DEVELOPMENT OF REGRESSION MODEL FOR SPINNING FORCE USING PARABOLIC MANDREL

[1]Ravikumar B, [2]Gajanana S, [3]Hemachandra Reddy K, [4]Rahul Teja G

[1,2,4]Department of Mechanical Engineering, MVSR Engineering College, Nadergul, Hyderabad
[3]Department of Mechanical Engineering, JNTUA, Anantapuram
[1]E-mail: brkmvsr@gmail.com

Abstract: *Metal forming involves deforming of metal physically into various derived shapes and sizes under the effect of externally applied forces. Flow forming is an advanced, near net shape, chip less metal forming process, which employs an increment rotary point deformation technique for manufacturing seamless, dimensionally precise tubular and other rotationally symmetrical products. Spinning is an advanced continuous and local metal forming process, which is widely used in many fields due to its advantages of flexibility, high quality and low cost. It is frequently used for manufacturing axisymmetric shapes where press tooling might not be justified on grounds of size and production volumes. It also has the possibility of producing parts that could not be deep drawn. Initial workpiece shape is either a flat blank or a preformed hollow component. It is characteristic of this process that the deformation does not occur in an annular zone around the axis of rotation but that the tools act upon a much localized area in which plastic flow takes place. During spinning tools are moved relative to the rotating workpiece. In this paper, a Regression model showing the relation among input process parameters, Mandrel speed (rpm), Roller type and Thickness of sheet (mm) and output response spinning force is developed using full factorial design of experiments conducted on Aluminum 2024-T3 sheets with parabolic mandrel. Contribution of each factor on output is determined by Analysis of Variance (ANOVA).*

Keywords: *Metal Spinning, Factorial Design of Experiments, ANOVA, Spinning Force*

1. INTRODUCTION

Metal spinning is a sheet metal working process by which a sheet or tube of metal is rotated at high speed and formed into an axially symmetric part. Spinning can be performed by hand tools on conventional lathe machine. Conventional metal spinning involves localized bending of a sheet metal blank through a series of sweeping strokes to produce a desired shape without the change of the original blank thickness shown in Figure. 1. The incremental passes of the forming tool induce compressive tangential (hoop) stresses in the flange region. As the roller moves towards the edge of the blank, radial tensile stresses are generated, which produce a flow of material in the direction along the Preform. In conventional spinning, defects occur when the radial tensile and tangential compressive stresses are not induced in the appropriate combination progressively through the material.

The following parameters are considered during experimentation of process on Aluminum 2024-T3 sheet. Mandrel speed (rpm): The speed at which the mandrel is rotated along its own axis which is fixed in lathe chuck and holding the work sheet.

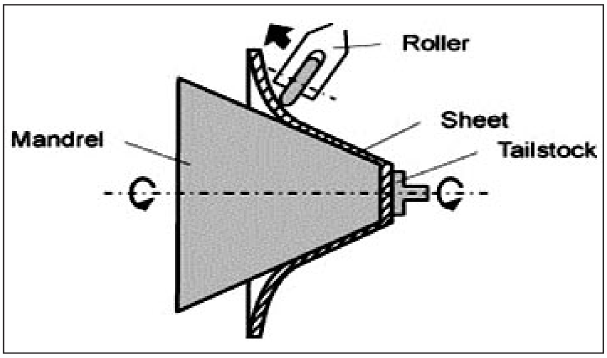

Fig 1. Metal Spinning Process

2. LITERATURE SURVEY

Lin Wang, Hui Long in their work "Roller Path Design by Tool Compensation in Multi-pass Conventional Spinning" published in ELSEVIER in the year 2012 stated that in conventional spinning, multiple roller passes are required to prevent material failures and to minimize thinning of wall thickness of spun parts. In the present industrial practice, the process design still relies on the trial-and-error approach to determine roller path and passes. In this paper, a tool compensation technique has been proposed and employed in multiple roller passes design, to ensure the work piece fully conforming onto the profile of a mandrel.

O. Music, J.M. Allwood, K. Kawai in their work "A review of the mechanics of metal spinning" presented a thorough survey of academic work on the analysis and application of the mechanics of spinning. The review aims to provide insight into the mechanics of the process and act as a guide for researchers working on both metal spinning and other modern flexible forming processes. The review of existing work has revealed several gaps in current knowledge of spinning mechanics: the evolution of the stress state and the strain history of the work piece in both conventional and shear spinning is not well understood, mainly due to the very long solution times that would occur in modelling the process throughout its duration with a sufficiently fine mesh to capture detailed behavior through the work piece thickness; the evolution of microstructure, residual stress and hence spring back, has not been examined—either numerically or by experiment; the failure mechanisms of spinning – fracture and wrinkling – are only partially understood, through analogy with other processes, and as yet models of the process have not made use of contemporary damage mechanics; the design of tool paths required to make particular parts without failure remains an art, and cannot currently be performed automatically with confidence. Studies on novel process configurations in spinning have shown that great potential for innovation in spinning exists. The process has the potential to be more flexible, to produce a wider range of shapes, and to form more challenging material.

3. FACTORIAL DESIGN OF EXPERIMENTS

The factorial design of an experiment is the procedure of selecting the number of trials and conditions for running them, essential and sufficient for solving the problems that has been set with the required precision. Factorial designs are widely used in experiments involving several factors where it is necessary to study the joint effect of the factors on a response. However there are several special cases of the general factorial design that are important because they are widely used in research work and also because they form the basis of other designs of considerable practical value.

3.1 Objectives and Methodology

The mathematical model is developed by using factorial design of experiments to predict the force required for spinning of AL2024-T3 by EN8 spinning Tool. The three factors, namely, Speed, Thickness of Sheet and Roller Type are analyzed simultaneously by the main effects with two and three factor interactions. The developed model is tested for its adequacy and significance of each coefficient is checked by student's t-test at 5% significance level.

The investigation study is planned with the following objectives

1. Postulation of mathematical model for resultant force resultant spinning force.
2. Adoption of two level factorial design of experiments and selection of test regions for the variables (factors).
3. Conducting the experiments as per design matrix.
4. Estimation of coefficients of postulated model.
5. Analysis of results
    - Checking the adequacy of the postulated model by 'F-test'
    - Testing the significance of each coefficient of the model by 't-test'
    - Determination of percentage contribution of each factor.

3.2 Postulation of Model for Spinning Force

Objectives and Scope of work

Objectives:

- To study the effect of process parameters on spinning force in metal spinning process

Table 1: Factors and Levels

Factors	Units	Designation		Test levels	
		Natural form	Coded form	Low	High
Thickness	mm	T	X_1	1	1.2
Roller Type	-	R	X_2	R1	R2
speed	rpm	S	X_3	133	150

Table 2: Design Matrix

Trial No.	DESIGN MATRIX			SPINNING FORCE (Kgf)		
	X_1	X_2	X_3	Y_1	Y_2	Y
1	-1	-1	-1	199.64	199.44	199.54
2	+1	-1	-1	195.02	195.05	195.04
3	-1	+1	-1	75.32	75.28	75.30
4	+1	+1	-1	79.12	79.22	79.17
5	-1	-1	+1	110.16	110.08	110.12
6	+1	-1	+1	100.64	100.24	100.44
7	-1	+1	+1	68.30	68.10	68.20
8	+1	+1	+1	105.84	105.64	105.74

Scope:

- Using EN8 spinning tool
- Using AL2024-T3 as work piece.
- Applied a Spinning process with parabolic mandrel.
- Determination of spinning force using Dynamometer**.**

The spinning variables (factors) are identified to develop the mathematical model to predict the maximum force before fracture (response). These include Speed (rpm), Thickness of Sheet (mm) and Roller Type. The first order regression model is assumed with two and three factor interactions which can be expressed as,

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{123}X_1X_2X_3$$

where 'Y' represents maximum force X_1, X_2, X_3 represent the coded values of Speed ,Thickness of sheet and Roller type respectively; $b_0, b_1, \ldots, b_{123}$ are the regression coefficients of polynomial to be determined. A two level full factorial design of experiments is adopted for calculating the main and the interaction effects of the three factors at two levels; 2^3 = 8 experiments are conducted to fit an equation. The design plan with high and low limits as indicated Table -1

Fig 2. Spinning with Single Radius Roller

Fig 3. Spinning with Double Radii Roller

4. EXPERIMENTATION

The experiments were carried out on a Capstan Lathe Machine using an EN8 Spinning Tool and the spinning force values are measured by Lathe Tool DYNAMOMETER(620 series). The design matrix and summary of the experimental results are shown in the table-2.

Fig 4. Specimen after Experimentation

5. MATERIAL PROPERTIES

EN8 is unalloyed mild steel with less carbon content. It has good tensile strength and is normally supplied in cold drawn or as rolled. Tensile properties can vary but are usually between 500-800N/mm2.

Composition:

- C 0.35-0.45%;
- Si 0.05-0.35%;
- Mn 0.6-1.0%;
- S, P <0.06%.

General 2024-T3 characteristics are Good machinability and surface finish capabilities. A high strength material of adequate workability

Composition:

- Mg 1.2-1.8%:
- Cu 3.8-4.9%;
- Mn 0.3-0.9%;
- Cr max.1%.

6. MODEL DEVELOPMENT

In the present work, sequences of steps followed in development of model are

6.1 Calculation of Regression Coefficients

Here the number of replications for the response are two i.e., y1 and y2 and average of these is 'y'. Regression coefficients b_0, b_1, b_2, b_{12} etc., are calculated by using the formula given below

$b_j=[\ \sum\ x_{ij}\ y_i]/N$

Where N = number of trails (N=8)

Fisher test for adequacy of model (f-test for 5% significance level)

Variance for reproducibility = $S_y^2 = [2\sum(\text{dely})^2]/N$

N=number of trails, dely = (y1-y)

Variance of adequacy,

$S_{ad}^2=[2\sum(y-y_p)^2]/DOF$

y_p = predicted response.

$y_p=b_0x_0[i]+b_1x_1[i]+b_2x_2[i]+\ldots\ldots.$

where DOF = degree of freedom

= [N-(k+1)]

where N = number of trails

k = number of factors

F-model = S_{ad}^2/S_y^2

For given values of f1 and f2, F-table value is found from fisher table.

Here f1=N-(k+1), f2=N

If F-model ≤ F-table, model is adequate in linear form otherwise it is not adequate.

6.2 Student's t-test (for 5% significance level)

When the model is adequate in linear form, then t-test is to be conducted to test the significance of each Regression coefficient.

Standard deviation of each coefficient,

$S_{bj}=\sqrt{(S_y^2/N)}$

t-ratio = $|\ b_j|\ /\ (S_{bj})$

For f = N, t value is to be taken from t-table and compared with t-ratio of each regression coefficient. If t-ratio ≥ t-table corresponding regression coefficient is significant. Non-significant coefficients are to be eliminated from the model to arrive the final form of mathematical model in linear form as

$Y = b_0+b_1X_1+b_2X_2+b_3X_3+b_{12}X_1X_2+b_{13}X_1X_2+b_{23}X_2X_3+b_{123}X_1X_2X_3$

The column of each variable X_1, X_2 and X_3

Table 3: Analysis of Variance

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-ratio
A treatments	SS_A	a-1	$MS_A= SS_A$	$F_A=MS_A/ MS_E$
B treatments	SS_B	b-1	$MS_B=SS_B$	$F_B= MS_B/ MS_E$
Interactions	SS_{AB}	(a-1)(b-1)	$MS_{AB}= SS_{AB}/(a-1)(b-1)$	$F_{AB}=MS_{AB}/ MS_E$
Error	SS_E	ab(n-1)	$MS_E= SS_E/ ab(n-1)$	
Total	SS_T	abn-1		

Table 4: (ANOVA)

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-ratio
X_1	185.30	1	185.30	4959.52
X_2	19144.18	1	19144.18	512390.27
X_3	6768.76	1	6768.76	181164.65
X_1X_2	772.70	1	772.70	20681.19
X_2X_3	10351.54	1	10351.54	277056.84
X_1X_3	202.99	1	202.99	5433.02
$X_1X_2X_3$	377.23	1	377.23	10096.58
Error	0.15	4	0.04	-
Total	37802.86	7	-	-

are arranged in standard order. The values of regression coefficients b_0, b_1, b_2...b_{123} are calculated by regression analysis.

The values of regression coefficients b_0, b_1, b_2...b_{123} are calculated for Spinning Force and given below.

Regression coefficients for Spinning Force are

b_0= 116.69 b_{12}=6.95
b_1=3.40 b_{13}=3.56
b_2= -34.59 b_{23}= 25.44
b_3= -20.57 b_{123}=4.86

The adequacy of the model was then tested by Fisher test. As per this technique, F-ratio of the model developed does not exceed the standard tabulated value of f-ratio for a 95% confidence level. Hence the model was adequate. The significance of the coefficients was checked by using student's t-test and only the significant coefficients were used to develop final mathematical model.

The final model in coded form for Spinning Force is

$$Yp = 116.69X_0 + 3.40X_1 - 34.59X_2 - 20.57X_3 + 6.95X_1X_2 + 3.56X_1X_3 + 25.44X_2X_3 + 4.86X_1X_2X_3$$

The final model in decoded form for spinning force is

Force (Kgf) = 1081 - 566.1 Thickness + 350.0 Roller Type - 7.079 Speed
- 734.7 Thickness* Roller Type
+ 4.241 Thickness*Speed
- 3.257 Roller Type*Speed+5.682 Thickness*Roller Type*Speed

7. ANALYSIS OF VARIANCE

The Analysis of Variance is done to find out the percentage contribution of each factor and relative significance of each factor

'a' and 'b' are the levels of A and B factors

SS_A = {Sum [$x_1(i)$ * $y_t(i)$]}^{2} / Nn

SS_T = {Sum [$y_1(i)^2$ + $y_2(i)^2$]}^{2} - {Sum [$y_1(i)$]^2 / Nn}

Here N = number of trials

$SS_E = SS_T - SS_A - SS_B$ ......

Percentage contribution of factor A = (SS_A / SS_T) * 100

Analysis of variance is done to find out the percentage contribution of each factor and relative significance of each factor for Spinning Force.

Percentage contribution of the Factors and their Interactions for Spinning force

Table 5. Percentage Contribution of Factors

Factor	% Contribution
X_1	0.49
X_2	50.64
X_3	17.91
X_1X_2	2.04
X_2X_3	27.38
X_1X_3	0.54
$X_1X_2X_3$	1.00

8. GRAPHICAL REPRESENTATION

The following graphs have been plotted between input parameters and corresponding output value using equation generated.

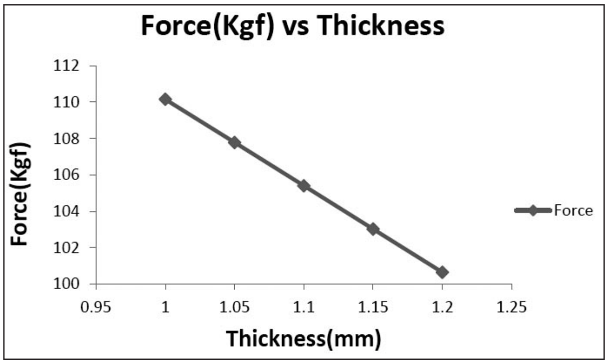

Fig 8.1. The value of Speed is Kept Constant at 150 rpm and Roller Type 1 is taken. The value of Thickness is Varied Between 1mm and 1.2 mm

In the above Fig 8.1 as the Thickness varies from 1mm to 1.2 mm, the force decreses from 110.16kgf to 100.64kgf and has a negative slope

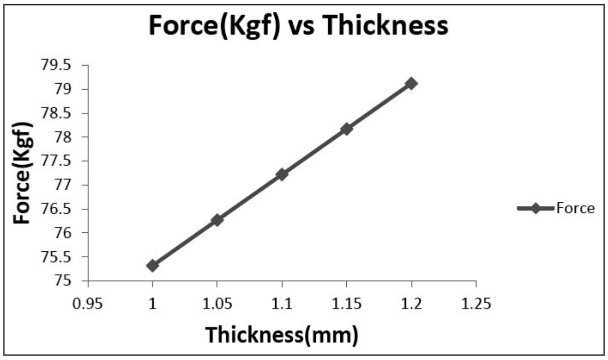

Fig 8.2. The value of Speed is Kept Constant at 133 rpm and Roller Type 2 is taken. The value of Thickness is Varied Between 1mm and 1.2 mm

In the above Fig 8.2 as the Thickness varies from1mm to 1.2mm, the force increases from 75.32kgf to 79.12kgf and has a positive slope.

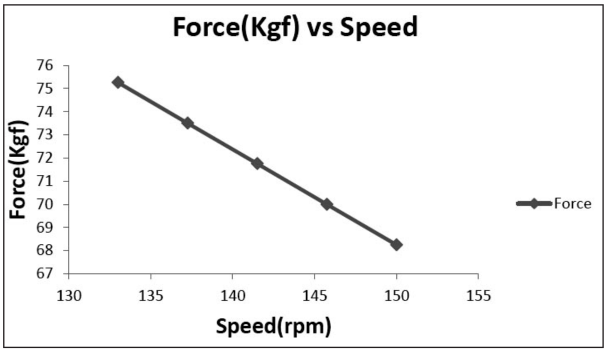

Fig 8.3. The value of Thickness is Kept Constant at 1mm and Roller Type 2 is taken. The value of Speed is Varied Between 133rpm and 150 rpm

In the above Fig 8.3 as the speed varies from 133 rpm to 150 rpm, the force decreases from 75.271 kgf to 68.25kgf and has a negative slope.

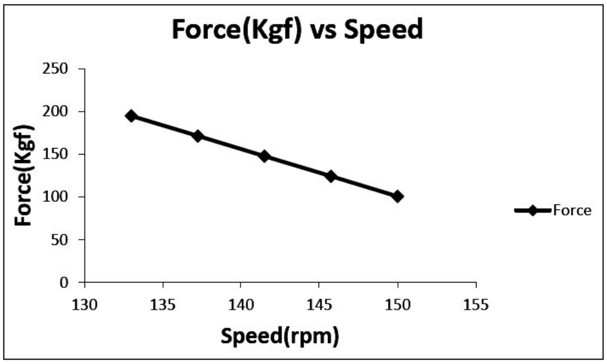

Fig 8.4. The Value of Thickness is Kept Constant at 1.2mm and Roller Type 2 is taken. The Value of Speed is Varied Between 133rpm and 150 rpm

In the above Fig 8.4 as the speed varies from 133 rpm to 150 rpm, the force decreases from 195.02kgf to 100.64kgf and has a negative slope.

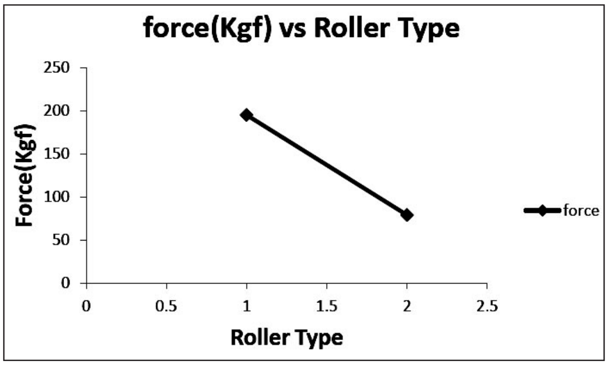

Fig 8.5. The value of Thickness is Kept Constant at 1.2mm and Speed 133 is Kept Constant. The Roller Type is Varied from 1 to 2.

In the Fig 8.5 as the Roller changes from 1 to 2, the force decreases from 195.02kgf to 79.12kgf and has a negative slope.

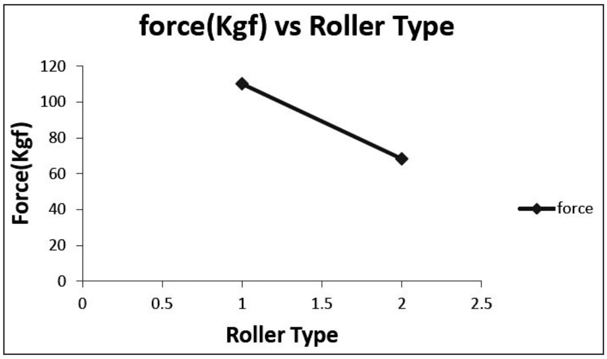

Fig 8.6. The Value of Thickness is Kept Constant at 1mm and Speed 150 is Kept Constant. The Roller Type is Varied from 1 to 2.

In the above Fig 8.6 as the Roller changes from 1 to 2, the force decreases from 110.16kgf to 68.3kgf and has a negative slope.

9. RESULTS AND CONCLUSIONS

- From all the trials conducted, Force was highest (199.64Kgf) when Roller Type R1, thickness 1mm, Speed 133rpm were considered.
- The value of the force was least i.e., 68.30Kgf when Thickness of Sheet was 1 mm, Roller Type was R2 and Speed was 150 rpm.
- From ANOVA table-3, it is clear that, percentage contribution of Roller Type X_2, is 50.64% on the spinning force, next followed by interaction effect of speed and Roller Type, Speed X_3 and Thickness X_1 and remaining percent is contributed by other interactions. Determination of contribution of factors helps the operator to set the parameters at required values in order to get desired quality of products.

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B Ravikumar presently working as Assistant professor in Mechanical Engineering, MVSR Engineering College, Hyderabad. He did his B.Tech (1994) in Mechanical Engineering from JNTU, Hyderabad. Master's Degree in Mechanical Engineering (2004) Specialization in Production from JNTU, Hyderabad. Currently he is pursuing Ph.D under JNTU, Hyderabad.

Dr. S Gajanana presently working as professor in Mechanical Engineering & Chief Coordinator(Exams), MVSR Engineering College, Hyderabad. He did his B.Tech (1995) in Mechanical Engineering from S.K.University, Anantapur. Master's Degree in Mechanical Engineering (1999) Specialization in Production Technology from University College of Engineering, S.V. University, Tirupati. Ph.D from S.V. University in the year 2007. Currently he is guiding 7 PhDs and published more than 50 research papers in various International & National journals and International & National Conferences. He also completed one research project, sponsored by UGC. He served as Head, Department of Mechanical Engineering, and Director (SA) at MVSR Engineering College.

Dr. Hemachendra Reddy has 17 years of teaching experience and 10 years of administrative experience in engineering education. He has guided 15 Phd scholars. He has produced around100 international and national papers. Currently He is working as professor at JNTUA Anantapur.

G Rahul Teja is graduate in Mechanical Engineering from MVSR Engineering College. Currently he is preparing for his higher studies. He has presented paper in National conference organized by JNTUH, Hyderabad (2018) under the guidance of Prof. S.Gajanana