observed the effect of the displacement of part with respect to the bending dies and variation in yield strength of the material. Explicit dynamic analysis is performed to simulate the sheet metal bending process. In this work 1 mm misalignment between the die and work-piece affects the bending force and residual stress. The bending force is calculated based on the material behaviour. This is performed with the adaptive control system with the help of CNC press brakes.

YanWang et al. (2019) observed the characteristics on the thick material plate and the roll bending mechanism of extra thick plate material. It has been found that the maximum equivalent stress increase $15.3 \%$ because of the strong anti-deformation ability. The maximum
deviation of the forming radius is $5.7 \%$, forming radius of extra thick has maximum deviation is $19.8 \%$ compared with other plate thickness. In this process roll processing speed is between 0.15 and $0.45 \mathrm{rad} / \mathrm{s}$. In this process friction co-efficient is between 0.1 to 0.3 and the forming radius of extra thick plate is $20 \%$ higher compared to the 30 mm plate thickness.

He Yang et al. (2000) observed in plane bending of strip metal work-piece under unequal compression with advanced precision forming process with high quality, high efficiency, low consumption, and good flexibility of size changing. In this work an experiment conduct on the LF21M strip work piece and sheet thickness consider as a 1.90 mm and 1.50 mm . In this paper some of the criteria, for a given material the original thickness $t_{0}$, original width $b_{0}$, unequal compression width $a_{z}$, and the smallest thickness of the formed work piece $t_{1}$, there are the instability parameters of $K_{1}, K_{2}, K_{3}, m_{1}$, and $m_{2}$. which satisfy the conditions of $0<K_{1}<K_{2}<$ $K_{3}$ and $0<m_{1}<m_{2}$. It is possible for the work piece to produce external wrinkling when $a_{2} / b_{0}$ $\leq K_{1}$ or $t_{1} / t_{0} \leq m_{1}$, turning when $K_{1}<\mathrm{a}_{2} / \mathrm{b}_{0} \leq \mathrm{K}_{2}$ and $\mathrm{m}_{1}<\mathrm{t}_{1} / \mathrm{t}_{0} \leq \mathrm{m}_{2}$, and internal wrinkling when $K_{2}<\mathrm{a}_{7} / \mathrm{b}_{0} \leq \mathrm{K}_{3}$ and $\mathrm{m}_{1}<\mathrm{t}_{1} / \mathrm{t}_{0} \leq \mathrm{m}_{2}$. When $\mathrm{a}_{7} / \mathrm{b}_{0}>\mathrm{K}_{3}$ and $\mathrm{m}_{1}<\mathrm{t}_{1} / \mathrm{t}_{0} \leq \mathrm{m}_{2}$, the work piece can perform a stable process of in-plane bending and greatly improve the bending forming limit without any mode of instability, which is difficult with any conventional process. In the values parameters are $\mathrm{K}_{1}, \mathrm{~K}_{2}, \mathrm{~K}_{3}, \mathrm{~m}_{1}$ and $\mathrm{m}_{2}$ are $0.25,0.45,0.60,0.30$ and 0.95 respectively.

Zhi-qiang ZHANG et al. (2014) analysed on the pre-bending mode is compare with that after roll- bending mode. It has been give relationship among edge pre-bonding angle, edge length, and cylindrical roll with the help of the three roller bending process. It analysis on the model of spring-back and stress-strain relationship of material. The accuracy increases with the increase of the ratio of width to thickness. This model has been performed on the elastoplastic material. The results are shown that error between numerical and practical data, the influence of bottom roller, relative curvature, bending arc length on spring back.

### 2.2 Summary of Literature Review and Research Gap

In this literature review, researcher's mostly focused on the bending process. It has been discovered by analysing the literature, that the main focus on the spring back, analysis of different software with different parameters on the bending process. Three roller bending process has been given the proper choice of the process parameters such as number of pass, thickness pf the plate, distance between three rollers, roller force etc. It is also providing the
information of the trial and error strategy helpful in our research. It might be an addition information on which software is useful for the analysis of the work.

Moreover, it does not ensure certainly the required properties and quality of the finish products. The machine manufacturer does not provide specific value of the process parameters for the specific material. Hence it is necessary to analyse the given range of process parameters recommended by the manufacturer for the specific material. In addition, it has been found any application of the algorithm to find optimal parameters for the three roller bending process on ALUMINIUM material. Therefore, it is essential to conduct investigation to determine the process and optimal parameter. After a comprehensive literature review, a number of research gap have been observed.

- Few researchers have been explored an ALUMINIUM alloys on the three roller bending process, but extremely limited work found on the 6063 material with the help of three roller bending process.
- From the literature review, it has been observed that the several investigations on the v bending, two roller bending, four roller bending but limited work on the cone bending process with the three roller bending process.
- Some of the researcher, work on different parameters with limited process parameters on bending process.
- A limited study is conducted using the proper design of experiments methods like Taguchi, response surface methodology and full factorial


### 2.3 Problem Statement

ALUMINIUM is useful in the real life. In the modern era, everywhere for the light duty work ALUMINIUM 6000 grade is used. In the bending process material get stretch and get the fatigue stress. In the bending process apply some force above than elastic force so it is not get to the real position. Some force applies on the material with different process so it is impact on the particular point on the material. But in the roller bending process Force can be distributed on the whole plate. Also number of pass increase the force on the plate step by step get the proper position. Three roller bending process is compared to other bending process stress relieving process and spring back is less.

From the above discussion we make statement "INVESTIGATION \& OPTIMIZATION OF PROCESS PARAMETERS OF ROLL BENDING MACHINE IN REALIZING CONICAL SHELLS IN ALUMINIUM MATERIALS".

### 2.4 Objectives of the Research Work

- To find out an optimum process parameter to improve Spring back effect of material Al 6063 by bending operation with three roller bending process.
- Identify number of parameters responsible for Spring back effect for Al 6063 material using 3 roll bending machine during rolling process.
- Application of taguchi method to identify effectiveness of identified parameters with experimental result.
- Develop mathematical model to check effectiveness of parameters identified by experimental method for Al 6063 for 3 roll bending Process.
- Identify (\% error) between experimental result and mathematical model.
- Develop an approach to simulate the 3 roller cone bending and springback effect in FEA analysis.
- Study the Springback effect in simulation results from FEA analysis.
- Validation of experimental result, and mathematical model by using FEA analysis.


### 2.5 Contribution of Research and Society

This research attempts to provide enough knowledge to those industries that use the bending process for making different parts in the industries. Research has also provided the optimal process parameters for desired performance evaluation criteria in specific industry application. This prior knowledge reduces the bending time of making parts, increase the roller life and get the perfect shape by adjusting the parameter setting. In addition, it is easily predicting the performance criteria by varying the value of the process input parameters with help of the mathematical equation.

## CHAPTER - 3

## Methodology and Experimental Work

This chapter describes methodology and experimental work of three roller bending process.

To select the materials as per the application. Three roller bending process select process, number of pass, roller pressure, pilot test with different input parameters and final experiment with Design of experiment (DOE) and characteristics are discussed here.

This section describes the methodology used in current research.

- Identification of independent, dependent, and independent extraneous variables.
- Reduction of independent variables adopting dimensional analysis.
- Determination of test envelope, test points, test sequence, and experimentation plan.
- Physical design of an experimental set up.
- Execution of experimentation for data collection.
- Purification of experimentation data.
- Analysis of practical data.
- Model optimization.
- Sensitivity analysis and validation of the model.


### 3.1 Material Selection

AA 6063 is an ALUMINIUM alloy, with magnesium and silicon as the alloying elements. The standard controlling its composition is maintained by The ALUMINIUM Association. It has generally good mechanical properties and is heat treatable and weldable.

It is widely used in boiler, shipbuilding, petroleum, chemical, metal structure and machinery manufacturing industries. AA 6063 is the most common alloy used for ALUMINIUM extrusion. It allows complex shapes to be formed with very smooth surfaces fit for anodizing and so is popular for visible architectural applications such as window frames, door frames, roofs, and
sign frames. Applications requiring higher strength typically use 6061 or 6082 instead. Mechanical properties of the AA 6063 have been given Table No. 3.1.

Table 3.1 Mechanical Properties of AA6063

| Density <br> (g/cc) | Hardness, <br> Brinell | Ultimate <br> Tensile <br> Strength <br> (Mpa) | Elongation <br> at Break | Modulus <br> of <br> Elasticity <br> (Gpa) | Poisson's <br> Ratio | Fatigue <br> Strength <br> (Mpa) | Shear <br> Modulus <br> (Mpa) | Shear <br> Strength <br> (Mpa) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 2.7 | 60 | 186 | $12 \%$ | 68.9 | 0.33 | 68.9 | 25.8 | 117 |

Chemical properties of the AA 6063 has been given below given Table No 3.2.

Table 3.2 Chemical Composition of AA 6063

| Comp. | Al | $\mathbf{C r}$ | $\mathbf{C u}$ | $\mathbf{F e}$ | $\mathbf{M g}$ | $\mathbf{M n}$ | $\mathbf{S i}$ | $\mathbf{T i}$ | $\mathbf{Z n}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\%$ | balanced | 0.1 | 0.1 | 0.35 | 0.45 | 0.1 | 0.5 | 0.1 | 0.1 |

### 3.2 Machine Specifications

Three roller cone shape bending process has been performed on the below machine Figure No. 3.1. In this machine three roller plate machine usually take place two lower rollers as the active rollers, which can realize forward and reverse rotation. One upper roller is the driven roller, which can move up and down vertically. The driven rollers (bottom rollers) are driven by motor and reducer and rotate in the same direction and at the same speed (or in the opposite direction).

Due to the friction between the roller and the plate, the plate is driven forward and the roller rotates. Appropriate adjustment of the upper roller position can make rolls of different
curvature plates. If the work-piece cannot reach the required curvature after rolling processing, the upper roller can be lowered appropriately and then reverse rolling can be repeatedly performed until it is rolled into the required shape. The three rolls of the symmetrical threeroller bending machine are arranged in an isosceles triangle, so the two ends of the work-piece are bound to leave a straight line during the rolling process. The below Figure No. 3.1 shows the image of the three roller bending machine and its specifications are shown in the Table No. 3.3.


Fig 3.1 Three Roller Bending Machine

Table 3.3 Three Roller Bending Specifications

| Sr. No. | Specifications | Range |
| :---: | :---: | :---: |
| 1 | Range | $4-50 \mathrm{~mm}$ |
| 2 | Length | 550 mm |
| 3 | Max Plate Width | 1500 mm |
| 4 | Max Plate Thickness | 5 mm |


| 5 | Upper Roller Diameter | 150 mm |
| :---: | :---: | :---: |
| 6 | Lower Roller Diameter | $130-200 \mathrm{~mm}$ |

### 3.3 Pilot Run Experiments

In this research work total three pilot runs have been performed with different input parameters. A successive pilot test has been performed to overcome the limitations of previous test. All the results such as inner and outer diameter of the cone plate, bending process, number of pass, thickness of the plate etc. of the third pilot test have been founded satisfactory. Final process parameter ranges have been finalized based on all positive aspects of three pilot tests. Pilot test image shown in the Figure No 3.2.


Fig 3.2 Pilot Test Images (i) Top View (ii) Bottom View

### 3.4 Design of Experiments

Before Design of Experiments (DOE), the knowledge of the product/process under their investigation is of prime importance for identifying the factors likely to influence the outcome. The methods of design of experiment such as full factorial method, taguchi method, response surface method. Below Table No. 3.4 Shows the factors and levels of process parameters.

Table 3.4 Factors and Levels of Process Parameters

| Factors | Notations | Level 1 | Level 2 | Level 3 |
| :--- | :---: | :---: | :---: | :---: |
| Roller pressure | $\mathrm{kg} / \mathrm{cm}^{2}$ | 1200 | 2400 | 3600 |
| Roller speed | rpm | 8 | 9 | 10 |
| Sheet thickness | mm | 1 | 2 | 3 |
| Number of pass | nos. | 1 | 2 | 3 |

### 3.4.1 Taguchi Method

Taguchi Orthogonal Array (OA) design is a type of general fractional factorial design. It is a highly fractional orthogonal design that is based on a design matrix proposed by Dr. Genichi Taguchi and allows you to consider a selected subset of combinations of multiple factors at multiple levels.

The Taguchi method are used to optimize the combination of a selected parameters because it has so many numbers of combination that is a full factorial method and it is difficult to do project so that Taguchi method are used to optimize the number of combinations to make the project cost-effective. When a new material is used in the concrete all the mix variables are taken into account so that it may cost so much, it means more need for money and material, personnel, time. In order to reduce the number of mix combination parameters.

In the Table No. 3.5 gives information of the Design of Experiments (DOE) table for an experimental work.

Table 3.5 DOE Table

| Sr. <br> No. | Roller Speed (rpm) | Pressure (kg/cm ${ }^{2}$ ) | Thickness (mm) | No. of Pass |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 8 | 1200 | 1 | 1 |
| 2 | 8 | 1200 | 1 | 1 |
| 3 | 8 | 1200 | 1 | 1 |
| 4 | 8 | 2400 | 2 | 2 |
| 5 | 8 | 2400 | 2 | 2 |
| 6 | 8 | 2400 | 2 | 2 |
| 7 | 8 | 3600 | 3 | 3 |
| 8 | 8 | 3600 | 3 | 3 |
| 9 | 8 | 3600 | 3 | 3 |
| 10 | 9 | 1200 | 2 | 3 |
| 11 | 9 | 1200 | 2 | 3 |
| 12 | 9 | 1200 | 2 | 3 |


| 13 | 9 | 2400 | 3 | 1 |
| :---: | :---: | :---: | :---: | :---: |
| 14 | 9 | 2400 | 3 | 1 |
| 15 | 9 | 2400 | 3 | 1 |
| 16 | 9 | 3600 | 1 | 2 |
| 17 | 9 | 3600 | 1 | 2 |
| 18 | 9 | 3600 | 1 | 2 |
| 19 | 10 | 1200 | 3 | 2 |
| 20 | 10 | 1200 | 3 | 2 |
| 21 | 10 | 1200 | 3 | 2 |
| 22 | 10 | 2400 | 1 | 3 |
| 23 | 10 | 2400 | 1 | 3 |
| 24 | 10 | 2400 | 1 | 3 |
| 25 | 10 | 3600 | 2 | 1 |
| 26 | 10 | 3600 | 2 | 1 |
| 27 | 10 | 3600 | 2 | 1 |

### 3.5 Measurement Evaluation Criteria

The qualitative and quantitative measurement of the experiment work has an important aspect of research and optimization. In the current investigation, bending have been evaluated through a number of performance evaluation criteria as per the material and its application requirements. In this research work, spring back has been done. Input parameters have been observed with the help of the spring back effect.

### 3.5.1 Spring Back

Spring back is the geometric change made to a part at the end of the forming process when the part has been released from the forces of the forming tool. Upon completion of sheet metal forming, deep-drawn and stretch-drawn parts spring back and thereby affect the dimensional accuracy of a finished part. The final form of a part is changed by spring back, which makes it difficult to produce the part. As a result, the manufacturing industry is faced with some practical problems: Firstly, prediction of the final part geometry after spring back and secondly, appropriate tools must be designed to compensate for these effects.

Through the application of new materials, the number of problems increases. Forming parts made of these materials are more affected by springback than parts made from conventional deep-drawn steel. Concerning classic sheet metal defects such as splits and wrinkles, strain in the sheet metal is decisive. If springback occurs, such models are not enough to predict a deformation. In this case, the stresses are decisive and a considerably higher accuracy is crucial.

During the development of tools, springback is compensated by software in order to remove the part from the tool straight away in the required dimensions. Intense tryout loops, which occur at a very late stage in the development of the tool, are reduced to a minimum.

### 3.6 Analysis of Variance (ANOVA)

ANOVA is a standard statistical technique to interpret the experimental results. The percentage distribution of various process parameters to the selected performance characteristics can be estimated by ANOVA. Thus information about how significant the effect of each controlled parameter is on the quality characteristics of interest can be obtained. ANOVA for raw data has been performed to identify the significant parameters and to quantify their effect on the
performance characteristics. The ANOVA based on the raw data identifies the factor which affects the average response rather than reducing variation.

ANOVA helps in formally testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels. A study of ANOVA table for a given analysis helps to determine which of the factors need control and which do not. Analysis of variance many quantities such as degree of freedom, a sum of squares, mean squares etc. are computed and organized.

Degree of Freedom: It is a measure of the amount of information that can be uniquely determined from a given set of data. DOF for data concerning a factor equals less than the number of levels. The degree of freedom measures how much independents information is available to calculate of each sum of square.

Degree of Freedom Total $=\mathrm{k}-1$

Sequential Sum of Squares (Seq. SS): These sequential sum of squares for each term in the model measures the amount of variation in the response.

Adjusted Sum of Square (Adj. SS): The adjusted sum of squares for a term in the model measure the amount of additional variation in the response.

Adjusted Mean Square (Adj. MS): The adjusted mean square for a term is simply the adjusted sum of squares divided by the degree of freedom.

Variance Ratio: Variance ratio is the ratio of variance due to the effect of a factor and variance due to error term. This ratio is used to measure the significance of the facto under investigation with respect to the variance of all the factors included in the error term. The F value obtained in the analysis is compared with a value from standard F - tables for a given level of significance. When the computed F value is less than the value determined from the F tables at the selected level of significance, the factor does not contribute to the sum of squares within the confidence level.

The formula for the pure sum of squares is given below:

SS' $=$ Seq. SS $-(\mathrm{DF} \times$ Adj. MS error $)$

## CHAPTER - 4

## Result and Analysis

The result of three roller bending process and discussion on which parameters is impact on the spring back. Different results of the output parameters have been reported here with their discussion of which parameters is impact on the output. Results of qualitative explanations included in this chapter. An ANOVA has been produced a connection between performance characteristics and input parameters in second order regression equation.

### 4.1 Results of Spring Back

The result of the spring back has been shown in the below Table No. 4.1.

Table 4.1 Result of Spring Back

| Sr. | Roller <br> Speed <br> (rpm) | Pressure <br> $\left(\mathbf{k g} / \mathbf{c m}^{2}\right)$ | Thickness <br> $(\mathbf{m m})$ | No. Of Pass | Springback <br> $(\mathbf{m m})$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 8 | 1200 | 1 | 1 | 1.206 |
| 2 | 8 | 1200 | 1 | 1 | 1.237 |
| 3 | 8 | 1200 | 1 | 1 | 1.223 |
| 4 | 8 | 2400 | 2 | 2 | 0.932 |


| 5 | 8 | 2400 | 2 | 2 | 0.957 |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 6 | 8 | 2400 | 2 | 2 | 0.926 |
| 7 | 8 | 3600 | 3 | 3 | 0.856 |
| 8 | 8 | 3600 | 3 | 3 | 0.844 |
| 9 | 8 | 3600 | 3 | 3 | 0.801 |
| 10 | 9 | 1200 | 2 | 3 | 0.794 |
| 11 | 9 | 1200 | 2 | 3 | 0.789 |
| 12 | 9 | 1200 | 2 | 3 | 0.798 |
| 13 | 9 | 2400 | 3 | 1 | 0.979 |
| 14 | 9 | 2400 | 3 | 1 | 0.963 |
| 15 | 9 | 2400 | 3 | 1 | 0.954 |
| 16 | 9 | 3600 | 1 | 2 | 1.075 |
| 17 | 9 | 3600 | 1 | 2 | 1.089 |
| 18 | 9 | 3600 | 1 | 2 | 1.099 |

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| 19 | 10 | 1200 | 3 | 2 | 0.934 |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 20 | 10 | 1200 | 3 | 2 | 0.918 |
| 21 | 10 | 1200 | 3 | 2 | 0.907 |
| 22 | 10 | 2400 | 1 | 3 | 0.931 |
| 23 | 10 | 2400 | 1 | 3 | 0.945 |
| 24 | 10 | 3600 | 2 | 3 | 0.967 |
| 25 | 10 | 3600 | 2 | 1 | 1.084 |
| 26 | 10 | 10 | 2600 |  | 1 |

### 4.2 Optimization Problem Formulation

The present study aimed to determine the set of optimal parameters of the bending process to ensure springback condition. The optimization obtained in terms of roller speed, Pressure, Thickness and number of pass. After generated equations, it is implement in the regression equation:

Spring back $(\mathbf{m m})=0.0036+0.0227 \times$ Roller Speed $(\mathrm{rpm})-0.0014 \times$ Pressure $\left(\mathrm{kg} / \mathrm{cm}^{2}\right)-0.1973$
$\times$ Thickness (mm) $-0.1284 \times$ No. of Pass

As per ANOVA analysis, test experiment articulates that the chording experimental combination is a top-notch condition of optimization and offers better product quality. Further, the approximation of marginal effect as well as the determination of exceptional proportion for all governable factors can be achieved from the established. Since it is known that elevated value of ANOVA will provide the best value of spring back. Therefore, it is exhibited that the response will be the best at roller speed: 8 rpm , roller pressure: $3600 \mathrm{~kg} / \mathrm{cm}^{2}$, thickness: 3 mm , and a number of passes.

Table 4.2 Response Table for Signal to Noise Ratios

| Level | Roller Speed <br> (rpm) | Pressure <br> $\left(\mathbf{k g} / \mathbf{c m}^{2}\right)$ | Thickness <br> $(\mathbf{m m})$ | No. of Pass |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 2.310 | 2.2007 | -0.6893 | 0.2085 |
| 2 | 2.1538 | 1.4383 | 3.2744 | 2.5954 |
| 3 | 1.4572 | 2.2734 | 3.3272 | 3.1084 |
| Delta | 0.8441 | 0.8351 | 4.0166 | 2.8999 |
| Rank | 3 | 4 | 1 | 2 |



Fig. 4.1 Spring Back Signal to Noise Ratios
In Figure No. 4.1 shows that the main effects vs. SN ratios. Roller speed increase from 8 to 10 impact is decreased. For the second parameter pressure $\left(\mathrm{Kg} / \mathrm{Cm}^{2}\right)$ increase from 1200 to 1400 at the time decrease the SN ratio. After from the 1400 to 1600 pressure is increased SN ratio increased. Third parameter thickness 1 to 2 highly increased and then after slight increase. Last parameter Number of pass from 1 to 3 SN ratios increased highly from 1 to and from 2 to 3 slightly increase.


Fig 4.2 Main Effect Plot of SN Ratio for Spring Back

In Figure No. 4.2 gives information about the main effect vs. Mean. In this graph roller speed 8 to 9 (rpm) Mean is slightly decreased below the point. Roller speed increased from 9 to 10 means is increased to above the center point. For the second parameter pressure $\left(\mathrm{kg} / \mathrm{cm}^{2}\right)$ increase from 1200 to 1400 at the time increase the SN ratio. After than the 1400 to $1600\left(\mathrm{~kg} / \mathrm{cm}^{2}\right)$ decreased the mean reach to below the average of the means. Thickness is increased from 1 to 2 highly decreased of the means of means and from 2 to 3 slightly decreased. Number of pass from 1 to 3 increased it is opposite impact of the means. Number of pass increase means decreased.


Fig. 4.3 Main Effect Plot for Means for Spring Back

In the Figure No 4.3 shows that the Mean od SN ratio. Roller speed increased from 8 to 10 increased the mean of SN ratio. Thickness and number of pass increased Means of the SN ratios decreased. Pressure on the roller is increased from 1400 reached to the maximum and then after decreased the values of the SN ratios.

In Figure No. 4.4 gives the information about the relation of the parameters to the spring back impact. For output parameter roller speed is increased so increased the value. If thickness is increased spring back decreased. Number of pass increased spring back decreased. Pressure is increased spring back increased up to limit and then after decreased.


Fig 4.4 Main Effect Plot of Grey Relational Grade

### 4.3 Finite Element Analysis

In this research work validation of the work with the help of the finite element analysis. Figure No. 4.5 shows the generated 3D CAD model of 3-Roll Bending Assembly Setup which consists asymmetric arrangement of rollers and a flat sheet made from Al 6063 -T5. It is subjected to rolling and bending forces exerted on it due to rollers during its forming operation for producing cone. The present FEA analysis simulate the rolling bending operation for producing cone and measuring Spring-back effect in sheet for the given operating parameters. All guiding, rolling and bending rollers are considered rigid bodies as 2D surfaces and only sheet is analyzed as solid flexible body.


Fig 4.5 Roll Bending Assembly Setup

In this model document of the finite element analysis results of 3-Roll Bending operation to form a cone for the given operating parameters (1) Sheet thickness: 2 mm , (2) Roller Speed: 9 RPM, (3) No. of Pass: 1 and (4) Roller displacement: 52.5 for the desired cone dimensions (OD: 350 mm , ID: $175 \mathrm{~mm}, \Theta=30$ Degree). Below Figure No. 4.6 represent the work found after the analysis as (i) is Equivalent elastic stress, (ii) is permanent elastic strain, (iii) is deformation, it is found maximum 642 mm , and (iv) gives information about the spring back effect. In the whole process put the input parameters and found total deformation, and spring-back effect on the ALUMINIUM plate.

(i)

(iii)

(ii)

(iv)

Fig 4.6 (i) Equivalent Elastic Stress (ii) Permanent Elastic Strain (iii) Deformation (iv) Spring Back Effect

### 4.4 Result of the Finite Element Analysis

Table 4.3 Result of Finite Element Analysis

| CAS <br> E | COMPONE NT | $\begin{gathered} \text { SHEET } \\ \text { THK } \\ (M M) \end{gathered}$ | ROLLE R SPEE D (RPM) | NO. <br> of <br> PAS <br> S | ROLLER DISPLACEME NT (MM) | ANALYSIS RESULTS |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  | MAX. <br> STRES <br> S <br> VALU <br> E <br> (MPA) | MAX. <br> STRAI <br> N <br> VALU <br> E | MAX. DEFORMATI ON (MM) | MAX. <br> SPRINGBAC <br> K, U1 (MM) | MAX. SPRINGBA CK, U3 (MM) |
| 1 | FEA_3- <br> ROLL <br> BENDING_1 <br> 3 | 3 | 9 | 1 | 52.51 | 110 | 0.05 | 642 | 2.72 | 3.16 |

### 4.5 Mathematical Model

The main objective of this section is to formulate a mathematical model to predict Spring Back effect of A16063 in three-roller bending machine using dimensional analysis. A mathematical model is a description of a system or a process in mathematical forms. A model helps to explain a system or a process and to study the effects of different parameters influencing the response. Dimensional analysis is a powerful tool for understanding and analyzing engineering problems. Dimensional analysis computes dimensionless groups of parameters and provides information to what group of parameters affects the response. To formulate the mathematical model, Buckingham pi theorem is used. Buckingham's Pi Theorem [10] states that if there is a physically meaningful equation involving a certain number $n$ of physical variables, then the original equation can be rewritten in terms of a set of $p=n-k$ dimensionless parameters $\pi 1, \pi 2, \ldots, \pi p$ constructed from the original variables. To calculate dimensionless pi terms, all dependent and independent parameters are expressed in terms of fundamental [MLT] physical quantities.
$\mathrm{D}=$ Top Roller Diameter in mm

E = Young's Modulus of Material N/mm ${ }^{2}$
$\mathrm{T}=$ Thickness of Plate in mm .
$\sigma=$ Yield Strength of Material N/mm ${ }^{2}$
$\mathrm{n}=$ Number of Passes
$\mathrm{k}=$ Curve Fitting Constant
a to $\mathrm{d}=$ Exponents of Independent Parameters
$\mathrm{S}=$ Spring Back in mm.
$\mathrm{G}=$ Acceleration due to gravity of Top Roller in $\mathrm{mm} / \mathrm{sec}^{2}$

For three-roller bending process, total 08 parameters are selected, out of which 03 are selected as repeating variables $(D, \sigma, G)$. Hence, 05 independent pi groups are formed. Here the development of mathematical model is for Spring back. So, for model development, 05 independent pi groups are used. Description of parameters with fundamental form and dimensionless pi groups are as shown in Table No. 4.1.

Each dependent pi term is the function of the available independent Pi terms.

Hence,
$f(\pi 1, \pi 2, \pi 3, \pi 4, \pi 5)=0$. $\qquad$

A probable exact mathematical form for the dimensional equations of the phenomenon could be assumed to be of exponential form as
$\pi_{1}=k\left(\pi_{2}\right)^{a}\left(\pi_{3}\right)^{b}\left(\pi_{4}\right)^{c}\left(\pi_{5}\right)^{d}$

In this modelling total variable 8, Repeating variable is 3 so total pi terms are 5. $\pi 1=$ Spring Back, $\pi 2=$ Effect of Roller Pressure, $\pi 3=$ Effect of Roller Rpm, $\pi 4=$ Effect of Thickness of Material, $\pi 5=$ Effect of No. of Passes.

After Solving above equation,

$$
\begin{gathered}
\mathrm{a}=1 / 2, \mathrm{~b}=0, \mathrm{c}=1 / 2 \\
\pi 4=\mathrm{T} \mathrm{D} \\
\mathrm{a} \sigma^{\mathrm{b}} \mathrm{G}^{\mathrm{c}}
\end{gathered}
$$

$$
\mathrm{M}^{\mathrm{o}} \mathrm{~L}^{0} \mathrm{~T}^{0}=\mathrm{M}^{\mathrm{o}} \mathrm{~L}^{1} \mathrm{~T}^{0}\left(\mathrm{M}^{\mathrm{o}} \mathrm{~L}^{1} \mathrm{~T}^{0}\right)^{\mathrm{a}}\left(\mathrm{M}^{1} \mathrm{~L}^{-1} \mathrm{~T}^{-2}\right)^{\mathrm{b}}\left(\mathrm{M}^{0} \mathrm{~L}^{1} \mathrm{~T}^{-2}\right)^{\mathrm{c}}
$$

After Solving above equation,

$$
\mathrm{a}=-1, \mathrm{~b}=0, \mathrm{c}=0 .
$$

$$
\begin{aligned}
& \pi 1=\mathrm{S} \mathrm{D}^{\mathrm{a}} \sigma^{\mathrm{b}} \mathrm{G}^{\mathrm{c}} \\
& M^{0} L^{0} T^{0}=M^{0} L^{1} T^{0}\left(M^{0} L^{1} T^{0}\right)^{a}\left(M^{1} L^{-1} T^{-2}\right)^{b}\left(M^{0} L^{1} T^{-2}\right)^{c} \\
& \text { After Solving above equation, } \\
& \mathrm{a}=-1, \mathrm{~b}=0, \mathrm{c}=0 . \\
& \pi 2=\mathrm{P} \mathrm{D}^{\mathrm{a}} \sigma^{\mathrm{b}} \mathrm{G}^{\mathrm{c}} \\
& M^{0} L^{0} T^{0}=M^{1} L^{-1} T^{2}\left(M^{0} L^{1} T^{0}\right)^{a}\left(M^{1} L^{-1} T^{-2}\right)^{b}\left(M^{0} L^{1} T^{-2}\right)^{c} \\
& \text { After Solving above equation, } \\
& \mathrm{a}=0, \mathrm{~b}=1, \mathrm{c}=0 . \\
& \pi 3=\mathrm{ND}^{\mathrm{a}} \sigma^{\mathrm{b}} \mathrm{G}^{\mathrm{c}} \\
& \mathrm{M}^{0} \mathrm{~L}^{0} \mathrm{~T}^{0}=\mathrm{M}^{0} \mathrm{~L}^{0} \mathrm{~T}^{-1}\left(\mathrm{M}^{0} \mathrm{~L}^{1} \mathrm{~T}^{0}\right)^{\mathrm{a}}\left(\mathrm{M}^{1} \mathrm{~L}^{-1} \mathrm{~T}^{-2}\right)^{\mathrm{b}}\left(\mathrm{M}^{0} \mathrm{~L}^{1} \mathrm{~T}^{-2}\right)^{c}
\end{aligned}
$$

$$
\begin{gathered}
\pi 5=\text { Effect of No. of Passes. } \\
\pi 5=\mathrm{n} \mathrm{D}^{\mathrm{a}} \sigma^{\mathrm{b}} \mathrm{G}^{\mathrm{c}} \\
\mathrm{M}^{0} \mathrm{~L}^{0} \mathrm{~T}^{0}=\mathrm{M}^{\mathrm{o}} \mathrm{~L}^{0} \mathrm{~T}^{0}\left(\mathrm{M}^{0} \mathrm{~L}^{1} \mathrm{~T}^{0}\right)^{\mathrm{a}}\left(\mathrm{M}^{1} \mathrm{~L}^{-1} \mathrm{~T}^{-2}\right)^{\mathrm{b}}\left(\mathrm{M}^{0} \mathrm{~L}^{1} \mathrm{~T}^{-2}\right)^{\mathrm{c}}
\end{gathered}
$$

After Solving above equation,

$$
\mathrm{a}=0, \mathrm{~b}=0, \mathrm{c}=0 .
$$

A probable exact mathematical form for the dimensional equations of the phenomenon could be assumed to be of exponential form as

$$
\begin{gathered}
\pi_{1}=k\left(\pi_{2}\right)^{a}\left(\pi_{3}\right)^{b}\left(\pi_{4}\right)^{c}\left(\pi_{5}\right)^{d} \\
\mathrm{~S} / \mathrm{D}=\mathrm{K}(\mathrm{P} / \sigma)^{\mathrm{a}}(\mathrm{~N} \sqrt{ } \mathrm{D} / \mathrm{G})^{\mathrm{b}}(\mathrm{~T} / \mathrm{D})^{\mathrm{c}}(\mathrm{n})^{\mathrm{d}}
\end{gathered}
$$

Here, K is curve fitting constant and $a$ to $d$ be indices which needs to be calculated by multi variable regression analysis at 95 percent confidence interval.

By using data obtained in experimental part of this investigation and substituting these parameters in equation number (A). The predictive model for spring back follow as.

$$
\begin{equation*}
\log \pi l=\log k+a \log \pi 2+b \log \pi 3+c \log \pi 4+d \log \pi 5 \tag{2}
\end{equation*}
$$

As per multi variable regression analysis at 95 percent confidence interval using data obtained in experimental part of this investigation

Spring back $(\mathrm{mm})=0.0036+0.0227 \times$ Roller Speed $(\mathrm{rpm})-0.0014 \times$ Pressure $\left(\mathrm{kg} / \mathrm{cm}^{2}\right)-0.1973$ $\times$ Thickness $(\mathrm{mm})-0.1284 \times$ No. of Pass.

By analyzing above equations,

The constant $\mathrm{K}=0.0036$
$\mathrm{a}=-0.0014, \mathrm{~b}=0.0227, \mathrm{c}=-0.1973, \mathrm{~d}=-0.1284$

$$
\begin{array}{r}
\mathrm{S}=\mathrm{K} \mathrm{D}(\mathrm{P} / \sigma)^{\mathrm{a}}(\mathrm{~N} \sqrt{ } \mathrm{D} / \mathrm{G})^{\mathrm{b}}(\mathrm{~T} / \mathrm{D})^{\mathrm{c}}(\mathrm{n})^{\mathrm{d}} \\
\mathrm{~S}=\mathrm{K} \mathrm{D}(\mathrm{P} / \sigma)^{-0.0014}(\mathrm{~N} \sqrt{ } / \mathrm{D} / \mathrm{G})^{0.0227}(\mathrm{~T} / \mathrm{D})^{-0.1973}(\mathrm{n})^{-0.1284 \ldots} \tag{4}
\end{array}
$$

Developed model for $\pi l$ related to spring back of three-roller bending machine is analyzed by calculating percentage error between experimental values and values obtained from mathematical model. Values of dependent parameter $\pi l$ from mathematical model are obtained by putting the experimental values of independent variables in mathematical model formed. Deviation of the values obtained from mathematical model from actual experimental values of dependent parameters shows closeness of the mathematical model with real-life process. Deviation of the values can be obtained in terms of percentage error. Following mathematical relationship will give percentage error between actual values and mathematical values.

$$
\begin{equation*}
\text { Percentage Error }=\left(\frac{(\text { Experimental values-Model values }) \times 100}{\text { Experimental values }}\right. \tag{5}
\end{equation*}
$$

Percentage error for $\pi l$ related to spring back obtained is less than $10 \%$. In the below Table No. 4.4 shows that values obtained from mathematical model are close with actual experimental values.

Table 4.4 Validation of Experimental and Model Value

| Sr. <br> No. | $\begin{gathered} \text { Spring back } \\ (\mathrm{mm}) \end{gathered}$ | $(\mathrm{P} / \sigma)^{-0.0014}$ | $(\mathbf{N} \sqrt{ } \mathbf{D} / \mathbf{G})^{\mathbf{0 . 0 2 2 7}}$ | (T/D) $)^{-0.1973}$ | $\mathbf{n}^{-0.1284}$ | K | Model <br> Spring <br> back (mm) | Percentage <br> Error(\%) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 1.206 | 1.000289 | 1.027584272 | 2.57171276 | 1.000 | 0.0036 | 1.14195 | 5.31 |
| 2 | 1.237 | 1.000289 | 1.027584272 | 2.57171276 | 1.000 | 0.0036 | 1.14195 | 7.68 |
| 3 | 1.223 | 1.000289 | 1.027584272 | 2.57171276 | 1.000 | 0.0036 | 1.14195 | 6.62 |
| 4 | 0.932 | 0.999322 | 1.027584272 | 2.24299984 | 0.915 | 0.0036 | 0.9103 | 2.32 |
| 5 | 0.957 | 0.999322 | 1.027584272 | 2.24299984 | 0.915 | 0.0036 | 0.9103 | 4.88 |
| 6 | 0.926 | 0.999322 | 1.027584272 | 2.24299984 | 0.915 | 0.0036 | 0.9103 | 1.69 |
| 7 | 0.856 | 0.998755 | 1.027584272 | 2.0705534 | 0.868 | 0.0036 | 0.79723 | 6.86 |
| 8 | 0.844 | 0.998755 | 1.027584272 | 2.0705534 | 0.868 | 0.0036 | 0.79723 | 5.54 |
| 9 | 0.801 | 0.998755 | 1.027584272 | 2.0705534 | 0.868 | 0.0036 | 0.79723 | 0.47 |
| 10 | 0.794 | 1.000289 | 1.030335374 | 2.24299984 | 0.868 | 0.0036 | 0.86727 | 9.22 |
| 11 | 0.789 | 1.000289 | 1.030335374 | 2.24299984 | 0.868 | 0.0036 | 0.86727 | 9.92 |

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| 12 | 0.798 | 1.000289 | 1.030335374 | 2.24299984 | 0.868 | 0.0036 | 0.86727 | 8.68 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 13 | 0.979 | 0.999322 | 1.030335374 | 2.0705534 | 1.000 | 0.0036 | 0.92099 | 5.92 |
| 14 | 0.963 | 0.999322 | 1.030335374 | 2.0705534 | 1.000 | 0.0036 | 0.92099 | 4.36 |
| 15 | 0.954 | 0.999322 | 1.030335374 | 2.0705534 | 1.000 | 0.0036 | 0.92099 | 3.46 |
| 16 | 1.075 | 0.998755 | 1.030335374 | 2.57171276 | 0.915 | 0.0036 | 1.0459 | 2.70 |
| 17 | 1.089 | 0.998755 | 1.030335374 | 2.57171276 | 0.915 | 0.0036 | 1.0459 | 3.95 |
| 18 | 1.099 | 0.998755 | 1.030335374 | 2.57171276 | 0.915 | 0.0036 | 1.0459 | 4.83 |
| 19 | 0.934 | 1.000289 | 1.03280256 | 2.0705534 | 0.915 | 0.0036 | 0.8454 | 9.48 |
| 20 | 0.918 | 1.000289 | 1.03280256 | 2.0705534 | 0.915 | 0.0036 | 0.8454 | 7.90 |
| 21 | 0.907 | 1.000289 | 1.03280256 | 2.0705534 | 0.915 | 0.0036 | 0.8454 | 6.79 |
| 22 | 0.931 | 0.999322 | 1.03280256 | 2.57171276 | 0.868 | 0.0036 | 0.99579 | 6.95 |
| 23 | 0.945 | 0.999322 | 1.03280256 | 2.57171276 | 0.868 | 0.0036 | 0.99579 | 5.37 |
| 24 | 0.967 | 0.999322 | 1.03280256 | 2.57171276 | 0.868 | 0.0036 | 0.99579 | 2.97 |
| 25 | 1.084 | 0.998755 | 1.03280256 | 2.24299984 | 1.000 | 0.0036 | 0.99951 | 7.79 |

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| 26 | 1.078 | 0.998755 | 1.03280256 | 2.24299984 | 1.000 | 0.0036 | 0.99951 | 7.28 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 27 | 1.071 | 0.998755 | 1.03280256 | 2.24299984 | 1.000 | 0.0036 | 0.99951 | 6.67 |

## CHAPTER - 5

## Conclusion and Future Scope

### 5.1 Conclusion

In three roller bending process is a high potential in the field of the metal bending with various metals. This research presents an investigation \& optimization of process parameters of roll bending machine in realizing conical shells in ALUMINIUM 6063. In this research, design of the three roller bending has been done using Abaqus to analyze the shear stress and strain. A systematic approach has been adopted for the perform the bending. Experiments have been conducted for various combinations of parameters. Three levels of roller pressure, roller speed, sheet thickness, number of pass have been taken during experimental investigation using a Taguchi L9 Method of experiment. The spring-back of the bending plate has been analyzed by quantitative method. Pie- theorem has been used for the generate mathematical model for the work. Regression analysis has been done for the which parameter is highly impact on the three roller bending process. Experimental validation has been done using Abaqus analysis work. The following conclusions are derived.

- From the above work first generate design of three roller bending machine with Abaqus software to analysis of the work.
- From the ANOVA it is found that the main factor of the spring back is thickness of the material, second number of pass, third roller speed and last pressure.
- For all parameters p value is below than $5 \%$ so work is accepted.
- In FEA analysis maximum stress found as 110 Mpa , Max strain is 0.05 , Max spring back U1 and U3 have 2 to 3 mm
- It also validates this work with FEA to experimental work.
- The curve fitting constant in the model is 0.0036 , this value represents the effect of clearances and other factors which affect the phenomena.
- Percentage error for Spring back obtained is less than $10 \%$. It shows that values obtained from mathematical model are close with actual experimental values.
- A generalized field data-based model is developed to predict Spring back effect. Methodology of dimensional analysis is used. It is found that the independent pi terms influencing the dependent pi term $\pi 1$ in descending order. The following primary conclusions appear to be justified from the above model.
- The absolute index value of $\pi 3$ (Rpm) is highest and is equal to 0.0227 . Thus, terms used in $\pi 3$ group are most influencing. The value of the index is positive indicating $\pi 1$ directly varying with respect to $\pi 3$.
- The absolute index value of $\pi 4$ (Thickness) is lowest and is equal to -0.1973 . Thus, terms used in $\pi 4$ group are least influencing. The value of the index is negative indicating $\pi 1$ inversely varying with respect to $\pi 4$.
- The sequence of influence of the other independent pi terms present in the model are $\pi 5$ (No. of pass) and $\pi 2$ (Roller pressure) having absolute indices -0.1284 and -0.0014 respectively.
- Above details presented a new methodology of dimensional analysis to develop relationship of various parameters of bending process. It is concluded that dimensional analysis is simple and excellent when functional relationship among variables is unknown.


### 5.2 Future Scope

The future scope of research work described as below given.

- An experimental investigation can also be carried out with other than A1 6063 material.
- Process can be carried out with FEA analysis with certain boundary layer condition.
- An experimental investigation can be carried out with other than material thickness, no. of passes, roller rpm and roller pressure.
- An experimental investigation can be carried out by varying the mixing parameters including hot working process.
- We had bent the material at different roller pressure of the work surface but with the help of programming one can bend the material at constant roller rpm as well thickness for performance evaluation.


## List of References

1. A. Mercuri, P. Fanelli, F. Giorgetti, G. Rubino \& C. Stefanini (2021). Experimental and numerical analysis of roll bending process of thick metal sheets. IOP Conference Series: Materials Science and Engineering, 1038(1), 012067. https://doi.org/10.1088/1757899x/1038/1/012067
2. A. H. Gandhi, A. A. Shaikh and H. K. Raval (2009). Formulation of spring-back and machine setting parameters for multi-pass three-roller cone frustum bending with change of flexural modulus, International Journal of Material Forming, 2, 45-57.
3. A. H. Gandhi, and H. K. Raval (2008). Analytical and empirical modeling of top roller position for three-roller cylindrical bending of plates and its experimental verification, Journal of Materials Processing Technology 197 (1-3) 268-278.
4. Chatti, S., Hermes, M., Tekkaya, A. E., \& Kleiner, M. (2010). The new TSS bending process: 3D bending of profiles with arbitrary cross-sections. CIRP Annals, 59(1), 315318. https://doi.org/10.1016/j.cirp.2010.03.017
5. Chudasama, M. K., \& Raval, H. K. (2013). Bending force prediction for dynamic rollbending during 3-roller conical bending process. Journal of Manufacturing Processes, 16(2), 284-295. doi:10.1016/j.jmapro.2013.09.008
6. D. E. Hardt, C. E. Wright, and A (1992). A model of sequential bending process for manufacturing simulation, J Eng Ind 114 (1992) 181-187.
7. Dametew, A. W., \& Gebresenbet, T. (2017). Study the Effects of Spring Back on Sheet Metal Bending using Mathematical Methods. Journal of Material Sciences \& Engineering, 06(05). https://doi.org/10.4172/2169-0022.1000382
8. Dang, X., He, K., Zhang, F., \& Du, R. (2018). A new flexible sheet metal forming method of incremental bending. Procedia Manufacturing, 15, 1298-1305. https://doi.org/10.1016/j.promfg.2018.07.355
9. E. A. Kulikov, Y. I. Berliner, and G. I. Shevyakov (1969). Bending thick-walled conical vessel sections on roll bending machines, Chemical and Petroleum Engineering 5 (12) 977-979.
10. Esat, V., Darendelıler, H., \& Gökler, M. İ. (2002). Finite element analysis of springback in bending of Aluminium sheets. Materials in Engineering, 23(2), 223-229. https://doi.org/10.1016/s0261-3069(01)00062-0
11. Feijun, X., He, Y., \& Hongsheng, X. (2000). Finite element analysis of effects of parameters on in-plane bending process of strip metal. Journal of Materials Processing Technology, 102(1-3), 78-83. doi:10.1016/s0924-0136(00)00460-x
12. G. Pradeep Dev, P. Sam Livingston, M. Shunmuganathan, R. Surendar, A. Siva Subramanian, A. Simon Christopher, K. C. Ganesh (2016). Analysis of 6061 ALUMINIUM Alloy Sheet Metal Bending Process for Various Thickness Using Finite Element Modelling. International Journal of Theoretical and Applied Mathematics. Vol. 2, No. 2, pp. 93-99. doi: 10.11648/j.ijtam. 20160202.20
13. Gattmah, J., Ozturk, F., \& Orhan, S. (2019). Numerical Simulation of Bending Process for Steel Plate Using Finite Element Analysis. Arabian Journal for Science and Engineering. doi:10.1007/s13369-019-04119-8
14. Gavrilescu, I.; Boazu, D.; Stan, F (2021). Estimating of Bending Force and Curvature of the Bending Plate in a Three-Roller Bending System Using Finite Element Simulation and Analytical Modeling. Materials 2021, 14, 1204. https://doi.org/10.3390/ ma14051204
15. Ghiotti, A., Simonetto, E., Bruschi, S., \& Bariani, P. F. (2017). Springback measurement in three roll push bending process of hollow structural sections. CIRP Annals, 66(1), 289-292. https://doi.org/10.1016/j.cirp.2017.04.119
16. Giagmouris, T., Kyriakides, S., Korkolis, Y. P., \& Lee, L. (2010). On the localization and failure in ALUMINIUM shells due to crushing induced bending and tension. International Journal of Solids and Structures, 47(20), 2680-2692. https://doi.org/10.1016/j.ijsolstr.2010.05.023
17. H. Huh, J. H. Heo, and H. W. Lee (2003). Optimization of a roller levelling process for Al7001T9 pipes with finite element analysis and Taguchi method, International Journal of Machine Tools and Manufacture 43 (4) 345-350.
18. Ha, T., Ma, J., Blindheim, J., Welo, T., Ringen, G., \& Wang, J. (2020). In-line springback measurement for tube bending using a laser system. Procedia Manufacturing, 47, 766-773. https://doi.org/10.1016/j.promfg.2020.04.233
19. Hai Gong, Xiaoliang Sun, Yaoqiong Liu, Yunxin Wu, Yanan Wang and Yanjie Sun, Residual Stress Relief in 2219 ALUMINIUM Alloy Ring Using Roll-Bending: Materials 2020, 13, 105; doi:10.3390/ma13010105
20. Hu, Z. Q., Li, M. Z., Cai, Z. Y., \& Gong, X. P. (2009). Continuous flexible forming of three-dimensional surface parts using bendable rollers. Materials Science and 1Engineering: A, 499(1-2), 234-237. doi:10.1016/j.msea.2007.11.107
21. Hua, M., Sansome, D. H., Rao, K. P., \& Baines, K. (1994). Continuous four-roll plate bending process: Its bending mechanism and influential parameters. Journal of Materials Processing Technology, 45(1-4), 181-186. doi:10.1016/0924-0136(94)90338-7
22. J. Zeng, Z. Liu, and H. Champliaud, FEM dynamic simulation and analysis of the rollbending process for forming a conical tube, Journal of Materials Processing Technology 198 (1-3) (2008) 330-343.
23. Jan SLOTA, Ivan GAJDOS, Emil SPIŠÁK, Marek ŠISER: Springback prediction of stretching process using finite element analysis for dp600 steel sheet: acta mechanica et automatica, vol. 11 no. 1 (2017)
24. Jenan Mohammed Naje: Effect of radius and angle of bending on the concentration of stresses in the ALUMINIUM sheet: ISSN (Online) : 2454 -7190 Vol.-14, No.-5, September

- October (2019) pp 379-395

25. Ktari, A., Abdelkefi, A., Guermazi, N., Malecot, P., \& Boudeau, N. (2021). Numerical investigation of plastic flow and residual stresses generated in hydroformed tubes. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 235(5), 1100-1111. doi:10.1177/1464420721989746
26. Ktari, A., Antar, Z., Haddar, N., \& Elleuch, K. (2012). Modeling and computation of the three-roller bending process of steel sheets. Journal of Mechanical Science and Technology, 26(1), 123-128. doi:10.1007/s12206-011-0936-4
27. Leacock, A. G., Mccracken, D. J., Brown, D., \& McMurray, R. J. (2012). Numerical simulation of the four roll bending process. Materials and Manufacturing Processes, 27(4), 370-376. https://doi.org/10.1080/10426914.2011.560228
28. Li, Q., Jin, M., Zou, Z., Zhao, S., Zhang, Q., \& Li, P. (2017). Experiment Research on tensile and compression cyclic loading of sheet metal. Procedia Engineering, 207, 1916-1921. https://doi.org/10.1016/j.proeng.2017.10.961
29. Liedl, G., Bielak, R., Ivanova, J., Enzinger, N., Figner, G., Brückner, J., Paśič, H., Pudar, M., \& Hampel, S. (2011). Joining of ALUMINIUM and steel in car body manufacturing. Physics Procedia, 12, 150-156. https://doi.org/10.1016/j.phpro.2011.03.019
30. Ling, J., Abdullah, A.B., \& Samad, Z. (2016). Application of Taguchi method for predicting Springback in V-bending of ALUMINIUM alloy AA 5052 strip. ," Journal of Scientific Research and Development, vol. 3, no. 7, pp. 91-97, 2016.
31. Liu, Y., Wang, L., Zhu, B., Wang, Y., \& Zhang, Y. (2018). Identification of two ALUMINIUM alloys and springback behaviors in cold bending. Procedia Manufacturing, 15, 701-708. https://doi.org/10.1016/j.promfg.2018.07.303
32. LIU Zhi-wen, LI Luo-xing, YI Jie, et al. Influence of heat treatment conditions on bending characteristics of 6063 ALUMINIUM alloy sheets [J]. Transactions of Nonferrous Metals Society of China, 2017, 27: 1498-1506. DOI: https://doi.org/10.1016/S1003-6326(17)60170-5.
33. M. Hua, D. H. Sansome, and K. Baines, Mathe- matical modeling of the internal bending moment at the top roll contact in multi-pass four-roll thin- plate bending, Journal of Materials Processing Technology 52 (2-4) (1995) 425-459. G. Kajrup, and A. Flam
34. M. K. Chudasama, and H, Bending force prediction for dynamic roll-bending during 3roller conical bending process, Journal of Manufacturing Processes 16 (2) (2014) 284295.
35. Nejad, M. Z., Jabbari, M., \& Ghannad, M. (2015). Elastic analysis of FGM rotating thick truncated conical shells with axially-varying properties under non-uniform pressure loading. Composite Structures, 122, 561569. doi:10.1016/j.compstruct.2014.12.
36. Öztürk, F., Toros, S., \& Kılıç, S. (2009). Tensile and spring-back behavior of DP600 advanced high strength steel at warm temperatures. Journal of Iron and Steel Research International, 16(6), 41-46. https://doi.org/10.1016/s1006-706x(10)60025-8
37. Park, S.-M., Lee, J., Park, S., Lee, J.-W., Park, M., Kim, Y., \& Noh, G. (2020). Practical bending-angle calculation for an automated surgical plate bending apparatus. Journal of Mechanical Science and Technology, 34(5), 2101-2109. doi:10.1007/s12206-020-0432-9
38. Peng, J., Li, W., Wan, M., Zhang, C., Li, J., \& Sun, G. (2017). Investigation on threeroller cylindrical bending of $2060-\mathrm{T} 8 \mathrm{Al}-\mathrm{Li}$ alloy plate for aircraft fuselage skin components. International Journal of Material Forming, 11(2), 269278. doi:10.1007/s12289-017-1350-y
39. Péter Máté András Szek rényes: Numerical modelling of the three-roll bending process of a thin plate : Műszaki Tudományos Közlemények vol. 13. (2020) 133-136.
40. Pol, S. M., Parmar, D. N., Rane, H., \& Pawar, O. (2022). Literature Review on Analysis of spring back in Sheet metal forming Processes. International Journal for Research in

Applied Science and Engineering Technology, 10(10), 1194-1198. https://doi.org/10.22214/ijraset.2022.47156
41. Prasad, B. L., Neelaiah, G., Krishna, M. V., Ramana, S., Prakash, K. S., Sarika, G., Reddy, G. P. K., Dumpala, R., \& Sunil, B. R. (2018). Joining of AZ91 Mg alloy and Al6063 alloy sheets by friction stir welding. Journal of Magnesium and Alloys, 6(1), 71-76. https://doi.org/10.1016/j.jma.2017.12.004
42. R. I. Nepershin, Bending of a thin strip by a circular tool, Mechanics of Solids 42 (4) (2007) 568-582.
43. Ramulu, P. J. (2020). ALUMINIUM Alloys Behavior during Forming. In IntechOpen eBooks. https://doi.org/10.5772/intechopen. 86077
44. Rameshwar J. Sherepatil, Prof. R. L. Karwande, Prof. P. S. Thakare: The optimization of Three roller bending process parameter by using the Taguchi method : IJARIIE-ISSN(O)-2395-4396- Vol-6 Issue-6 2020
45. Rameshwar J. Sherepatil, R. L. Karwande, Prafull S. Thakare, Mohamad Javed: Comprehensive review on three roller bending operation; International Journal of Advance Research, Ideas and Innovations in Technology; volume 5 issue 62020
46. S. L. Zang, J. Liang, and C. Guo, A constitu- tive model for spring-back prediction in which the change of Young's modulus with plastic de- formation is considered, International Journal of Machine Tools and Manufacture 47 (11) (2007) 1791-1797.
47. Sakin, R. (2018). Investigation of bending fatigue-life of ALUMINIUM sheets based on rolling direction. Alexandria Engineering Journal, 57(1), 35-47. https://doi.org/10.1016/j.aej.2016.11.005
48. Shanmuganatan SP, Kumar VS. Experimental investigation and finite element modeling on profile forming of conical component using Al 3003 (O) alloy. Mater Des (1980-2015). 2012; 36: 564-569. https://doi.org/10.1016/j.matdes.2011.11.066
49. Sheu, J., Liang, C., Yu, C., Hsu, W., \& Lee, P. (2018). Flexible roll forming of Usection product with curved bending profile using advanced high strength steel. Procedia Manufacturing, 15, 782-787. https://doi.org/10.1016/j.promfg.2018.07.321
50. Shlyannikov, V., Tumanov, A., \& Boychenko, N. (2016). Surface Crack Growth Rate under Tension and Bending in ALUMINIUM Alloys and Steel. Procedia Engineering, 160, 5-12. https://doi.org/10.1016/j.proeng.2016.08.856
51. Śliwa, R. E., Myśliwiec, P., Ostrowski, R., \& Bujny, M. (2019). Possibilities of joining different metallic parts of structure using friction stir welding methods. Procedia Manufacturing, 27, 158-165. https://doi.org/10.1016/j.promfg.2018.12.059
52. Sutasn Thipprakmas and Arkarapon Sontamino: Spring-Back Characteristics on Bent Holed Parts in V-Die Bending Process : Hindawi Advances in Materials Science and Engineering Volume 2022, Article ID 6488261, 11 pages https://doi.org/10.1155/2022/6488261
53. Sweeney, K., \& Grunewald, U. (2003). The application of roll forming for automotive structural parts. Journal of Materials Processing Technology, 132(1-3), 9-15. doi:10.1016/s0924-0136(02)00193-0
54. Thakare, P. S., Salodkar, S. M., \& Handa, C. C. (2018). Development of Mathematical Model for Top Roller Displacement of Three-Roller Bending Machine Using Dimensional Analysis. Lecture Notes in Mechanical Engineering, 125132. doi:10.1007/978-981-13-2490-1_12
55. Thakare, P. S., Salodkar, S. M., \& Handa, C. C. (2019). Experimental Investigation of Three-Roller Bending Operation for Multi-Pass Cylindrical Forming of Plates. Materials Today: Proceedings, 18, 2779-2786. doi:10.1016/j.matpr.2019.07.143
56. Tran, Q. H., Champliaud, H., Feng, Z., \& Dao, T. M. (2014). Analysis of the asymmetrical roll bending process through dynamic FE simulations and experimental study. The International Journal of Advanced Manufacturing Technology, 75(5-8), 1233-1244. doi:10.1007/s00170-014-6176-x
57. Rashaq Abdullah Mohammed, https://www.uoanbar.edu.iq/eStoreImages/Bank/2068.pdf
58. Triawan, F., Kishimoto, K., Adachi, T., Inaba, K., Nakamura, T., Zhao, L., \& Hashimura, T. (2011). Elastic bending behavior of ALUMINIUM alloy foam. Procedia Engineering, 10, 2994-2999. https://doi.org/10.1016/j.proeng.2011.04.496
59. Vaibhav Suresh Deore, Gauri Rajendra Bauskar, Karan Sanjay Bhadane, Siddhesh Mukesh Gaikwad: pyramid type plate bending machine: International Journal of Research in Engineering and Technology: Volume: 04 Issue: 10| OCT-2015
60. Viswanathan Shrinaath, Ramalingam Vairavignesh, Ramasamy Padmanaban : Parametric study on the spring-back effect in aa5052 alloy in the course of three-point roll bending process: SCIENDO: DOI 10.2478/ama-2020-0019
61. Waheed, R., Saeed, H. A., Butt, S. U., \& Faraz, Z. (2021). Process Optimization of Bending SS 304L Sheets using Multi-Objective Genetic Algorithm and FEA. 2021 International Bhurban Conference on Applied Sciences and Technologies (IBCAST). doi:10.1109/ibcast51254.2021.9393
62. Wang, Y., Zhao, L., Cui, X., \& Zhu, X. (2019). Research on numerical simulation and process parameters of three-roll bending based on thickness characteristics of extrathick plate. Advances in Mechanical Engineering, 11(4), 168781401984786. doi:10.1177/1687814019847861
63. Wang, Y., Zhu, X., Wang, Q., \& Cui, X. (2018). Research on multi-roll roll forming process of thick plate. The International Journal of Advanced Manufacturing Technology. doi:10.1007/s00170-018-3200-6
64. X. Li, Y. Yang, Y. Wang, J. Bao, and S. Li, Effect of material hardening mode on the Springback simulation accuracy of V-free bending, J Mater Process Technol 123 (2002) 209-211.R. Hill, The mathematical theory of plasticity, (Lon- don, 1950).
65. Yang, H., Feijun, X., \& Hongsheng, X. (2000). Instable modes of in-plane bending of strip metal under unequal compressing. Journal of Materials Processing Technology, 99(1-3), 197-201. doi:10.1016/s0924-0136(99)00420-3
66. Yu, G., Zhao, J., \& Xu, C. (2019). Development of a symmetrical four-roller bending process. The International Journal of Advanced Manufacturing Technology. doi:10.1007/s00170-019-04104-3
67. Yu, G., Qi, S., Chen, S., Zhu, B., Zhao, J., \& Zhai, R. (2022). Prediction model of forming force on single-roller bending (SRB) and two-roller bending (TRB) process. The International Journal of Advanced Manufacturing Technology, 120(3-4), 25472558. https://doi.org/10.1007/s00170-022-08922-w
68. Z. Fu, X. Tian, W. Chen, B. Hu, and X. Yao, Analytical modeling and numerical simulation for three-roll bending forming of sheet metal, International Journal of Advanced Manufacturing Technology 69 (5-8) (2013) 1639-1647.
69. Zhao, J., Yu, G., \& Ma, R. (2016). A mechanical model of symmetrical three-roller setting round process: The static bending stage. Journal of Materials Processing Technology, 231, 501-512. doi:10.1016/j.jmatprotec.2016.01.002
70. Zhao, W., Liao, T. W., \& Kompotiatis, L. (2016). Stress and Springback analyses of API X70 Pipeline Steel Under 3-Roller Bending via Finite Element Method. Acta Metallurgica Sinica (English Letters), 30(5), 470-482. https://doi.org/10.1007/s40195-016-0527-6
71. http://www.mecanicaufrj.educacao.ws/util/b2evolution/media/blogs/annacarla/Global Manufacturing/Class2_print.pdf, ARAUJO, Anna Carla, AUG, 2015, Mechanical Engineering Department - POLI/COPPE/UFRJ
72. https://uomustansiriyah.edu.iq/media/lectures/5/5_2020_10_18!12_38_18_PM.pdf

## List of Publications

## Journal papers

1. Nimesh Patel, Prof. Dr. Jeetendra Vadher \& Dr. Hetalkumar N Shah (2022). Investigation of Roll Bending machine in realizing Conical Shells, Aegaeum Journal, Volume 10, Issue 9, 2022, ISSN: 0776-3808
2. Nimesh Patel, Prof. Dr. Jeetendra Vadher \& Dr. Hetalkumar N Shah (2022). Review on Spring back effect in bending of Conical Shells in Roll Bending machine, Gradiva Review Journal, Volume 8 Issue 10 2022, ISSN NO : 0363-8057

## Reviewed Conference Publications:

1. Nimesh Patel, Prof. Dr. Jeetendra Vadher \& Dr. Hetalkumar N Shah (2022). Investigation \& Optimization of process parameters of Roll Bending machine in realizing Conical Shells in ALUMINIUM 6063, International Multidisciplinary Engineering Conference (IMEC'22), Sankalchand Patel University, Gujarat

# Journal Paper 1 

# Investigation of Roll Bending machine in realizing Conical Shells 

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#### Abstract

The sheet metal forming process has been used in various manufacturing industries of aerospace or automobile with high efficiency in mass production and quality. Sheet surface is stivned by the rotating probe which advances on the surface, plastic deformation and heat resulted by friction and deformation incur changes in the micro structure and macroscopic mechanical properties. Therefore, the form ability and spring-back performance of the overall sheet. The spring-back is one of the key factors influencing the quality of rolled sheet metal parts. In this research paper problems on sheet metal bending by roller benaing machine in conical shells is identified and investigation made on sheet metal thickness, numbers of passes, roller pressure, and roller rpm on spring back for Aluminium 6063. The empirical results show that increasing sheet metal thichness from 1 mm to 3 mm the spring back is reduced remarkably. When increasing of roller pressure. spring back increases because spring back of the sheet should depend on the yield strength of the material. As number of passes increases, the spring back after unloading condition also increases. In addition to these, if increasing the rpm of roller from 8 to 10 , the spring back also increases. Since, ultimately high roller pressure. thickness and more number of passes is considered for prevention of spring back and optimizing of sheet metal bending process as by roller bending machine.


Keywords: Three roller bending machine; spring back; alumimium 6063; Tagachī; ANOVA; Grey Relational Analysiz.

## 1. Introduction

Continuous roller bending is an efficient technique for forming of metal plate into wide dimensional range of cylindrical, elliptical or comical cylinders. Metal forming is backbone of modern manufacturing industry, be- sides being the largest industry in itself. As much as $20 \%$ of the Gross Domestic Product of industrialized nations comes from the metal forming industry. Cylindrical or conical shells and sections are widely used in many engineering applications. Even a small saving in resources can result into the considerable cost reduction Over the last two decades, many research articles are reported on roller bending processes. Several siguificant literatures are summarized here briefly in modern manufacturing industries, aluminium has been a common and widely used material Especially in aerospace, defence and automotive industries, aluminium alloys are preferred because of their relatively lighrweight and satisfactory strength properties. Although aluminium alloys have relatively low tensile properties compared to steel, their strength weight ratio appears to be satisfy. In the bending process, after release of the load by withdrawal of the punch, an elastic recovery occurs because of the release of the elastic stresses. This elastic recovery is called spring back. Spring back is an important and key parameter in obtaining the desired geometry of the part and design of the corresponding tooling. In manufacturing industry, it is still a hands-on problem to predict the final geometry of the part after spring back and to design appropriate tooling in order to compensate for spring back. Conventional approaches, which involve using empirical formulae and several trial-and-error procedures, result in consumption of material, time and efforts. In recent years, with Taguchi, ANOVA and Optimization techniques have been considered as an effective way of describing bending operations and predicting spring back. Design of Experiments provides numerical trial and error procedures, which lead to a less-timeconsuming and


# Journal Paper 2 

# Review on Spring back effect in bending of Conical Shells in Roll Bending machine 

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## Abstract

Bending is one of the froquently used processes in the production of ahominium components. Bending operation includes damping, which is deffned as the elastic recovery of a component during unloading. In the manufacturing industry, it is still the practical problem of prodicting the final geometry of a part after springing and designing appropriate tooling to make this possible of compensate for suspension. In this paper, commercially available FEA software for fnite element analysis is used for the analysis bending and springing of different aluminium materials of different thichnesses. Suspension height, total equivalent plastic strains and equivalent von Mises stresses are presented. FEA results are compared with empirical data.

Keywords: Three roller bending machine; spring back; slaminium 6063; Taguchi; ANOVA; Grey Relational Analysis.

## 1. Introduction

In the modern manufacturing industry, aluminium has was a popular and widely used material. Especially in aerospace, defence and automotive industries, aluminium alloys are advantageous for their relatively low weight and satisfactory strength properties. Although aluminium alloys have relatively low tensile strength properties compared to steel, their strength weight the ratio appears to be satisfactory. According to the method of production, aluminium alloys can be divided into two main groups as wrought and cast alloys. Wrought alloys are shaped plastic deformation, which have significantly different microstructure and composition for casting alloys. Several wrought aluminium alloys have different characteristics and mechanical properties to meet the requirements. Design of Experiments provides numerical trial and error procedures, which lead to a less-time-consuming.

Several studies have been carried out on different aspects of finite element analysis of springback Karafifillis and Boyce 1 studied tooling design in sheet metal-forming compensating for springback and devel oped a so-called force descriptor algorithm based on calculating the traction distributions on the deformed sheet in order to optimize the tool design. They also examined 2 the manufacturing problems in sheet metalforming processes and proposed a method for tooling and binder design to obtain the desired part shape. Shu and Hung 3 studied finite element analysis and the optimization of springback reduction using the doublebend technique. Chou and Humg 4 analyzed several springback reduction techniques used in U-bending with the finite element method. Rebelo et al. 5 discussed several aspects of finite element analysis for sheet forming processes through some case studies of practical applications. Li et al. 6 proposed a new method for springback analysis of sheet-forming processes employing the explicit finite-element method in conjumction with an orthogonal regression analysis. In this study, they implemented the orthogonal regression analysis to establish the explicit relationship between springback and some design parameters.

Ninew


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# Investigation \& Optimization of process parameters of Roll Bending machine in realizing Conical Shells in Aluminum 6063 

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#### Abstract

For the sheet metal forming by roller bending machine, achieving the accurate geometry of components is the crucial task of many manufacturing industries. This is because of the "Springback" which refers to the elastic recovery of the deformed component. The microstructure and macroscopic mechanical properties of the sheet undergo changes during its forning process which results in inaccurate geometry of the component. These changes are common and inevitable in each phase of the production process Hence to predict and controlling the Springback as per the geometrical shape requirements is one of the key factors influencing the qualiy of rolled sheet metal parts. In this research paper, the investigation is made on realizing accurate conical shell-shaped components by roller bending machine for the material of construction (MOC) Ahuminum 6063. Effects of sheet metal thichness, number of passes, roller pressure, and roller rpm on Springback for Aluminum 6063 are analyzed.

Keywords: Three roller bending machine; Springback; Aluminum 6063; Taguchi; ANOVA; Grey Relational Analysis


## 1. INIRODUCTION

For the broad configuration of cylindrical, conical, or elliptical shells and sections, the continuous roller bending process has been an efficient metal forming technique. Along with its position as the largest industry in itself, metal shaping is the foundation of the latest manufacturing industry. Metal forming industry contributes as much as $20 \%$ in GDP of industrialized countries. For many engineering applications, cylindrical, conical, or ellipticalshaped hollow and solid components are extensively used. Considerable cost savings can be yielded because of optimum resource usage. Extensive research work and articles have been reported on the roller bending process over the last two decades. Several siguificant literatures are summanized here briefly.


## Appendix 1

## Report Generated by 'Abaqus Report Generator'

## 1. Overview

This report was generated by user on 2022-12-22 18:25:17 India Standard Time from output database file C:/Windows/system32/springback4.odb.

The information included in this report reflects the options selected in the HTML Report Generator plug-in when the report was generated. Therefore, the report does not necessarily include all of the model and results data available in the output database (.odb) file. In addition, this report may include information in 3D XML format; to view the 3D XML content properly, you must use Internet Explorer as your browser.

You can distribute this report by copying all of the files listed in the File Summary.
This report is organized into sections that match the organization of modules in Abaqus/CAE:

## Table of Contents

- Assembly Information
- Material Information
- Step Data
- Load Information
- Interaction Information
- Job Diagnostics
- Results
- Appendix
- File Summary


## Basic Model Information



User's name
Output database $\mathrm{C}: /$ Windows/system32/springback4.odb
Time created Thu Dec 22 10:38:50 India Standard Time 2022
Solver
Precision SINGLE_PRECISION
Work directory $\mathrm{C}: /$ Windows/system 32
HTML directory $\mathrm{C}: /$ Windows/system32/htmIReport
Image directory $\mathrm{C}: /$ Windows/system32/htmIReportlimages

## 2. Assembly Information

This section includes the following information about the part instances in the assembly:

- Instance Table
- 3DXML for Instances in the Model
- Figures Containing All Instances
- Additional Figures

| Table 2.1 Instance Table |  |  |  |  |
| :---: | :---: | :---: | :--- | :--- |
| Instance Name | Color | \# Elements | \# Nodes | Element type (\# elements) |
| SRF1 |  | 209 | 225 | R3D4 : (208), ROTARYI : (1), |
| SRF1_1_9 |  | 741 | 761 | ROTARYI : (1), R3D4 : (740), |
| SRF1_1_8 |  | 741 | 761 | R3D4 : (740), ROTARYI : (1), |
| SRF1_6 |  | 209 | 225 | R3D4 : (208), ROTARYI : (1), |
| SRF1_1_7 |  | 741 | 761 | R3D4 : (740), ROTARYI : (1), |
| SRF1_4 |  | 209 | 225 | R3D4 : (208), ROTARYI : (1), |
| SRF1_3 |  | 209 | 225 | R3D4 : (208), ROTARYI : (1), |
| SRF1_2 |  | 209 | 225 | R3D4 : (208), ROTARYI : (1), |
| SRF1_1 |  | 209 | 225 | R3D4 : (208), ROTARYI : (1), |
| SOLID2 |  | 2720 | 5670 | C3D8R : (2720), |
| SRF1_5 |  | 209 | 225 | R3D4 : (208), ROTARYI : (1), |

3DXML for Instances in the Model
Note: The "artificial ground" in the 3DXML is a visual artifact and not part of the model

Figures Containing All Instances


Figure 2.1 Figures Containing All Instances Bottom view


Figure 2.2 Figures Containing All Instances Front view


Figure 2.3 Figures Containing All Instances Iso view


Figure 2.4 Figures Containing All Instances Left view


Figure 2.5 Figures Containing All Instances Right view


Figure 2.6 Figures Containing All Instances Top view


Figure 2.7 Figures Containing All Instances User-1 view


Figure 2.8 Figures Containing All Instances User-2 view


Figure 2.9 Figures Containing All Instances User-3 view


Figure 2.10 Figures Containing All Instances User-4 view


Figure 2.11 Assembly setup for $\mathbf{3}$ roll bending

## Element Details

- R3D4 : 4-node 3-D bilinear rigid quadrilateral
- C3D8R : 8-node linear brick, reduced integration, hourglass control
- ROTARYI : Rotary inertia at a point


## 3. Material Information

This section includes figures that display the material information in the model. The default view orientations are provided, along with any user-defined views requested, and these figures are color coded according to the material definitions. A key to material definitions and their corresponding colors is provided after the figures. Hyperelastic material properties are included in the figures, if they are available.

- Material Color Table
- Elastic Behaviour
- Density Table
- Plastic Behaviour
- 3DXML for material data
- Figures Containing Material Information


Table 3.2 Elastic Behaviour

| Mate <br> rial | depende <br> ncies | moduli | noCompre <br> ssion | noTens <br> ion | temperatureDepe <br> ndency |
| :---: | :---: | :---: | :---: | :---: | :---: |
| AL | type |  |  |  |  |
| 6063 <br> T5 | 0 | LONG_T <br> ERM | OFF | OFF | OFF | | ISOTRO |
| :---: |
| PIC |


| Table 3.3 Elastic Table |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| Material | Young's modulus | Poisson's ratio |  |  |
| Temp |  |  |  |  |
| AL 6063 T5 | 71700.0 | 0.33 |  |  |
|  |  |  |  |  |


| Table 3.4 Density Table |  |  |
| :---: | :---: | :---: |
| Material | Density | Temperature |
| AL 6063 T5 | $2.78 \mathrm{e}-09$ | $\#$ |

Table 3.5 Plastic Behaviour

| Mat <br> erial | dataTy <br> pe | depend <br> encies | harde <br> ning | numBac <br> kstresses | ra <br> te | strainRange <br> Dependency | temperature <br> Dependency |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| AL | HALF |  | ISOT <br> 6063 <br> T5 | CYCLE |  | ROPI <br> C | 0 |
| O | OFF | OFF |  |  |  |  |  |

Table 3.6 Plastic Table

| Material | Nominal Stress | Nominal Strain | Lateral Nominal Strain | Temp |
| :---: | :---: | :---: | :---: | :---: |
| AL 6063 T5 | 17.35 | 0.0 | $\#$ | $\#$ |


| AL 6063 T5 | 23.61 | 0.0003 | \# | \# |
| :---: | :---: | :---: | :---: | :---: |
| AL 6063 T5 | 30.57 | 0.0004 | \# | \# |
| AL 6063 T5 | 37.18 | 0.0005 | \# | \# |
| AL 6063 T5 | 45.88 | 0.0007 | \# | \# |
| AL 6063 T5 | 52.84 | 0.0008 | \# | \# |
| AL 6063 T5 | 61.54 | 0.0009 | \# | \# |
| AL 6063 T5 | 69.89 | 0.001 | \# | \# |
| AL 6063 T5 | 79.28 | 0.0011 | \# | \# |
| AL 6063 T5 | 88.33 | 0.0012 | \# | \# |
| AL 6063 T5 | 97.73 | 0.0014 | \# | \# |
| AL 6063 T5 | 109.21 | 0.0015 | \# | \# |
| AL 6063 T5 | 118.61 | 0.0017 | \# | \# |
| AL 6063 T5 | 129.4 | 0.0019 | \# | \# |
| AL 6063 T5 | 138.44 | 0.002 | \# | \# |
| AL 6063 T5 | 149.23 | 0.0022 | \# | \# |
| AL 6063 T5 | 158.28 | 0.0024 | \# | \# |
| AL 6063 T5 | 168.03 | 0.003 | \# | \# |
| AL 6063 T5 | 175.0 | 0.0035 | \# | \# |
| AL 6063 T5 | 178.49 | 0.0046 | \# | \# |
| AL 6063 T5 | 181.29 | 0.0055 | \# | \# |
| AL 6063 T5 | 182.69 | 0.0067 | \# | \# |
| AL 6063 T5 | 184.1 | 0.0077 | \# | \# |
| AL 6063 T5 | 184.15 | 0.0088 | \# | \# |
| AL 6063 T5 | 184.17 | 0.0097 | \# | \# |
| AL 6063 T5 | 186.23 | 0.01 | \# | \# |
| AL 6063 T5 | 186.24 | 0.011 | \# | \# |
| AL 6063 T5 | 187.3 | 0.012 | \# | \# |
| AL 6063 T5 | 188.36 | 0.014 | \# | \# |
| AL 6063 T5 | 190.12 | 0.015 | \# | \# |


| AL 6063 T5 | 190.18 | 0.016 | $\#$ | $\#$ |
| :---: | :---: | :---: | :---: | :---: |
| AL 6063 T5 | 190.2 | 0.017 | $\#$ | $\#$ |
| AL 6063 T5 | 190.25 | 0.018 | $\#$ | $\#$ |
| AL 6063 T5 | 190.27 | 0.019 | $\#$ | $\#$ |
| AL 6063 T5 | 193.68 | 0.021 | $\#$ | $\#$ |
| AL 6063 T5 | 193.69 | 0.022 | $\#$ | $\#$ |
| AL 6063 T5 | 193.71 | 0.023 | $\#$ | $\#$ |
| AL 6063 T5 | 194.42 | 0.024 | $\#$ | $\#$ |
| AL 6063 T5 | 195.0 | 0.025 | $\#$ | $\#$ |
| AL 6063 T5 | 195.5 | 0.026 | $\#$ | $\#$ |
| AL 6063 T5 | 196.21 |  | $\#$ | $\#$ |

## 3DXML for material data in the model

Note: The "artificial ground" in the 3DXML is a visual artifact and not part of the model

Figures Containing Material Information


Figure 3.1 Figures Containing Material Information Bottom view


Figure 3.2 Figures Containing Material Information Front view


Figure 3.3 Figures Containing Material Information Iso view


Figure 3.4 Figures Containing Material Information Left view


Figure 3.5 Figures Containing Material Information Right view


Figure 3.6 Figures Containing Material Information Top view


Figure 3.7 Figures Containing Material Information User1 view


Figure 3.8 Figures Containing Material Information User2 view


Figure 3.9 Figures Containing Material Information User3 view


Figure 3.10 Figures Containing Material Information User-4 view

## 4. Step Information

This section gives details about steps used in this analysis. NLGeom controls whether nonlinear geometric aspects are taken into consideration in the analysis.

| Table 4.1 Step Information |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | Step Name | Procedure | Step Time | Total Time |  |
| Nlgeom |  |  |  |  |  |
| 1 | Step-1 | DYNAMIC, EXPLICIT | 0.100 | 0.100 |  |
| OFF |  |  |  |  |  |

## 5. Load Information

This section displays figures that show where loads are applied in the model. Only figures created in the load module of Abaqus/CAE, using a separate plug-in are included in this section.

Figures Containing Load Information


Figure 5.1 BC @ Bending Roller


Figure 5.2 BC @ Lower Roller


Figure 5.3 BC @ Upper Roller

## 6. Interaction Information

This section displays figures that show interactions in the model. Only figures created in the Interaction module of Abaqus/CAE, using a separate plug-in are included in this section.

Figures Containing Interaction Information


Figure 6.1 Coupling type constraint to Bending roller


Figure 6.2 STS Contact between Bending roller \& Sheet


Figure 6.3 STS Contact between Lower roller \& Sheet

## 7. Data Diagnostics Information

This section includes the following information about the analysis data:

- Job time Table
- Numerical problem summary Table
- Step Data

| Table 7.1 Job time (currently <br> unavailable) |  |
| :---: | :---: |
| System time | 0.0 |
| User time | 0.0 |
| Wallclock time | 0.0 |


| Table 7.2 Numerical problem <br> summary |  |
| :---: | :---: |
| Number of zero pivots | 0 |
| Number of numerical singularities | 0 |
| Number of negative eigenvalues | 0 |
| Converged zero pivots | OFF |
| Converged numerical singularities | OFF |
| Converged negative eigenvalues | OFF |


| Table 7.3 Step Data |  |  |
| :---: | :---: | :---: |
| Step | Package | Step-1 |
| Perturbation | OFF | OFF |
| Characteristic element length | $0.0000 \mathrm{E}+00$ | $0.0000 \mathrm{E}+00$ |
| Increments completed | 0 | 254185 |
| Minimum time increment | 0.0 | 0.0 |
| Step time completed | 0.0 | 0.10000000149 |
| Analysis type | Standard | Explicit |
| Maximum time increment | 0.0 | 0.0 |


| Initial time increment | 0.0 | 0.0 |
| :---: | :---: | :---: |
| Riks | OFF | OFF |
| Matrix solver | DIRECT_SOLVER | DIRECT_SOLVER |
| Time Period | 0.0 | 0.10000000149 |
| Stabilization | OFF | OFF |
| Maximum number of increments | 0 | 0 |
| Unsymmetric Solver | OFF | OFF |
| Stabilization Factor | 0.0 | 0.0 |
| Number of contact diagnostics | 0 | 0 |

Converged zero pivots: Whether any increment of the analysis converged on a zero pivot.
Converged numberical singularities: Whether any increment of the analysis converged on a numerical singularity.
Converged negative eigenvalues: Whether any increment of the analysis converged on a negative eigenvalue.

## 8. Results

This section displays results data requested from the output database file, including the maximum and minimum values for selected output variables. This section also includes any X-Y plots saved to the output database and requested for inclusion in the report.

- Additional Figures


## Additional Figures added from Abaqus/CAE



Figure 8.1 Sheet Condition @ Start

## 9. Appendix

This section presently contains information about any amplitude table specified in the model.

- AMP-1

| AMP-1 |  |
| :--- | :--- |
| type | TabularAmplitude |
| name | AMP-1 |
| smooth | 0.25 |
| timeSpan | TOTAL |


| AMP-1 Data |  |
| :---: | :---: |
| $0.00 \mathrm{e}+00$ | $0.00 \mathrm{e}+00$ |
| 0.100 | 1.000 |

## 10. File Summary

To transfer this report, following files and directories must be copied:

- htmIReportlimage
- htmlReportladditionalImages
- htmlReportladditionalFiles
- htmlReportlabaqus.css
- htmlReportlhtmIReport.html

