Simulation studies on Tube End Expansion of AA2014 Alloy Tubes

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Abstract. End forming is defined as forming the end of tubular forms either by inverting the tube or by expanding it. It finds application in many fields such as in automotive and aerospace sectors as power transmission elements, fuel lines, exhaust pipes etc. The main aim of the present work is to expand the AA2014 alloy tubes with different die sets without any fracture. Deform 2D software was used for performing simulations on expanding the tubes with different die set (punch) values having differed forming angles (α = 15°, 30° and 45°) and expansion ratios (rp/r0 =1.39, 1.53 and 1.67). Experiments were also conducted and the results correlate with the simulation results. The results shows that for the punch having less cone angle (α) values the linear displacement is more rather than higher cone angles. But in the case of higher cone angles the radial displacement is more than the linear displacement.

1. Introduction
Inter connectors such as elbows, reducers, adaptors; sockets etc. are required to join tubes together. Such shapes are often produced on the tube ends using secondary operations such as, punching, drilling and machining. Expansion and reduction operations done on such tubes are limited by the formability of the tubes concerned. Many researchers have performed experiments and simulations on the expansion and reduction of different materials.

B. P. P. Almeida et. al [1] performed expansion and reduction studies on AA6060 tubes. They explained three different modes of deformation. M. L. Alves et. al [2] conducted tube end forming experiments on AA6060 alloy. B.P.P.Gouveiaet. al [3] presented the compression beading and nosing of thin walled tubes using die sets. Experimental and theoretical investigations were performed on AA6060 alloy, a natural age hardening aluminium alloy, to determine its formability limits. To understand the specific energy absorption capacity of flared and expanded aluminum tubes. Jialing Yang et. al [4] conducted experiments by using four conical-cylindrical dies. The tubes were pressed on to a series of conical dies with different semi-angles. Based on these experimental results the characteristics of force-stroke curves in different deformation modes were discussed. They also discussed effect of lubrication, effect of material thickness, effect of conical angle, energy absorption efficiency during expansion of tubes. A. Karrechet. et al [5] developed an Analytical model for the expansion of tubes under tension. The model takes into account thickness along the expanded zone, contact pressure at the mandrel-tube interface and yielding threshold due to material hardening and also developed a mathematical model to predict the stress field in the expanded zone. Drawing force required for expansion and the resulting dissipated energy from which optimum mandrel shapes were calculated. Lee Kil Sung et. al [6] studied the energy absorption characteristics of thin-walled square tubes under impact loading, to develop the optimum structural members. They stated that the area under Load-displacement curve is equals to energy absorption of material. R.I.Nepershinet. al [7] developed a model for the process of thin-walled pipe expansion by a punch with curvilinear profile. During this process he mainly considered the wall thickness measurement, hardening, normal anisotropy and contact friction and this model determines the distribution of thickness, contact pressure, hardened material yield load and expansion punch force with respect to punch displacement.
P.A.R. Rosa et al. [8] performed external inversion of thin walled tubes on AA6060 alloy. Lirio Schaeffer et al. [9] gave the brief description of each forming process such as expansion, reduction, internal inversion and external inversion. Z.C. Sun et al. [10] conducted the experiments on AA5052 tubes using different dies. The formability limits of the alloy of different strain hardening index have been experimentally formed and their safe and unsafe working limits have been drawn. Elaborate discussions on the onset of tearing failure and buckling failures have been given. Zhubin He et al. [11] investigated the formability behavior of AZ31B tube at elevated temperature by bulging test. In this study they calculated maximum expansion ratio of the tube and also fracture behavior of the tube and corresponding hardness change were investigated. R. Velu et al. [12] measured interfacial friction Using spike and disc forming test, AA6063 alloy is used as the material. Simulation is carried out for various combinations of height/ diameter of the billet and for different spike diameters. The ratio of the height of the spike to the disc diameter is a measure of the friction force. This ratio is plotted to form calibration curves. Using these curves, the friction present during the cold forming process is quantified. K. Logesh et al. [13] hand Lay-up technique used to fabricate four fiber metals laminates comprising of aluminium alloy 5052-H32 as the skin material and E-glass fiber as the core. The formability behaviour of the laminate was found using Erichsen cupping test using an indigenously developed test setup. The Erichsen cupping index on the specimen varied from 5.95 to 7.28 respectively. The test specimens were investigated through microscope. V. Magesh et al. [14] performed the sheet metal forming punches and die clearance for the forming of automatic ticket vending machine kiosk. Sheet metal forming simulation was performed using ANSYS LS-DYNA and energy graph were obtained to validate the theoretically obtained clearance values. S. P. Sundar Singh Sivam et al. [15] presented a review on a short communication of cold orbital forging process, its characteristics and compare with classical forging. The review revealed the techno economical advantages of the orbital forming process and how advantageous it is over classical forming process. Shubham Dixit et al. [16] studied the surface of sheet metal forming tool is coated by physical vapour deposition with molybdenum disulphide with the aim of preventing their premature failure. The authors found that multilayer coatings has provided with improved adhesion, non-columnar microstructure and harder surfaces.

In the present study, the expansion of thin walled tubes made of AA2014 alloys is studied by varying forming parameters such as die ratio $(r_d/r_o)$, die angle ($\alpha$). Experiments were performed on tubes for different process parameter values and the condition for better formability has been critically analyzed. So, to reduce the cost of experiments we conducted the compression tests on disc samples. From these tests, material strain hardening exponent (n) and strength co-efficient (k) were measured. These n and k values are used as material data and performed the simulations by using Deform 2D software, which is FEM based software.

2. Experimental Work
The material used during the experiments is AA2014 alloy. The chemical composition and mechanical properties of AA2014 alloy is given in Table 1 and Table 2 respectively. The true stress-true strain curve obtained by means of compression test is shown in figure 1.

| Component | Amount (wt. %) | Component | Amount (wt. %) |
|-----------|----------------|-----------|----------------|
| Aluminium | Remaining      | Mn        | 0.605          |
| Cu        | 4.08           | Ni        | 0.020          |
| Mg        | 0.422          | Zn        | 0.009          |
| Si        | 0.697          | Pb        | 0.036          |
| Fe        | 0.273          | Ti        | 0.053          |
Table 2. Mechanical Properties

| Mechanical Property                  | Value    |
|--------------------------------------|----------|
| Ultimate Tensile Strength (MPa)      | 424.55   |
| Yield Stress (MPa)                   | 371.48   |
| Elongation (%)                       | 11.44    |
| Density (g/cm³)                      | 2.7      |
| Poisons Ratio                        | 0.33     |

Figure 1. True stress-true strain curve of AA2014 alloy

The end forming of the tube simulations were carried out on different dies made up of different expansion ratios ($r_p/r_0$) where $r_p$ is the punch radius at its top and $r_0$ is the punch radius at its bottom, different forming angle ($\alpha$) and a bottom die to hold the work piece and shown in figure 2. Experiments were conducted on tubular specimens of inner radius, $r_0 = 18$ mm and a wall thickness of 2 mm. The length of the tube was taken as 90mm. The experiments were planned with an aim of understanding the main process parameters that govern the expansion of thin-walled tubes.

Figure 2. Schematic representation of expansion of thin walled tubes
The governing process parameters considered for the expansion process are i) \( r_p/r_0 \) ratio (1.39, 1.53 and 1.67) and ii) the forming angle (\( \alpha = 15^\circ, 30^\circ \) and \( 45^\circ \)) of the punch. The simulations performed as per the plan given in Table 3.

| Run | \( \alpha \) (degrees) | \( r_p/r_0 \) | \( t_0 \) (mm) |
|-----|-------------------------|----------------|----------------|
| 1   | 15                      | 1.39           | 2              |
| 2   | 15                      | 1.53           | 2              |
| 3   | 15                      | 1.67           | 2              |
| 4   | 30                      | 1.39           | 2              |
| 5   | 30                      | 1.53           | 2              |
| 6   | 30                      | 1.67           | 2              |
| 7   | 45                      | 1.39           | 2              |
| 8   | 45                      | 1.53           | 2              |
| 9   | 45                      | 1.67           | 2              |

The experiments were done on a hydraulic press of 50 ton capacity. It consists of ram, A PC-based data logging system and thrust pad. The hydraulic press with the die set is given in figure 3.

Friction has an important influence in metal forming operations, as it contributes to the success or failure of the process. The friction condition at the contact interface between the tube and the die were estimated by means of ring compression tests on ring test samples (6:3:2 proportions) prepared. i.e. OD = 18 mm, ID = 9 mm and Height = 6 mm. Hydraulic press was used to compress the ring samples for different height reductions and shown in figure 5. The friction value found from the graph is 0.31. Figure 4 shows the compressed ring test samples to various % height reductions.
Compression test can be described as the compression of a cylindrical test piece between plane parallel dies with or without lubricated surfaces. Hydraulic press was used for compress the samples for different height reductions and measured the bulk diameter, final height and calculated the stress stain values and plot the graph between true stress and true strain. Figure 7 gives the n and k values and the values can be found 0.126 and 699 MPa respectively. Figure 6 shows the compressed cylindrical disc samples to various % height reductions.

Deform 2D is a simulation software has been used to analyze the modes of deformation and also to optimize the die angles and the process parameters. The work piece is constrained at the bottom end and other end is free to deform radially. This FEM model consists of two axi-symmetric parts one is tube and another one is punch. Aluminium 2014 material is used in this simulation. The flow-stress equation for the material is given below.

\[ \sigma = K \varepsilon^n \]

Where, \( \sigma \) is stress, \( K \) is strength co-efficient (699 MPa), \( \varepsilon \) is strain and \( n \) is strain hardening exponent (0.126).

The Deform software is used to simulate the plastic flow of work piece materials during the forming process. The minimum work rate principle can be expressed mathematically as the following functional form:
\[ \pi = \int \varepsilon \dot{\varepsilon} dV - \int \frac{\sigma}{\varepsilon} dV \]  
\[ \int \frac{F_s u_s ds}{s} \]  

(2)

Where \( \sigma \), \( \varepsilon \), \( F_i \), and \( u_i \) are the effective stress, effective strain-rate, surface tractions and the velocity components respectively. The first term in equation 2, is body forces and second term is the surface traction forces.

3. Results and Discussions

Experiments were conducted as per the experimental plan. The results are tabulated in Table 4. Figure 8(b) shows the photograph of the tube expanded with the process parameters \( \alpha = 30^\circ \) and \( r_p/r_0 = 1.53 \), \( t=2 \) mm. In this case the tube is fractured when the linear displacement of tube reached 6 mm length. Figure 8(c) is the simulated sample with same process conditions.

The load vs. displacement curves for the simulation as well as experimental results were plotted as shown in figure 8(a) to understand when and how the failure occurred. The path is almost same for both results. Good agreement obtained for both simulation and experimental results. The die was pressed up to 20 mm inside the tube of length 90 mm. The condition of the tube after deformation was observed and the different modes of forming were analyzed.

![Image](image.png)

**Figure 8.** (a) Load vs. Displacement curve for experimental and simulation (b) Experimental Sample (c) Simulation Sample.

**Table 4.** Summary of test results for aluminium tubes and dies

| Run | Load (KN) | Radial Displacement (mm) | Expansion ratio | Linear Displacement |
|-----|-----------|--------------------------|-----------------|-------------------|
| 1   | 53.2      | 41.75                    | 15.9            | 14                |
| 2   | 47.9      | 41.96                    | 16.5            | 12                |
| 3   | 46.8      | 41.792                   | 16              | 11                |
| 4   | 34.0      | 42.794                   | 18.8            | 9                 |
| 5   | 24.0      | 42.186                   | 17.1            | 6                 |
| 6   | 23.7      | 42.14                    | 17              | 6                 |
| 7   | 23.5      | 43.                       | 30.5            | 7                 |
| 8   | 23.5      | 43.                       | 30.5            | 5                 |
| 9   | 23.3      | 43.                       | 29.4            | 5                 |

The critical value of the damage factor (Cockcroft & Latham) \( D_f \), is defined by

\[ D_f = \int \frac{\sigma}{\varepsilon} d\varepsilon = 0.114 \]  

(3)
The calculated damage value through experiments is substituted in deform and performed the simulations. The location of crack initiation is as same as experimental results and the highest value is found to occur at the upper edge of the tube and its magnitude provides a good estimate of the critical level of damage. From figure 9 it is found that the punch having less cone angle (α) values the linear displacement is more rather than higher cone angles.

3.1 Expansion ratio

The radial expansion ratio is calculated by

\[ \lambda = \frac{D_{\text{max}} - D_0}{D_0} \times 100\% \]

(4)

Table 5 Formed tubes with combination of different process parameters

| \( r_p/r_0 \) | \( r_p/r_0=1.39 \) | \( r_p/r_0=1.53 \) | \( r_p/r_0=1.67 \) |
|---|---|---|---|
| \( \alpha = 15^\circ \) |
| \( \alpha = 30^\circ \) |
| \( \alpha = 45^\circ \) |

4. Conclusion

Simulation studies on AA2014 tubes were performed by subjecting the tubes to different dies having different profiles. Experiments conducted on tubes and found the critical damage value as 0.114 and using these damage value simulations were performed. The location of crack initiation is as same as experimental results and the highest value is found to occur at the upper edge of the tube and
its magnitude provides a good estimate of the critical level of damage. The simulations revealed that the punch having less cone angle (α) values the linear displacement is more rather than higher cone angles. But in the case of higher cone angles the radial displacement is more than the linear displacement.

References

[1] B. P. P. Almeida, M. L. Alves, P. A. R. Rosa, A. G. Brito, P. A. F. Martins, “Expansion and reduction of thin-walled tubes using a die: Experimental and theoretical investigation”, International Journal of Machine tools & Manufacture, 2006, 46, pp. 1643-1652

[2] M. L. Alves, B. P. P. Almeida, P. A. R. Rosa, P. A. F. Martins, “End forming of thin-walled tubes”, Journal of Material Processing Technology, 2006, 177, pp. 183-187

[3] B. P. P. Gouveia, M. L. Alves, P. A. R. Rosa, P. A. F. Martins, “Compression beading and nosing of thin-walled tubes using a die: experimental and theoretical investigation” International Journal of Mechanics and Materials in Design, 2006, 3, pp. 7-16.

[4] Jialing Yang, Min Luo, Yunlong Hua, Guoxing Lu, “Energy absorption of expansion tubes using a conical-cylindrical die: Experimental and numerical simulation”, International Journal of Mechanical Sciences, 2009

[5] A. Karrech, “Analytical Model for the Expansion of tubes under tension” Journal of Material Processing Technology, 2010, 210, pp. 356-362.

[6] Lee, Kil-Sung., Yang, Yong-Jun., Sun, Kyu-Kim., Yang, In-Young, “Energy absorption control Characteristics of aluminium Thin-Walled Tubes under Impact Load”, Acta Mechanica Sinica, 2008, 21(4).

[7] R. I. Nepershin, “Thin-walled pipe expansion by a punch with curvilinear profile”, Journal of Machinery Manufacture and Reliability, 2010, 39, pp. 66-72.

[8] P. A. R. Rosa, J. M. C. Rodrigues, P. A. F. Martins, “External inversion of thin-walled tubes using a die: experimental and theoretical investigation”, International Journal of Machine tools & Manufacture, 2003, 43, pp. 787-796.

[9] Lirio. Schaeffer, Brito, M. G. Alberto, “FEM Numerical simulation and experimental investigation on end forming of thin-walled tubes using a die”, Steel research int., 2007, 78, pp. 10-11.

[10] Z. C. Sun, H. Yang, “Study on forming limit and feasibility of tube axial compressive process”, Journal of Material Processing Technology, 2007, 187-188, pp. 292-295.

[11] Zhubin He, Yanli Lin, Jia Wu, Shijian Yuan, “Study on the formability and deformation behavior of AZ31B tube at elevated temperature by tube bulging test”, Journal of Materials Engineering and performance, 2010, DOI: 10.1007/s 11665-010-9744-8.

[12] R. Velu, Moses Raja Cecil, “Spike and disc forming test for friction measurement in cold forming of aluminium alloys”, Indian Journal of Science and Technology, 6(4), 2011 June, pp. 652-656.

[13] K. Logesh, V. K. Bupesh Raja, R. Velu, “Experimental Investigation for Characterization of Formability of Epoxy based Fiber Metal Laminates using Erichsen Cupping Test Method”, Indian Journal of Science and Technology, 8(33), DOI: 10.17485/ijst/2015/v8i33/72244, 2015 December, pp. 2-6.

[14] V. Magesh, S. Sundar, S. Karuppudaiyan, “Finite Element Analysis of Wrinkling and Shearing of Sheet Metal Forming”, Indian Journal of Science and Technology, 9(34), DOI: 10.17485/ijst/2016/v9i34/95252, 2016 September, pp. 2-5.

[15] S. P. Sundar Singh Sivam, V. G. Uma Sekar, Avishek Mishra, Arpan Mondal, Shubham Mishra, “Orbital Cold Forming Technology - Combining High Quality Forming with Cost Effectiveness - A Review”, Indian Journal of Science and Technology, 9(38), DOI: 10.17485/ijst/2016/v9i38/91426, 2016 October.

[16] Shubham Dixit, Pokharkar Pankaj Popat, Siddharth Singh Rawat, S. Sivarajan, “Multilayer PVD Surface Engineered Coatings for Sheet Metal Forming Tools”, Indian Journal of Science and Technology, 9(41), DOI: 10.17485/ijst/2016/v9i41/103311, 2016 November, pp. 1-5.
[17] DEFORM-2D V8.1. Scientific Forming Technologies Corporation, Graphical User Interface (8.1.0.15.23) Built on 2004/09/02.