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Research Article

Analysis of Tube End Formability of AA 2024 Tubes Using FEM

Bharathi . P[a*], Venkateswarlu. G[a], Davidson. M.J[a], Selvaraj. N[a], Venugopal. L[a]

[a] Department of Mechanical Engineering, NITW, India

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Abstract

The objective of this paper is to determine the optimal values of end forming process parameters namely die angle (α), ratio of the radius of the die and the radius of the tube (r_p/r_0), punch velocity (v), friction (μ), resulting in an optimal value of formability of tube in radial and linear directions. In this investigation, the combination of Taguchi analysis and finite element method was used to determine the influence of process parameters on formability of aluminium 2024 tube. Using signal-to-noise ratio and the ANOVA technique, the influence of each parameter was studied. Simulations were observed as per orthogonal array using finite element code. Based on the predicted expansion of length in the radial and linear directions and analysis of variance, it was observed that the die angle has the greatest influence on formability of tube in radial direction followed by punch velocity, friction and ratio of the radius of the die to the radius of the tube. Whereas, in linear expansion, the die angle has the most outstanding influence on the formability followed by ratio of the radius of the die to the radius of the tube, punch velocity, and co-efficient of friction.

***Keywords**: End forming, Formability, Taguchi, ANOVA*

1. Introduction

Forming the end of a tube to different shapes and profiles by performing different metal forming processes like expanding, reducing, beading, bulging, chamfering, crimping, tapering, notching, rounding etc is referred to as tube end forming process. These expanded and reduced tubes are used in various application such as in automobiles, aerospace (e.g. for airframes or the fuselage of airplanes), civil engineering, military components and medical tubing etc for pneumatic, hydraulic and exhaust system machines. Most of the tubular parts manufactures are looking for improving the end formability of the tube by optimizing the process. The process parameters of end forming of a tube are the inner radius of the tube, radius of the punch, forming die angle and coefficient of friction. Hence, it is essential to determine the degree of influence of these process parameters on the end formability in order to optimize appropriate conditions to maximize the formability of the tube. Almeida et al. (2006)carried out experiments on the expansion and reduction of thin walled tubes using a die and studied the different modes of deformation associated with the formability limits induced by ductile fracture, wrinkling and local buckling and also mentioned that co-efficient of friction plays a key role in the overall formability of tube. Alves et al. (2006) focused on the influence of the process parameters on the formability limits for the expansion of the tubes into circular, elliptical and square cross sectional shapes. They recommended that circular shapes are successfully expanded without cracking below the critical level. Rosa et al. (2004) carried out research work on the internal inversion of the thin-walled tubes using a die to establish the formability diagrams in terms of the influence of the lubrication, frictional conditions etc. Sun et al. (2007) studied the forming limit of tube axial compressive process. The tube failed either by tearing or buckling. The failure mechanism was mathematically analyzed to determine the forming limits and concluded that the forming limit is mainly depending on the material parameters of the tube blank and fillet radius or half cone angle of the die. Martins et al. (2003) presented the study on the occurrence of inadmissible modes of failure and examined the influence of friction/lubrication regime on process formability. Sekhon et al. (2003) examined the external inversion of round tubes by conducting experimental and computational studies and concluded that the energy absorbing capacity of a tube increases with decrease in the die radius. Daxner et al. (2005) presented experimental evidence and numerical simulations for two instability phenomena related to buckling and periodic necking at the free end and observed that long tube specimens failed due to buckling whereas short specimens failed by necking and rupture. The aluminum alloy 2024 is an important engineering alloy which plays an important key role for the structural components in transportation (e.g. auto mobiles, motorcycles, aerospace, ship building) including military and marine applications due to their

* Corresponding author: Bahrti

attractive and excellent properties such as strength to weight ratio, good fatigue resistance, high thermal and electrical conductivity, ductility, machinability and toughness. However, in this work, much focused on tube end forming process to understand the general behavior of the AA2024 tube as such a knowledge base is not available in the literature. This information may help the design engineers in designing tube end forming and to the manufactures who are engaged in manufacturing tubes of different and complex end profiles. In this present work, a statistical approach based on Taguchi and ANOVA techniques was adopted to determine the degree of importance of the process parameters namely die angle, ratio of the radius of the die and the tube, punch velocity and friction on the formability of thin walled tubes.

2. Methodology

The end forming of the tube simulation was carried out with a tool set of dimensions shown in "Figure 1" and a tube that was expanded through simulation shown in "Figure 2". AA 2024 Tube with internal diameter of 36 mm and with 2mm wall thickness was taken for the simulation. The damage factor based on Cockcroft& Latham algorithm was taken as the fixing fracture damage value (0.23) (J. Lemaitre. *et al*, 2005). The elastic properties of material are Young's modulus E= 76 GPa and Poisson ratio= 0.33 and the hardening parameters are: strength coefficient K= 690 MPa and strain-hardening exponent n=0.20. Dr.Genichi Taguchi developed the Taguchi techniques. Taguchi developed the foundations of robust design and validated its basic philosophies by applying them in the development of many products (Phadke *et al*, 1989). Using Taguchi method, a balanced comparison of levels of the process parameters and significant reduction in the total number of required simulations can both be achieved. The Taguchi techniques place a great deal of importance on the reduction of variability of products and process. Improved robustness can often be achieved without major capital expenditure with these techniques. Davidson et al. (2008) used Taguchi method to optimize flow-forming process for maximum deformation of the formed cups. The surface roughness of the flow-formed tube was predicted by Davidson et al. (2008) using surface methodology. Padmanabhan et al. (2009) used Taguchi analysis to determine the influence of process parameter on drawbility mild steel and it was observed that contact friction plays a major role in deep drawing of cross geometry compared to the blank holder force and blank shape. Venkateswarulu et al. (2010) investigated the effect of process parameters on the cup drawing of aluminum alloy 7075 sheet using Taguchi analysis. Results indicated that the blank temperature has greatest influence on the formability of cup as compared to die radius and velocity of punch. In this investigation, Taguchi experimental design with four levels of process parameters was used to plan numerical simulations Table 1 shows the chosen parameters and their levels used in the finite element (FE) simulation. The higher orders interactions among the above factors are assumed to be negligible and the information on the main effects can be obtained by running 44 =256 experiment. The appropriate Taguchi orthogonal array for the above parameters with four levels is L16 which requires only sixteen simulations as shown in the Table 2. After designing the experiments with various combinations of process parameters levels, FE simulations were carried out to predict the expansion behavior of the aluminum sheet in the radial and linear direction. The results obtained from the FE simulations were treated using statistical approach, namely ANOVA.

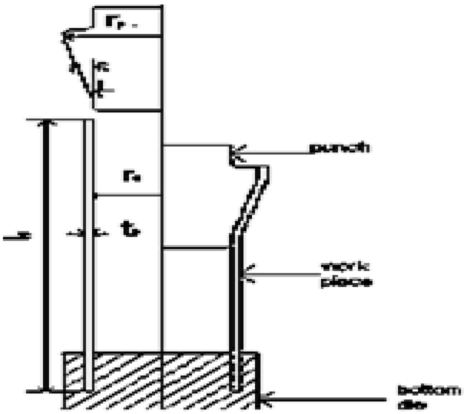

Fig. 1 Tools Used In Simulation

Fig. 2 Expansion of Tube

Table 1 Process parameters and their levels

Process parameters	Levels and their range			
	1	2	3	4
Die angle(α)	150	300	450	600
Ratio of (r_p/r_o)	1.39	1.53	1.67	1.81
Punch Velocity(v)	0.5	1	1.5	2
Friction(μ)	0.1	0.2	0.3	0.4

3. Results and discussions

3.1. Punch force evolution

In tube expansion, the material is subjected to both ductile damage and strain hardening. The feasibility of forming process as well as the final mechanical tubular parts is controlled by the mechanisms of strain hardening and ductile damage of material. The distribution of punch force for the expansion of tube, as shown in "Figure.3", is taken from the decoupled finite element analysis based on the normalized Cockcroft-Latham ductile fracture criterion (eq. 1). For higher values of α and larger ratio of r_p/r_0, linear formability is limited by the occurrence of plastic instability, but higher radial formability due to high stretching in the circumferential direction. It is observed that the peak load decreases with the increase in die angle and the peak load for die angles of 15^0, 30^0, 45^0 and 60^0 are 53.7KN, 46.4KN, 44.3KN, 41.5KN respectively.

$$\left(\int_0^{\varepsilon f} \sigma_1 / \bar{\sigma}\, d\bar{\varepsilon} = 0.23\right) \quad (1)$$

3.2 ANOVA

ANOVA (analysis of variance) is a statistical technique for determining the degree of difference or similarity between two or more groups of data. It is based on the comparison of the average value of common components. The percentage contribution of various process parameters to the selected performance characteristic can be estimated by ANOVA. Taguchi recommended a logarithmic transformation of mean square deviation called signal-to-noise ratio (S/N ratio) for analysis of the results. Signal-to-noise ratio (SNR) is utilized to measure the deviation of quality characteristic from the target. In this experiment, the response is the formability radial expansion (R.E) and linear expansion (L.E). In this investigation, the S/N ratio was chosen according to the criterion, the "larger-the-better" in order to maximize the responses. The S/N ratio for the "larger-the-better" target for all the responses was calculated as follows. The S/N ratio is used to measure the deformation deviation (eq.2)

$$\frac{1}{n}\sum_{i=0}^{n}\left[\frac{1}{Y_i^2}\right] \quad (2)$$

for the output characteristics: n is the number of experiments (for one set of parameters n=1) and Y_i is the simulation result for i^{th} experiment. In this study, S/N ratio is used to measure the radial and linear expansion length deviation. The analysis was performed using a statistical package, MINITAB Release 15, to quantify the effect of process parameters on the responses.

It can be observed from Table 3, that the die angle and punch velocity are the most significant parameters for improving formability of tube in radial direction. Table 4 indicates that die angle is the mostly influence factor for the improvement of the formability in linear direction.

Table 2 Basic Taguchi L16 (44) orthogonal array

Run	Parameters (α)	(r_p/r_0)	(v)	(μ)	R.E	L.E
1	1	1	1	1	14.7949	36.5
2	1	2	2	2	9.9795	20.3
3	1	3	3	3	9.523	20.3
4	1	4	4	4	9.4514	20.3
5	2	1	2	3	11.4124	14
6	2	2	1	4	11.9845	15.7
7	2	3	4	1	11.1985	13
8	2	4	3	2	11.3638	13.5
9	3	1	3	4	12.4091	13
10	3	2	4	3	13.3263	12.4
11	3	3	1	2	13.8949	10.3
12	3	4	2	1	13.5502	9.7
13	4	1	4	2	13.1424	10.3
14	4	2	3	1	12.781	9.7
15	4	3	2	4	15.0576	9.7
16	4	4	1	3	15.214	9.7

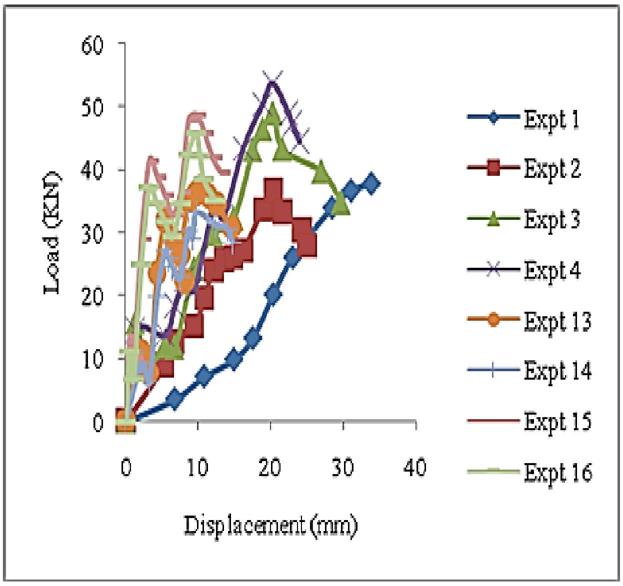

Fig. 3 Deformed Tube Height vs. Punch Force

Table 3 Analysis of variance for radial expansion

Source	DOF	SS	MS	F Ratio	Contribution
α	3	25.922	8.641	3.33	49.58
r_p/r_0	3	1.722	0.574	0.22	3.292
v	3	14.539	4.846	1.87	27.8
μ	3	2.324	0.775	0.3	4.444
Error	3	7.789	2.596		14.89
Total	15	52.295			100

Table 4 Analysis of variance for linear expansion

Source	DOF	SS	MS	F Ratio	Contribution
α	3	511.91	170.64	9.73	71.05
r_p/r_0	3	70.99	23.66	1.35	9.84
v	3	54.07	18.02	1.03	7.5
μ	3	31.2	10.4	0.59	4.32
Error	3	52.6	17.53		7.29
Total	15	720.78			100

3.3 Analysis of signal-to-noise (S/N) ratio

Signal-to-noise ratio is used to determine the deviation of quality characteristic from the target. In this investigation, as the radial expansion and linear expansion length which should be maximized, the desired SNR characteristic has been taken as "larger-the- better". Table 5 shows the SNR of the radial expansion length for each level of the factors. The difference of SNR between level 1 and 4 indicates that die angle contributes the highest effect (δ= 2.31) on the formability in radial direction followed by punch velocity (δ = 1.70), friction (δ= 0.71) and ratio of radius to punch to the radius of tube (δ= 0.65). The main effect plot of S/N ratio is shown in "Figure 4". It indicates that maximum formability occurs when the die angle inclination is set at its high value (60^0) and the ratio of the radius of the die to the tube, punch velocity and friction (μ) are set to its low levels [1.39, 0.5, and 0.1].

Table 5 S/ N ratio of the formability by radial expansion at different factor levels

Levels	**α**	**r_p/r_0**	**v**	**μ**
1	20.62	22.2	22.87	22.29
2	21.2	21.55	21.83	21.58
3	22.47	21.74	21.17	21.72
4	22.93	21.73	21.34	21.63
Delta	2.31	0.65	1.7	0.71
Rank	1	4	2	3

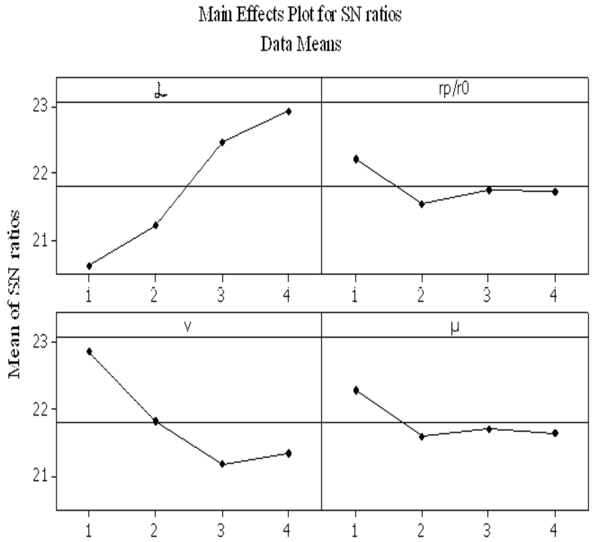

Fig. 4 Main Effect Plots of S/N Ratio for Maximum Formability (R.E)

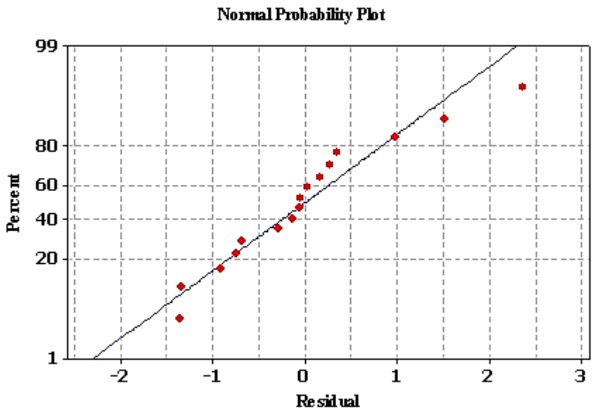

Fig. 5 Normal Probability Plot of the Residual for radial expansion

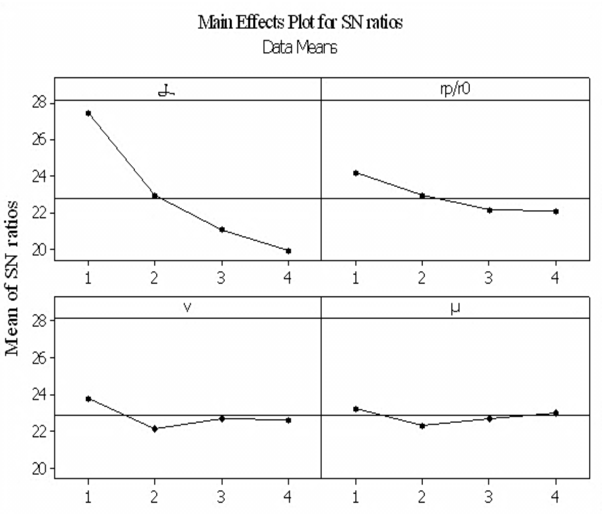

Fig.6 Main Effect Plots S/N Ratio for Maximum Formability (L. E)

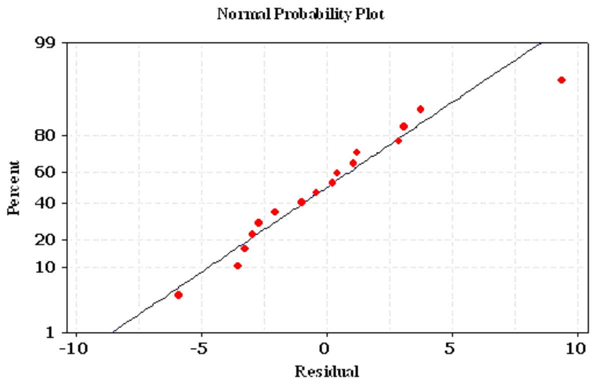

Fig. 7 Normal Probability Plot of the Residual for Linear Expansion

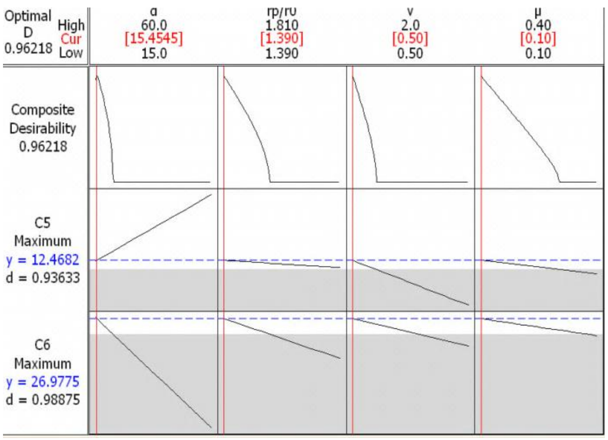

Fig. 8 Optimization Values

A regression equation relating the process parameters to the radial expansion was developed as shown in equation

$$R.E=13.5305+0.0742(\alpha)-0.8813(r_p/r_0)-1.511(v)-2.2927(\mu) \quad (3)$$

The model adequacy checking was conducted after performing ANOVA analysis to verify the normality assumption of the residual. The normal probability plot "Figure 5" shows that almost all the residuals follow a straight line pattern.

3.4. Multiple-response optimization

The optimal process parameters obtained by multiple-response optimization are shown in Table 7 and "Figure 8". For the optimized values of the process parameters, it is 96.21% desirable to get the R.E of 12.468 mm and L.E of 26.977 mm. Any other combination of the process parameters will either be statistically less reliable or give poor results of at least one of the responses. The analysis was done by using the MINITAB 15 computer software.

Table 7 Values of process parameters for the optimization of R.E&L.E

α	r_p/r_o	v	μ	R.E	L.E	%
15.45	1.39	0.5	0.1	12.468	26.977	96.21

4. Conclusion

This paper illustrates the use of FE simulation with Taguchi design of experiments technique to determine the proportions of contribution of the important process parameters in the tube end forming deformation response namely die angle, ratio of the radius of the die to the tube, punch velocity and friction. FEM simulation in combination with Taguchi DOE technique forms an effective method to predict the influence of process parameters. The analysis of variance was carried out to examine the influence of process parameters on the formability of the tube end and their percentage contribution. The die angle (49.58%) has major influence on the radial expansion of the tube end, followed by punch velocity (27.80%), friction (4.44%) and ratio of radius of the die angle to the tube (3.29%). For linear expansion, the major influence of the tube end is die angle (71.05%), followed by ratio of the radius of die angle to the tube (9.84%), punch velocity (7.50%) and friction (4.32%). The optimal process parameters obtained by multiple-response optimization, is 96.21% desirable to get the R.E of 12.468 mm and L.E of 26.977 mm. ANOVA and multiple-response optimization methods can provide optimal parameters; however, these parameters have to be validated by conducting experiments. This has not been done here but suggested for future research.

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