

Experimental investigations to predict mean diameter of AA6082 tube in flow forming process – A DOE approach

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ABSTRACT : - Flow-forming is effective, chipless metal forming process used for the manufacture of thin walled seamless tubes. In the present paper, a regression model has been developed to predict mean diameter of AA6082 flow formed tubes by Design Of Experiments. The process parameters chosen for the present investigation are axial feed of the roller, speed of the mandrel, and roller radius. Experiments are performed on a single roller flow forming machine to study the effect of process parameters on mean diameter of flow formed tube employing response surface methodology (RSM). The regression model generated by response surface methodology successfully predicts the mean diameter of AA6082 flow formed tube within the range of selected process parameters. It is found that, roller feed and roller radius are significant parameters influencing the mean diameter of Flow-forming AA6082 flow formed tube.

KEY WORDS- AA6082 alloy, Design Of Experiments, Mean diameter, Response surface methodology.

I. INTRODUCTION

Flow-forming is innovative, advanced manufacturing process for the production of thin walled seamless tubes. In flow-forming process, the length of pre-form is elongated by reducing wall thickness. The internal diameter of the pre-form remains unchanged. Flow-forming process is used for the manufacture of seamless tubes, cylinders, axi-symmetric sheet metal parts for high strength-to-weight ratio flanged components used in ship building, agricultural, railway, automobile, aerospace and missile applications etc. Outside mean diameter is one of the important parameter in the production of thin walled seamless tubes. Various process parameters namely roller feed, mandrel speed, roller radius, thickness reduction, roller attack angle influence the mean diameter of flow formed tube.

Kalpkioglu investigated on the shear-spinnability of metals. Ram Mohan and Mishra made studies on the power spinning of tubes. Rajanish Prakash and Singhal conducted experiments on shear spinning of Titanium, Inconel 600 and AISI-304 steel and proved that the process can be used for the production of thin-walled, high precision long tubes on commercial basis. Park Jae-Woo et al. optimized the total power consumption by flexible tolerance method to minimize multi-variable non-linear function in tube-spinning processes by employing upper-bound stream-function method. Lee and Lu conducted experiments on flow forming of cylindrical tubes and concluded that, size of roller influence the deformation ratio and forming force. They also found that, better surface finish was produced with a larger roller. Wong et al. investigated the Effects of roller path and geometry on the flow forming of solid cylindrical components. They reported that, metal flow takes place predominantly in radial direction with cylindrical roller and predominantly in axial direction with nosed roller. Makoto Murata et al. studied the effect of setting temperature of roller tool on the forming properties of spinning. They found that, spinning force and hardness increases with the increase of setting reduction. Joseph Davidson et al. studied effect of process parameters on the quality of AA6061 flow formed tubes. They proposed the optimum parameters for good surface characteristics. Razani et al. studied the out of roundness of AISI 321 steel tube by flow forming process employing Taguchi method. But, very small work has been found on flow forming of AA6082 tubes. The mean diameter is one of the important characteristic and precise control of average diameter of AA 6082 tube in flow forming is essential for critical aerospace and missile applications.

Alauddin et al. Predicted tool life in end milling process employing response surface methodology. Gunaraj and Murugan used response surface methodology to predict weld bead quality in submerged arc welding of pipes. Jae-Seob Kwak studied the effect of process parameters on the geometric error in grinding process and developed regression model to predict geometric error using Taguchi and response surface methodologies. Joseph Davidson et al. predicted surface roughness of AA6061 flow formed tubes by response surface methodology. Srinivasulu et al. used Taguchi method for optimizing the process parameters to produce the tubes with minimum surface roughness in flow forming of AA 6082 annealed pre-forms.

Experimental investigations to predict mean diameter of AA6082 tube A DOE approach

The literature review reveals that, no work has been reported on regression modeling for the manufacture of AA6082 thin walled tubes with precise mean diameter by flow forming process.

The aim of present investigation is to generate the regression model to predict the mean diameter of AA6082 thin walled tubes manufactured by flow forming process. The input process parameters selected for the present study are axial feed of the roller, speed of the mandrel and roller radius. The response parameter is the mean diameter of flow formed tube.

II. EXPERIMENTAL WORK

2.1 Material

The material selected for the present research is AA6082 alloy. The composition of AA6082 alloy is given in table-1. It has medium strength, good machinability and weldability with excellent corrosion resistance. Addition of Manganese controls the grain structure, which results in superior strength. The alloy age hardens by formation of Mg_2Si precipitates. This alloy has an ultimate tensile strength of 340 MPa, yield strength of 310 MPa and hardness of 95 BHN. AA6082 alloy used in automobiles, truck frames, ship building, motor boats, pylons, towers, aero space and missile applications.

TABLE-1
Composition of AA6082 alloy

Element	Al	Mg	Mn	Si	Fe	Cr	Cu
%	95.65	1.20	1.00	1.3	0.50	0.25	0.10

2.2 Flow forming process

In flow forming, a short and thick cylindrical blank (Pre-form), is stretched on a rotating mandrel by means of mechanically guided rollers. The pre-form is lengthened by decreasing in wall thickness. It is locked by means of serrations and rotates together with the mandrel at the same speed. The forming roller follows the contour of the mandrel with a preset gap. The gap between the rotating mandrel and the roller acts as an orifice through which the metal flow occurs (extruded). As the forming process produces localized deformation, lower forces are required as compared to other processes. The principle of flow forming is shown in Figure 1.

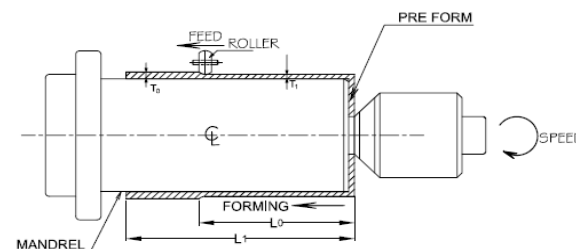


Fig. 1. Flow forming process

The flow forming is classified into two types as forward flow forming and backward (reverse) flow forming processes. In forward flow forming, the material flow takes place in the same direction as that of rollers. The forming is done near tail stock and requires tubes with closed ends. Material flows in the opposite direction to the roller feed in case of backward flow forming. Tubes longer than mandrel can be formed in backward flow forming process.

2.3 Pre-form Design

The design of pre-form was based on two parameters namely maximum possible deformation and constant volume principle. These pre-forms were made by hot forging. Generally 15% allowance is provided on the diameter for machining and other allowances. The pre-form was subjected to annealing at a temperature of $550^{\circ}C$ for two hours to take the precipitation into solution and quenched in water to retain solute in solution. The mandrel is made up of tool steel and hardened to 63HRC. A thin film of lubricant is applied on mandrel to avoid sticking of flow formed tube. The machined pre-form is shown in fig. 2.



Fig. 2. Machined Pre-form

2.4 Equipment

The present research work is carried out on a CNC flow-forming machine with single roller. The mandrel rotates at a speed, S rpm. The roller moves along the axis of the mandrel with a feed rate, F mm/min and decreases the thickness of pre-form when a thickness reduction t (%) is given by radial feed. The thickness reduction is effected by maintaining gap between the mandrel and the roller less than the thickness of pre-form. The axial and radial feeds are maintained by hydraulic power pack through servo motors. The thickness reduction of pre-form results in increase in length without altering inside diameter. It is aimed to manufacture seamless tubes with maximum percentage elongation ratio, good strength and minimum mean diameter.

III. THE METHODOLOGY

3.1 Design Of Experiments (DOE)

In the present research, Design Of Experiments, a powerful statistical tool is employed to achieve predictive knowledge of complex, multivariable process with minimum experimentation. It reduces the cost of experimentation and gives meaningful, valid conclusion with least number of experiments. This technique helps to identify the significant input process parameters. DOE also enables to determine the individual and interaction effects of input process parameters that could influence the response function. Response surface methodology (RSM) a statistical and mathematical method based on Design Of Experiments is employed to model mean diameter in flow forming of AA 6082 tubes.

3.2 Response surface methodology (RSM)

Response surface methodology is a collection of statistical and mathematical methods that are useful for the modeling and analyzing engineering problems. The main objective of this technique is to optimize the response function that is influenced by different process parameters. Response surface methodology also quantifies the relationship between the controllable input parameters and obtained response surface. The design procedure of RSM is as follows:

1. Identification of controllable input process parameter and desirable response parameter.
2. Planning of a series of experimental runs as dictated by design matrix for adequate and reliable measurement of the response function.
3. Developing a mathematical model of the second order response surface with the best fittings.
4. Finding the optimal combination of experimental parameters that gives a maximum or minimum value of response.
5. Reporting the direct and interactive effects of process parameters on the response through two and three dimensional plots.

3.3 Box-Behnken design

Box-Behnken design is one of the popular response surface designs is used in the present investigation. Box-Behnken design requires only three levels for each parameter. It has no points at the vertices of the cube defined by the ranges of the factors. This distinguished feature is sometimes useful when it is desirable to avoid the points at corner of the cube due to engineering considerations. For two or three factors, it requires fewer experimental runs as compared to compared to the central composite design. The design matrix requires 17 experimental runs only to model the process

IV. SELECTION OF INPUT PROCESS PARAMETRES

Initially trial runs were conducted to know the effect of various process parameters on the mean diameter in flow forming of AA 6082 tubes. The input process parameters chosen based on trial experiments. The input process parameters selected for the present investigation are axial feed of the roller, speed of the mandrel and radius of the roller. The input process parameters and their low and high levels are given in Table 2. The response surface model for mean diameter of flow formed tube is developed by trial version of Design Expert 8.0 software.

TABLE-2
Input Process parameters and their levels

<i>Sl. No.</i>	<i>Parameters</i>	<i>Low level</i>	<i>High level</i>
1	Axial feed, mm/min.	50	100
2	Mandrel speed, rpm	150	250
3	Roller radius, mm	4	12

V. DEVELOPING MATHEMATICAL MODEL FOR MEAN DIAMETER

The experimental plan is generated by Design Expert Version 8.0 software is given in Table 2. The experimental runs were conducted with different combinations of input process parameters as dictated by Box-Behnken design matrix. The mean diameter of flow formed tube for each experimental run is measured by a bore dial gauge. The resolution of bore dial gauge is 0.01mm. The mean diameter is calculated by the average of diameters at selected points on the flow formed tube. The measurement is taken at five points with a gap of 10 mm and is repeated for every 50mm length of the tube.

The response parameter values are given in Table 3. In the present investigation, equation for response function in terms of selected input process parameters obtained by using trial version of Design Expert 8.0 software. The flow formed tubes are shown in figure 3.



Fig. 2 Flow formed tube

The response equation generated by the model for mean diameter is given by

$$\begin{aligned} \text{Mean diameter (D)} = & +56.33 - 0.25315 \times (\text{Feed}) - 0.024075 \times (\text{Speed}) - 0.295 \times (\text{Radius}) \\ & - 1.620\text{E-}04 \times (\text{Feed} \times \text{Speed}) + 3.15\text{E-}03 \times (\text{Feed} \times \text{Radius}) \\ & + 8.0\text{E-}04 \times (\text{Speed} \times \text{Radius}) + 1.77\text{E-}03 \times (\text{Feed})^2 + 7.45\text{E-}05 \times (\text{Speed})^2 \\ & - 4.45313\text{E-}03 \times (\text{Radius})^2 \text{ -----(1)} \end{aligned}$$

Table-3
Experimental layout using Box-Behnken design

Run No.	Parameters			Mean diameter (In side) D (mm)
	Feed (F)	Speed (S)	Radius (R)	
1	75.00	200.00	8.00	43.56
2	75.00	200.00	8.00	43.56
3	75.00	150.00	12.00	43.73
4	100.00	200.00	12.00	45.10
5	50.00	200.00	12.00	44.25
6	75.00	200.00	8.00	43.56
7	100.00	250.00	8.00	44.85
8	75.00	200.00	8.00	43.56
9	75.00	200.00	8.00	43.56
10	100.00	200.00	4.00	44.31
11	50.00	250.00	8.00	44.96
12	50.00	150.00	8.00	44.45
13	100.00	150.00	8.00	45.15
14	75.00	150.00	4.00	43.73
15	75.00	250.00	12.00	43.94
16	75.00	250.00	4.00	43.30
17	50.00	200.00	4.00	44.72

VI. RESULTS AND DISCUSSION

6.1 ANOVA

The influence of input process parameters on the response function can be effectively studied by performing analysis of variance (ANOVA). The model summary statistics for mean diameter are given in table-4. It is found that, quadratic model best suggested for the present investigation where R² value is maximum. ANOVA for response surface model for mean diameter is presented in table-5.

Experimental investigations to predict mean diameter of AA6082 tube A DOE approach

ANOVA is generally used to summarize the test for significance on individual model co-efficient. The value of “prob>F” in the present case is less than 0.0001. The value of “prob>F” for the model is less than 0.0500, which indicates that, model terms are significant. It reveals that, model terms have significant effect on the response parameter. The F-value of model in the present experimentation is 126.86. The model F-value of 126.86 indicates that the model is significant. It is found that, feed, radius, (feed×speed), (feed×radius), (Speed×Radius), (feed²), (Spee d²) and (Radius²) are the significant terms for mean diameter

Table -4
Model summary statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRES S	Remarks
Linear	0.69	0.039	-0.182	-0.761	11.19	
2FI	0.74	0.1434	-0.370	-2.359	21.35	
Quadratic	0.074	0.9939	0.9861	0.9025	0.62	Suggested

6.2. Regression statistics

Regression statistics for the developed model are given in Table-6. The co-efficient of determination (R²), is used to find out approximation of the developed regression model. If R² value is equals to 1, it provides exact match. When residual increases the value of R² decreases in the range from 1 to 0. The residual can be decreased by increasing the number of input variables. A more precise regression model can be obtained by adjusting co-efficient of determination (R²) value for the degrees of freedom. Adj. R² is used for this purpose. Adj. R² compares residuals per unit degree of freedom. Adequate precision used to compare the range of predicted values at the design points to the average prediction error. It is the measure of Signal-to-Noise (S/N) ratio. The ratio more than 4 indicates adequate model discrimination. In the present case, the ratio is 31.40, which is much above 4. Hence the developed regression model could navigate response space. The co-efficient of discrimination, R² value required should be closer to 1. In the present experimentation, the R² value for the developed model is 0.9939 close to 1, which is desirable.

The adequacy of the model also confirmed by the examination of residuals. The normal probability plot and plot of residuals versus predicted response are used to examine the residuals. The condition for the model to be adequate is that, normal probability plot of the residual should give a straight line and plot of residuals versus predicted response should be structure less and should not have any obvious pattern. The normal probability plot for mean diameter is shown in fig. 3. From the plot it is clear that, residuals forms straight line and hence the errors are distributed evenly.

Table -5
ANOVA table for response surface model (Mean diameter)

Source	Sum of squares	D O F	Mean Square	F-Value	Prob>F	Remarks
Model	6.32	9	0.70	126.86	<0.0001	Significant
A-Feed	0.13	1	0.13	23.97	0.0018	Significant
B-Speed	0.00001	1	0.00001	0.002	0.9634	
C-Radius	0.12	1	0.12	20.82	0.0026	Significant
AB	0.16	1	0.16	29.65	0.0010	Significant
AC	0.40	1	0.40	71.74	<0.0001	Significant
BC	0.10	1	0.10	18.51	0.0036	Significant

A^2	5.15	1	5.15	931.4 3	< 0.0001	Significant
B^2	0.15	1	0.15	26.40	0.0013	Significant
C^2	0.021	1	0.021	3.86	0.0901	
Residual	0.039	7	0.0055			
Cor Total	6.36	16				

Table -6
Regression statistics

Std. Dev.	0.074
Mean	44.13
C.V. %	0.17
PRESS	0.62
R-Squared	0.9939
Adj R-Squared	0.9861
Pred R-Squared	0.9025
Adeq. Precision	31.40

The plot of residuals versus predicted response for the mean diameter of flow formed tube is shown in fig. 4. The plot of residuals gives no obvious structure, which confirms that, the predicted model is adequate. The plot of predicted versus actual for mean diameter is shown in fig. 5. The plot of predicted versus actual gives straight line, which indicate consistency of the developed model.

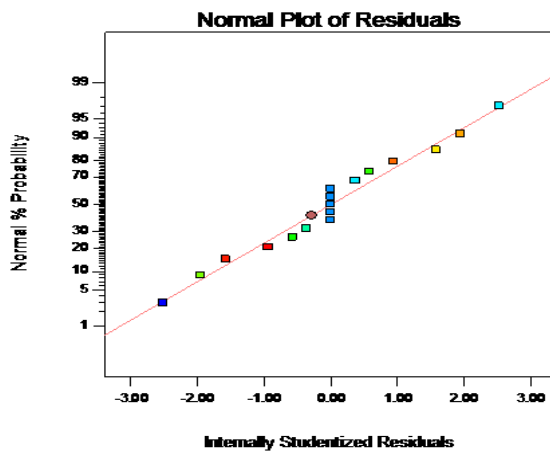


Fig. 3. Normal probability plot of residuals for mean diameter

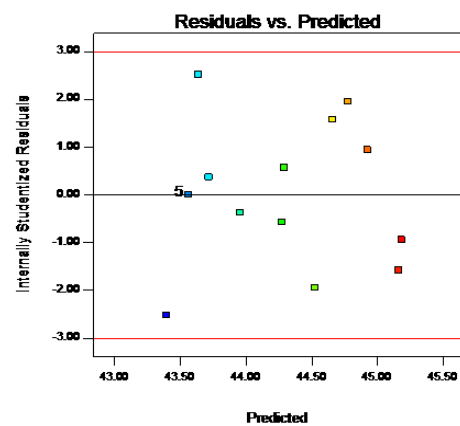


Fig. 4. Plot of residuals versus predicted mean diameter

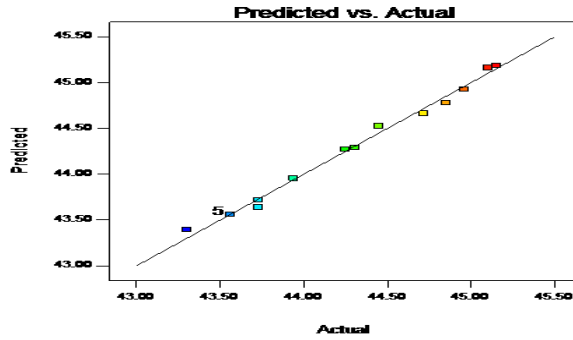


Fig 5. Plot of predicted values versus actual values for mean diameter

6.3. Response surface graphs

The three dimensional surface plots can be used to predict mean diameter values of flow formed tube for any suitable combination of input parameters. The three dimensional surface plots for the mean diameter are shown in fig. 6-8. Fig.6 shows the effect of roller feed and mandrel speed on the mean diameter of flow formed tube. The mean diameter first increases and then decreases with roller feed. Higher speeds of mandrel produce tubes with smaller mean diameter. The plastic deformation is insufficient at lower feed and becomes excess when it is at higher level. A feed of 75 mm/min produces lower roundness error. The speed of the mandrel does not have much influence on the mean diameter.

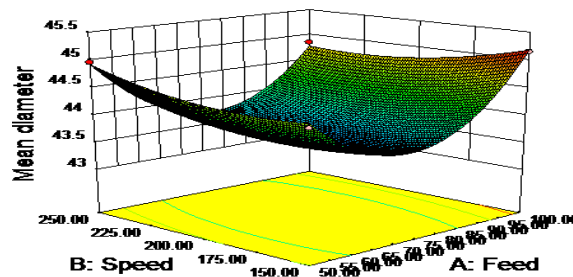


Fig. 6. 3D plot of feed and speed on mean diameter at radius=8 mm.

Fig.7 shows the three-dimensional surface plot of roller feed and roller radius on the mean diameter of flow formed tube. The mean diameter of flow formed tube increases with radius of roller. High forming forces resulted due to increase in radius responsible for larger mean diameter. A radius of 4 mm combined with a feed of 75 mm/min forms the tubes with minimum mean diameter.

Fig.8 shows three-dimensional plot of roller radius and mandrel speed at feed=75 mm/min on the mean diameter of flow formed tube. From the surface graph, it is clear that, a mandrel speed of in the range of 190-230 rpm manufactures the flow formed tubes with minimum mean diameter.

A roller feed of 65-80 mm/min, roller radius of 4-6 mm and mandrel speed of 190-230 rpm produces the flow formed tube with minimum mean diameter.

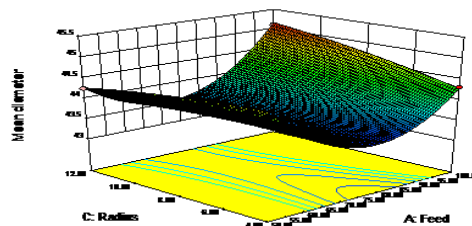


Fig. 7. 3D plot of feed and radius on mean diameter at speed=200 rpm .

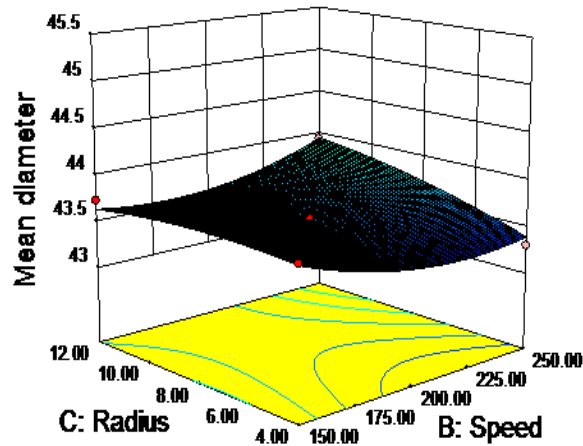


Fig. 8. 3D plot of speed and radius on mean diameter at feed=75 mm/min.

Table -7
Sample predicted data from response surface model

Sl. No.	Parameters			Mean diameter, D(mm)		Error (%)
	Feed	Speed	Radius	Experimental	RSM Predicted	
1	60	220	12	43.85	43.88	0.075
2	75	160	8	43.70	43.68	0.046
3	80	200	4	43.39	43.38	0.033

VII. CONFIRMATION TEST

A confirmation test is required to validate the developed model. Confirmation run was performed by setting the input parameters within the range of selected levels. The percentage of error was determined from the experimental value and corresponding predicted value. The experimental and predicted values are given in table-7. The maximum percentage of error is found to 0.075 %, which is within the allowable limits. Hence, the response equation developed for mean diameter of flow formed tube can be used to successfully predict the mean diameter values for any combination of input parameters within the range of defined levels.

VIII. CONCLUSIONS

In this research, response equation for mean diameter of flow formed tube has been developed by response surface methodology (RSM) for different input process parameters namely roller feed, mandrel speed and radius of roller. The predicted model can successfully navigate the response (mean diameter) within the range of selected levels. The confirmation test proves that, experiment values are in good agreement with predicted values.

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Experimental investigations to predict mean diameter of AA6082 tube A DOE approach

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