A Study on Effect of Process Parameters on the Expansion of Thin Walled Aluminium 7075 Tubes

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Abstract

This paper deals with the effect of process parameters on the peak load and the energy absorption of the expansion of thin walled tubes using a die. The energy absorption and peak load during the expansion process were calculated for various punch angles (α) and with different expansion ratios (r_p/r_o) *at different temperatures (T) by finite element analysis where* r_p *is the punch outer radius and* r_o *is the tube inner radius. The effect of these input parameters on the response parameters peak load, energy absorption and local buckling have been critically analyzed using Taguchi method. It is observed that the peak load and energy absorption of the expansion tube is influenced by expansion ratio* (r_p/r_o)*, punch angle followed by tube temperature. The energy absorption of the expanded tube increases as* the r_p/r_o *ratio increases and also larger punch angle improves the energy absorption. Whereas the minimum expansion ratio* (r_p/r_o) *decreases the peak load at higher temperature and medium punch angle. The ANOVA performed on the experimental results revealed that the expansion ratio* (r_p/r_o) *is the most important process parameter that minimizes the peak load followed by punch angle and tube temperature. Also it is found that the expansion ratio improves the energy absorption.*

Keywords: *Warm forming, Peak load, Energy absorption, Taguchi, ANOVA.*

1. Introduction

Aluminium alloy tubes with various structural shapes are used in various applications such as pneumatic, hydraulic and exhaust systems of machines and used as energy absorbing devices in transport vehicles like aircraft and automobiles to meet the demand of energy absorption for the low density and specific strength of the aluminium alloys. Tube end forming is performed by expanding the tube ends by pushing a conical punch into the tube while the bottom of the tube is fixed. However, due to poor formability at room temperature, the usage of this process to meet the required application is minimal. It is essential to improve the formability of the material to meet the industrial application needs and study of the influence of the process parameters on the expansion of thin walled tubes helps in achieving the goal in a better way. The formability of the material can be improved by forming at elevated temperature with low strain rate. The process parameters, tube temperature significantly improves the formability of the material as it increases the ductility and decreases the yield strength of the material, thereby reducing the forming forces and pressure [1]. Contact friction between tube and punch also has significant influence on the process stability and formability [2]. Tang ze-jun *et al.* [3] conducted the experimental and numerical simulation analysis on wrinkling behavior of magnesium alloy tube in warm hydro forming.

They have concluded that the expansion ration limit can be improved at a certain temperature by the application of proper loading path. Almeida *et al.* [4] conducted experimental and theoretical investigation on the expansion and reduction of thin walled tubes using a die. The effect of material damage and strain path on the occurrence of fracture, wrinkling and local buckling of the tubes were studied. They determined the critical plastic instability load as 46.8 KN for 2 mm thin walled AA6060 tubes for the occurrence of local buckling by axial compression of tubes between flat dies. Sekhon *et al.* [5] conducted the experimental and computational study of external inversion of round tubes and concluded that the energy absorbing capacity of a tube increases with decrease in die radius. Zhang *et al.* [6] conducted numerical quasi static axial crushing analysis by a non linear explicit finite element code LS-DYNA for the energy absorption of axially compressed thin walled square tubes with patterns. Ahn *et al.* [7] conducted a series of experiments for predicting the local buckling and the energy absorption characteristics of thin walled expansion tubes during the flaring process. They found that the absorbed energy of the expanded tube increases with the diameter and the wall thickness of the tube, punch angle and expansion ratio.

Yang *et al.* [8] presented experimental and numerical simulation using FEM for the expansion of the thin walled tubes for predicting the specific energy absorption using a conical cylindrical die. They found that the value of the specific energy increases with the semi cone angle of the die. Rosa *et al.* [9] investigated the combined theoretical and experimental analysis on the inversion and expansion with flaring. They were able to identify the factor which influences the material flow ductile damage and interface friction on the occurrence of successful and unsuccessful modes of deformation. However, even though some considerable experimental investigations have been done by several researchers, a huge knowledge gap is experienced. As most of the is restricted to few aluminium alloys, the present study is to determine the effect of process parameters namely tube temperature, punch angle and expansion ratio on the energy absorption and peak load experienced during expansion of thin walled AA7075 tubes using finite element analysis.

2. Methodology

Finite element based analysis is carried out for considering the effect of the punch angle, tube temperature and expansion ratio on the response parameters namely peak load, energy absorption on local buckling. Peak load, energy absorption and local buckling on an expanded tube were analyzed by carrying out the finite element analysis simulation. The model of the sample tube with die arrangement is shown in Fig 1 (A) and Fig 1(B) gives the expanded tube after simulation.

The material used for the present investigation is AA7075 alloy. The major alloying elements are 0.4Si, 0.5Fe, 1.2-2.0Cu, 0.3Mn, 2.1-2.9Mg, 0.18-0.28Cr, 5.1-6.1Zn and the remainder is aluminium. AA7075 has higher strength and improved corrosion resistance. The main components of the heat treatable AA7075 alloy are Mg, Cu, and Zn. The phases MgZn2 and MgAlCu forms an isomorphous series in which an aluminium atom and a copper atom substitute for two zinc atoms leading to precipitation hardening.

The warm forming of the tube depends on the process parameters such as tube temperature, punch angle, expansion ratio, die and punch clearance, punch velocity, and mechanical properties and its geometry. Proper forming of the materials can be achieved by forming at elevated temperature, which reduces the flow stress of the tube. In addition to this tube the temperature punch shape, and the expansion ratio also affects the expansion of the tube and gives more energy absorption. The objective of this study is to improve the energy absorption of the tube and to reduce the forming force during the tube expansion process. For this analysis, a 90 mm long of 2 mm thickness tube with 18 mm internal radius has been chosen. The simulations have been performed as per Taguchi design of experiments principle. Nine experiments were performed by varying three process parameters namely punch angle (α), tube temperature (T), and expansion ratio (r_p/r_o). Numerical simulation was performed at 1 mm/sec punch velocity with constant friction factor 0.25 between contact surfaces.

The present investigation uses Taguchi method, which is a powerful design of experiments tool. This method provides a simple, efficient and systematic approach to determine optimal machining parameters. Conventional experimental design methods are too complex and expensive. A large number of experiments have to be carried out to study the process. Taguchi method used an orthogonal array to study the entire process with only a small number of experiments. Moreover, traditional experimentation involves one factor at a time experiments, wherein one variable is changed while the rest are held constant. The major disadvantage of this method is that it fails to consider any possible interaction between the parameters. An interaction is failure of one factor not to produce the same effect on the response at different levels of a second factor varying. It is also not possible to study all the factors involved in the process and to determine their main effects (i.e., the individual effects) in a single experiment. Taguchi technique overcomes all these drawbacks. Taguchi method is used for optimizing process parameters and identifying the optimal combination of factors for the desired responses [10].

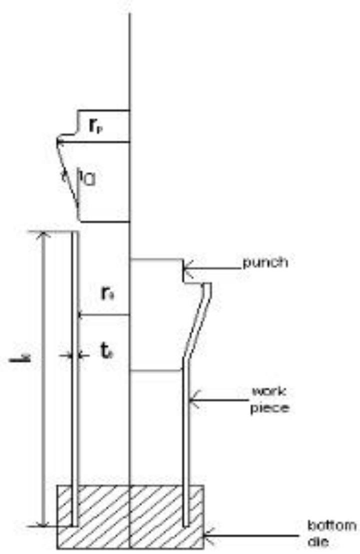

Figure 1 Finite Element Model of the Tube

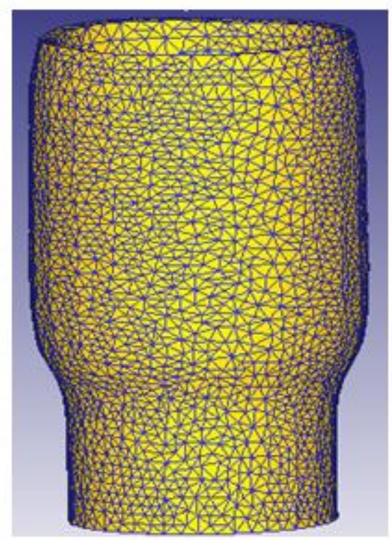

Figure 2 Deformed Tube

The steps involved are

1. Identification of the response functions and the process parameters.
2. Determination of the number of levels for the process parameters and possible interaction between them.
3. Selection of the appropriate orthogonal array.
4. Selection of the optimum level process parameters through ANOVA analysis.

5. Performing a confirmation experiment to verify the optimal process parameters.

The Taguchi method has created the S/N (signal to noise) ratio to quantify variations in experiments. There are several S/N ratios available depending on the types of characteristics, lower is best (LB), nominal is best (NB) and higher is best (HB). For the present investigation, lower is best is used for peak load and higher is best for energy absorption.

In the present work, a statistical approach based on Taguchi and ANOVA techniques are used to predict the importance of each of the process parameter on the end forming of thin walled tubes. However, Taguchi method is a famous method used by several researchers in the forming studies to design experiments and to determine the effect of process parameters on the formed tubes. Venkateswarlu *et al.* [11] applied Taguchi method to optimize the cup drawing process at elevated temperatures for maximum deformation of the sheet. Davidson *et al.* [12] used Taguchi method to optimize the flow forming process for maximum deformation of the formed tube. Rajenthirakumar *et al.* [13] studied experimental analysis and Taguchi method to study the effect of forming parameters in sheet hydro mechanical deep drawing process. The present work is on identification of process parameters namely punch angle, tube temperature and expansion ratio and also to determine the role played by these parameters on the required forming force and energy absorption of the formed tube in the expansion of thin walled AA7075 tubes during warm forming process. Table 1 shows the chosen process parameters with their levels used in FEM simulations.

Table1: Parameters and their Levels

Symbol	*Parameter*	*Level 1*	*Level 2*	*Level 3*
α	*Punch angle(degree)*	*15*	*30*	*45*
T	*Tube temperature(^0C)*	*100*	*150*	*200*
r_p/r_o	*Expansion ratio*	*1.25*	*1.39*	*1.53*

Table 2: Simulation Layout using L9 Array

Expt. No.	Parameter level			Peak load*10^4(P, N)	Energy absorbed*10^6(E, N mm)
	Punch angle	Tube temperature	Expansion ratio (r_p/r_o)		
1	1	1	1	2.99	1.74
2	1	2	2	4.07	2.07
3	1	3	3	4.16	1.93
4	2	1	2	3.96	2.3
5	2	2	3	4.08	2.28
6	2	3	1	2.5	1.51
7	3	1	3	5.44	3.04
8	3	2	1	3.26	2.04
9	3	3	2	4.11	2.32

By using Taguchi method, number of experiments can be decreased from actual experiments 33=27 to 9 experiments by introducing appropriate Taguchi L9 orthogonal array. The L9 orthogonal array with three columns and nine rows is used for the present study as shown in Table 2.

3. Results and Discussions

3.1. Effect of the Process Parameter on Peak Load

It can be seen from Table 2 that the lowest peak load is observed for the tube expansion performed in experiment number 6, in which the forming force has decreased with increase in the tube temperature and decrease in expansion ratio and punch angle. Hence, at the process parameters set at punch angle=30^0, tube temperature=200^0 C and expansion ratio=1.25, has been experienced least forming force for the expansion of AA7075 alloy tube. Therefore, the expansion ratio has the key role for the effective expansion of the thin walled tubes with least forming force, where as the experiment number 7 has the highest peak load which is unfavorable for the chosen process parameters. The punch angle and tube temperature also have only moderate effect on the peak load of the expansion of thin walled tube.

Figure 3(A) shows the punch displacement vs. peak load curves for different experiments. This graph was obtained during the numerical simulation of the process. It can be seen that the experiment number 6 has the least peak load compared to other experiments where as experiment number 7 has the highest peak load which leads to increased the flow stress for the expansion of the tube. For experiment number 3, the peak load has dropped after certain increment which indicates that the buckling of the tube is taking place as shown in figure 3(B).

3.2. Evaluation of Energy absorption

Figure 4 show the curve drawn between punch displacements verses the absorbed energy for the expansion of the thin walled AA7075 tubes. It can be observed that experiment number 7 has the highest energy absorption; whereas experiment numbers 4, 5 and 9 gives moderate energy absorption and experiment number 6 has the least energy absorption. Hence it is found that the energy absorption increases with increase in expansion ratio and punch angle and also observed that the tube temperature has moderate effect on the energy absorption of the expansion of the tube. Energy absorption has decreased after certain increment in experiment 3, which indicates that tube starts buckling (as shown in figure 3(B)).

The above results indicate that the energy absorption can be increased by increasing the expansion ratio and punch angle, and it decreases moderately with increase in the tube temperature.

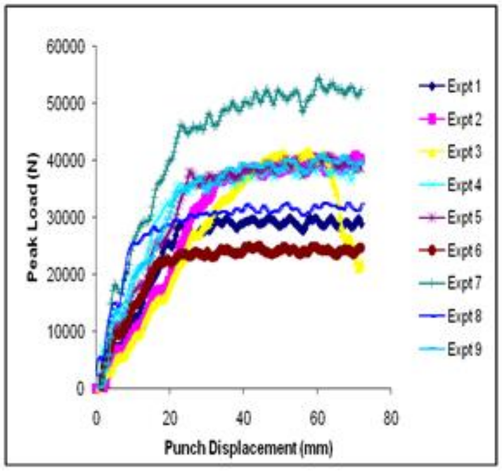

Figure 3 (a) Displacement Vs load

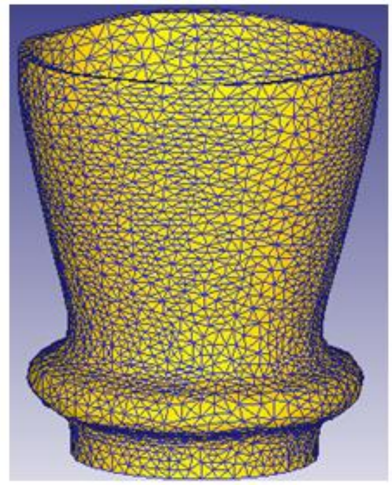

Figure 3 (b) Deformed tube when buckling

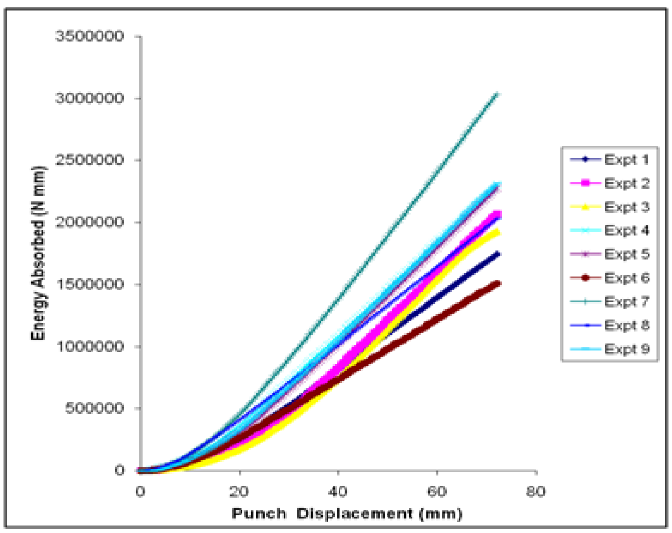

Figure 4 Punch Displacement Vs Energy Absorbed

3.3. Analysis of Variance (ANOVA)

The purpose of the analysis (ANOVA) is to find the percentage contribution of variance over the response parameters namely peak load and energy absorption. ANOVA is a collection of statistical models, and their associated procedures, in which the observed variance in a particular variable is partitioned into components attributable to different sources of variation. In the present investigation Pareto ANOVA method is used, which measures the importance of each process parameter in end forming process.

❄Table 3: ANOVA Data

ANOVA data						
Parameter	**Level**	**Expt. No.**	**S/N (peak load)**	**S/N_{ij} (peak load)**	**S/N (Energy absorbed)**	**S/N_{ij} (Energy absorbed)**
Punch Angle(α)						
		1	-89.5		124.81	
Level 1	15	2	-92.2	-91.36	126.32	125.61
		3	-92.38		125.71	
		4	-91.95		127.21	
Level 2	30	5	-92.21	-90.7	127.15	125.98
		6	-87.95		123.58	
		7	-94.71		129.66	
Level 3	45	8	-90.26	-92.41	126.2	127.72
		9	-92.27		127.31	
Tube Temp(T)						
		1	-89.5		124.81	
Level 1	100	4	-91.95	-92.05	127.21	127.23
		7	-94.71		129.66	
		2	-92.2		126.32	
Level 2	150	5	-92.21	-91.55	127.15	126.56
		8	-90.26		126.2	
		3	-92.38		125.71	
Level 3	200	6	-87.95	-90.86	123.58	125.54
		9	-92.27		127.31	
Expansion ratio(r_p/r_o)						
		1	-89.5		124.81	
Level 1	1.25	6	-87.95	-89.23	123.58	124.86
		8	-90.26		126.2	
		2	-92.2		126.32	
Level 2	1.39	4	-91.95	-92.14	127.21	126.95
		9	-92.27		127.31	
		3	-92.38		125.71	
Level 3	1.53	5	-92.21	-93.1	127.15	127.51
		7	-94.71		129.66	
			$\left(\frac{\overline{S}}{N}\right)_P = -91.50$		$\left(\frac{\overline{S}}{N}\right)_E = 126.44$	

Pareto ANOVA is a simplified method, which is based on Pareto principle. The Pareto Anova technique is quick and easy method to analyze results of the parameter design and does not need F-test. This technique identifies the important parameters and calculates the percentage influence of each parameter on different quality characteristics. The use of both Pareto Anova technique and S/N ratio approach makes it less cumbersome to analyze the results and hence, make it fast to arrive at the conclusion. In order to increase the robustness of design against noises and to accommodate wide ranging data, Taguchi [14] recommended a logarithmic transformation of MSD (called the signal to noise ratio) for analysis of the results. When the S/N ratio is used for results analysis, the optimum condition identified from such analysis is more likely to produce consistence performance. The factors considered for the numerical simulation and its levels are shown in Table 1. The experimental layout is shown in Table 2. The list of S/N ratios for the response parameters peak load and energy absorbed is shown in Table 3.

The S/N ratio is used to analyze the deformation deviation. That is explained as -10log (MSD), where MSD is mean square deviation for the output characteristics.

$MSD = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i^{\,2}\right)$ For lower is best (LB) i.e. for peak load (P)

$MSD = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{Y_i^{\,2}}\right)$ For higher is best (HB) i.e. for energy absorption (E).

Where n is the number of experiments (for one set of parameter, n=1) and Y is response i.e. peak load and energy absorption obtained from the simulations.

Example for calculation of S/N ratio for lower is best is given below.

For punch angle ($\alpha=45^0$)

$$MSD = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i^{\,2}\right) = \frac{1}{1}\sum_{1}^{1}\left(2.99*10^4\right)^2 = 894.01*10^6$$

$$\left\{\because n = 1, \text{Y} = 2.99*10^4\right\}$$

$$\frac{S}{N} = -10\log(894.01*10^6) = -89.5$$

The overall mean ratio is expressed as $\frac{\overline{S}}{N} = \frac{1}{9}\sum_{1}^{9}\frac{S}{N_i} = -91.50$

The sum of squares due to variation about overall mean is

$$SS_i = \sum_{i=1}^{9}\left[\frac{S}{N_i} - \left(\frac{\overline{S}}{N}\right)\right]^2 = 10.372$$

For the i^{th} process parameter, the sum of squares due to variation about is

$$SS_i = \sum_{i=1}^{3}\left[\frac{S}{N_j} - \left(\frac{\bar{S}}{N}\right)\right]^2$$

The percentage contribution can be expressed as

$$\%\text{ Contribution} = \frac{SS_i}{SS} * 100$$

Table 4 gives the effect of process parameters on desired output. It is found that the expansion ratio (r_p/r_o) has the highest percentage contribution of 78.32% on the peak load followed by punch angle (14.36%) and tube temperature (7.32%) by employing "lower is best", ANOVA principle.

For energy absorption, the ANOVA was calculated by employing "higher is best", principle. It is found that expansion ration (r_p/r_o) has the highest contribution (49.5%) followed by punch angle (32.1%) and tube temperature (18.4%).

Table 4: Contribution of Process Parameters on Warm Forming Process

Process parameter	Sum of squares(SS_i) (peak load)	% Contribution (peak load)	Sum of squares(SS_i) (energy absorbed)	% Contribution (energy absorbed)
Punch angle	1.49	14.36	2.53	32.1
Tube temp	0.76	7.32	1.45	18.4
r_p/r_o	8.123	78.32	3.9	49.5

4. Conclusion

The expansion of thin walled tubes was done by using the FEA simulation to study the influence of process parameters namely punch angle, tube temperature and expansion ratio at three levels on the peak load, energy absorption and local buckling on the expansion of thin walled tubes using Taguchi method. In present study, Taguchi analysis and Pareto ANOVA technique was used to investigate the percentage contribution of each parameter on peak load and energy absorption of expansion of thin walled tubes and found that the expansion ratio (78.32%) is the major process parameter to minimize the forming force followed by the punch angle (14.36%) and tube temperature (7.32%) and for energy absorption of the expanded tube expansion ratio (49.5%) has the key factor to improve the energy absorption followed by the punch angle (32.1%) and tube temperature (18.4%). The tube buckled at higher tube temperature, lower punch angle and higher expansion ratio. FEM, Taguchi methods and ANOVA method can give the optimal process parameters but there is a need to verify these process parameters experimentally which has not done in this study but suggested for further research.

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