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Energy Absorption and Axial Tearing Behaviour of Metallic Tubes Using Angled Dies: Experimental and Numerical Simulation

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***Abstract*—**This paper concerns about the experimental and numerical investigations of energy absorption and axial tearing behaviour of aluminium 6060 circular thin walled tubes under static axial compression. The tubes are received in T66 heat treatment condition with fixed outer diameter of 42mm, thickness of 1.5mm and length of 120mm. The primary variables are the conical die angles (15°, 20° and 25°). Numerical simulations are carried on ANSYS/LS-DYNA software tool, for investigating the effect of friction between the tube and the die.

***Keywords*—**Angled die, ANSYS/LS-DYNA, Axial tearing, Energy absorption.

I. INTRODUCTION

THIN walled metallic tubes are widely used as energy absorbing devices for absorbing kinetic energy during collisions. They absorb energy through their plastic deformation or crack propagation. Different kinds of impact energy absorbers which absorb energy through their plastic deformation were well reviewed in [1]. This paper is focused on energy absorption capabilities of circular aluminium tubes through their axial tearing or cracking.

The average force obtained by tearing the tubes is somewhat lesser than the average force obtained from progressive folding of a tube, however, high crush efficiencies in the order of 95% can be achieved [2]. The authors in [3] conducted the experiments to investigate the tearing behaviour of the square tubes, as they compressed the tubes between flat plate and pyramidal die. Axial tearing and curling behaviour of circular metallic tubes are studied by [4]. They compressed the tubes between flat plate and conical die.

For reducing the experimental costs and time consumption, finite element simulations are used as a powerful tool for solving most complex problems associated with crash. A lot of numerical investigations were found on energy absorbers in the literature. Most of them investigated the behaviour of metallic tubes which are collapsed by folding progressively [5] due to compression between two flat plates and small number of investigations was present focusing on tube internal inversion [6] and tube external inversion [7] using angled dies. But the number of numerical (simulations) investigations focusing axial tearing of metallic tubes and their capability of energy absorption within the literature might be very few or none. The software ANSYS/LS-DYNA [8] was used in this research, where the numerical modelling was developed using the ANSYS-preprocessor and later written as transient nonlinear explicit code LS-DYNA file for obtaining deformed modes and force-displacement graphs.

II. EXPERIMENTAL SETUP

The quasi-static experimental setup comprising of aluminium tube and conical die was shown in Fig. 1 (c) with the carried measurements. The Aluminium EN AW 6060 (AlMgSi0.5 alloy) tubes are received in T66 state. The tubes are designed with 42mm mean diameter (D), 1.5mm thickness (t) and 180mm in length (L_t). The solid conical die used for the analysis is made of stainless steel. It has a constant radius on top (R_t) of 17mm and also has a constant length from top to base of a die (L_d) equal to 50mm. The base radius of the die (R_b) is made to vary with respect to change cone angle (α). The cone angles used in the analysis are α= 15°, 20° and 25° respectively and the formula used for measuring the base radius of the cone which depends on R_t, α and $L_d$of the cone is given by,

$$R_b = R_t + (L_d * tan\alpha) \quad (1)$$

Before starting the experiments,5 evenly distributed slits are made at the lower end of the tubes which are in contact with die. Each slit has a pre-cut length of 6mm. The quasi static experimental setup was shown in Fig. 1. During quasi static compression of the tubes, the bottom of the die was fixed to zero displacement in all directions. The top (head) plate was made to move axially down with a velocity of 10mm/min. The force and cross head displacement values are automatically stored in the computer for every 5ms through data acquisition. The total energy absorption after the experiment is equal to the product of total crush displacement and average force.

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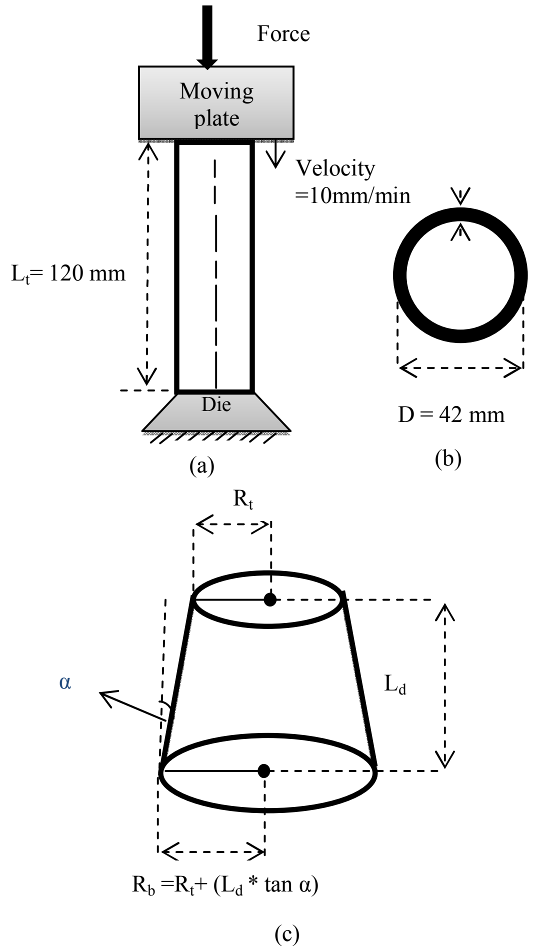


Fig. 1 Quasi-static experimental setup (a) 2D view of experimental set up (b) Top view of the tube (c) Illustration of conical die

III. Numerical Modelling

The software tool ANSYS/LS-DYNA features all the capabilities that are necessary for modelling a system with the characteristics of the given problem. The numerical modelling is classified into four steps as follows.

A. Element Type

For modelling metallic tube and conical dies, an element type ‘Shell 163’ (an explicit thin shell) was used. This element type has 4 nodes with 12 degrees of freedom at each node (i.e., translations, rotations, accelerations and velocities in X, Y and Z directions). “Belytschko-Tsay” fully integrated element formulation was used in order to eliminate the hour glassing problems that are likely to occur when large deformations take place. Three integrated points through the thickness of element was chosen throughout our analysis to obtain accurate results.

B. Material Modelling and Meshing

TABLE I
Material Properties of Aluminium and Rigid Materials

Material Properties	Steel	Al-6060(T66)
Density (kg/m^3)	7600	2800
Young’s Modulus (Pa)	210e9	69e9
Poisson's Ratio	0.3	0.3
Yeild strength (Pa)	-	206e6
Tangent modulus (Pa)	-	320e6
Failure strain	-	0.12

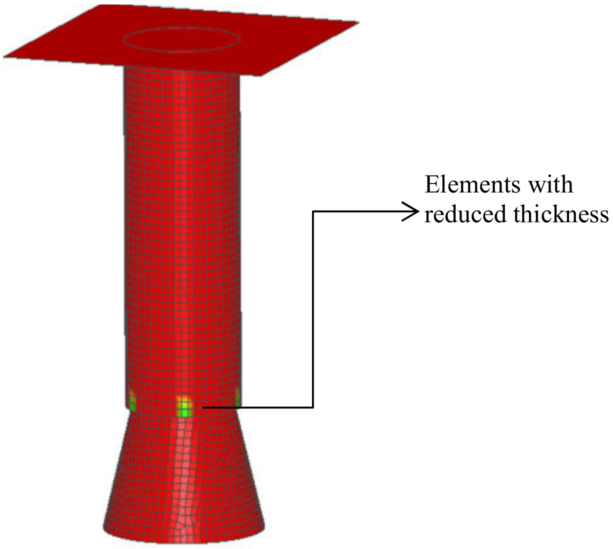


Fig. 2 Geometric model of tube, die and moving plate

The aluminium tube was modelled with strain rate independent inelastic bilinear isotropic hardening. The material properties thus required for material modelling of aluminium tube is given in Table I. For modelling top plate and bottom die, the material model ‘Rigid’ was chosen. The advantage of choosing `Rigid` model is that they do not show any deformation at all and significant reduction of solution time. Although the rigid materials are not subject to deformation, realistic values for the material properties must be defined [9]. The steel material properties are used for modelling rigid body as given in Table I. The tube and dies modelled in the simulations has the same dimensions as in the experiments. The tube thickness is the node thickness which can be defined using real constants of an element in ANSYS preprocessor. All the surface areas of the tube and the die are meshed with a constant element size of 3mm.The top moving plate modelled with single shell element, so no meshing is required. For modelling a slit of length 6mm on the tube as in experiments, two elements (each element size is 3mm) at the base are selected. Initially the selected element thickness is updated to 0mm, but it was found that LS-DYNA is not recognizing the value zero. In the next case the thickness value is updated to 10^{-7}mm, which is very much lesser than the original thickness of tube which is 1.5mm. Now in this case the LS-DYNA recognized the reduction of thickness on the selected elements. The same procedure of reducing the thickness of elements is carried at four other places with equal spacing between them on the bottom end circumference of the tube, in order to be sure that they may work as 5 initial slits as in experiments. The modelled tube which differentiates the thickness reduced elements from other elements along with a rigid plate and the die is clearly shown in Fig. 2.

C. Loading and Boundary Conditions

In transient analysis the loads must be defined in terms of time. Two array parameters "TIME" and “VELOCITY" are used. Under array parameter "TIME" we used the 1x2 array for setting the start time to zero and the solution end time to one second. Under array parameter “VELOCITY", the velocity of the moving plate was defined. The velocity curve is a straight line with constant velocity of 100mm/s. The rigid body has six degrees of freedom (i.e. rotations and translations in x, y, z directions). The moving plate is supposed to move in negative Z-direction axial to the tube, and constrained to all other translations and rotations. The bottom die is constrained to all rotations and translations.

D. Contact Definitions

After creating three parts (tube, rigid die and rigid plate), the contacts between them have to be defined. A‘NODE-TO_SURFACE’ contact was used between moving plate and tube with a static friction coefficient of 0.2. An ‘AUTOMATIC_SURFACE_TO_SURFACE’ was employed between tube and die, permitting the friction sliding. The friction coefficient values employed between the tube and the tube will be discussed in results section.

After modelling the system with the above steps the ANSYS (.DB) file was written or converted to LS-DYNA keyword (.k) file, where the inelastic rate independent isotropic hardened material aluminium was automatically transferred to ‘Plastic Kinematic’, material model 3 in LS-DYNA. In the material card β=1 indicates the material is isotropic hardened, β=0 indicates the material has kinematic hardened behaviour. In LS-DYNA it is possible to erode the elements when the elements reached the maximum strain. So a maximum (failure) strain value of 0.12 from Table I was used as input in the material card for propagating the crack during compression.

IV. RESULTS DISCUSSION AND COMPARISON

A. Experimental Results

The experimental force-displacement graphs thus obtained by axial tearing of aluminium tubes under static axial compression using different die angles are shown in Fig. 3 the collected experimental data was listed in Table II.

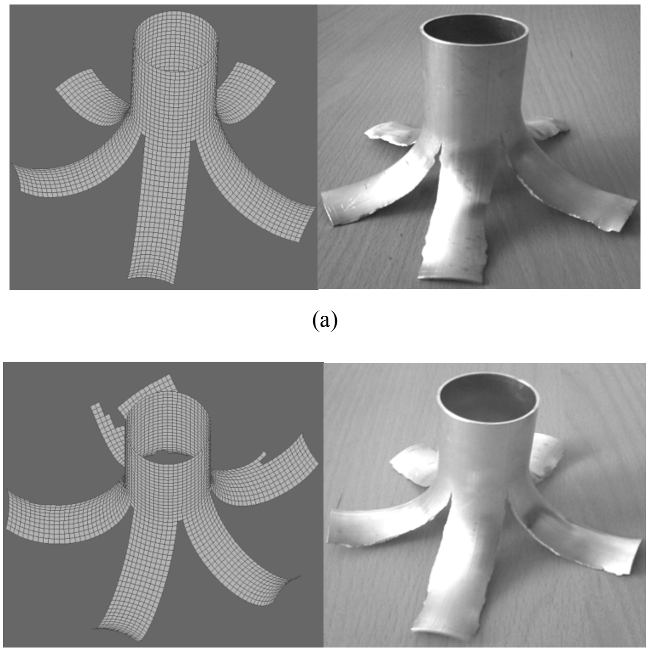
Fig. 3 Experimental force-displacement force with respect to varied die angles

The experimental results showed that the energy absorption of aluminium tube increased approximately 22.8% as the die angle increases 15° to 25°.The crash parameter called “Crush efficiency” which is the percentage ratio of maximum force to average force from a force-displacement graph was also listed in the TABLE II, a maximum of 80.4% was obtained from the tube crushed on 20° angled die and a minimum of 76.4% was obtained from the tube crushed on 25° angled die ° to 25°.

TABLE II
COLLECTED IMPORTANT DATA FROM EXPERIMENTS

Die angle (α)	Maximum force (kN)	Average force (kN)	Energy absorbed (J)	Crush efficiency (%)
15°	5.93	4.70	376	79.2
20°	6.46	5.20	416	80.4
25°	7.56	5.78	462	76.4

B. Comparison of Deformation Modes


(a)

(b)

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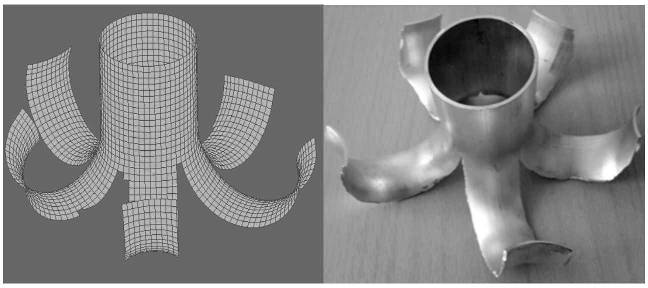


(c)

Fig.4 Comparison of deformation modes from simulations and experiments (a) 15° die (b) 20° die (c) 25° die

The deformation modes of aluminium tubes thus obtained after performing experiments and simulations are shown in Fig. 4 for comparison. All the tubes from the experiments and simulations tore axially with 5 strips because of 5 initial slits.

C. Comparison of Force-Displacement Graphs

Fig. 5 shows the experimental-numerical comparison of force-displacement curves of an aluminium tube compressed over 15° angled die. The experimental force-displacement curve shows that the force is gradually increasing with crushing or compressive displacement. Once the axial cracks starts forming from the slits, then the force in the system is equal to the sum of force required in stretching and tearing the tube, plastic bending of strips and the frictional force between the tube and the die [4]. For simplicity consider the tubes used in the experiments have uniform thickness and diameter, and they exhibit constant stretching and tearing force, throughout the crushing process. So the remaining factors which influences the force during the crushing is the plastic deformation of strips and the frictional force between the tube and the die. The numerical simulations are used to investigate the effect of plastic bending of strips and frictional coefficient (μ) on the force with respect to the crushing displacement, where μ is directly proportional to frictional force. In order to investigate the influence of plastic bending of strips on the crushing force, a constant friction coefficient of 0.25 was used throughout crushing time between the tube and the die. From the simulation curve it was observed that once after the axial cracks formed from the initial slits, the force curve with respect to displacement keeps on increasing from 3.8kN and ended up on 4.2kN (i.e., approximately 10% more). From the experimental curve the difference is observed as approximately 30%. So the reaming factor which needs to be adjusted is the friction between the tube and the die. After performing a series of simulations in order to fit the simulation curve with the experimental curve, different friction coefficients with incremental order as listed in Table III are chosen between the starting time of zero seconds and end solution time of one second. The simulated curve thus obtained is compared with experimental curve is shown in Fig. 6 (a). The same set of friction coefficients are also used in the simulations between the tube and 20° and 25° angles dies. The simulation curves are compared with their respective experimental curves as shown in Figs. 6 (b) and (c). The experimental-simulated force-displacement graphs showed reasonably good in agreement with each other.

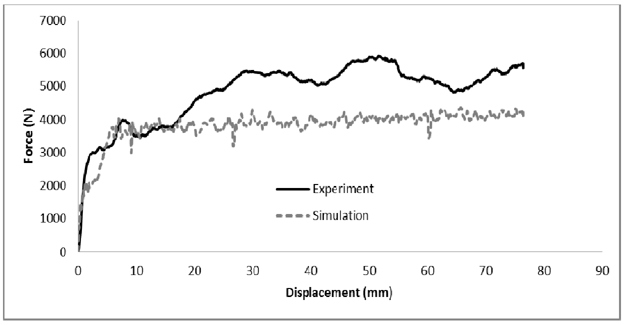
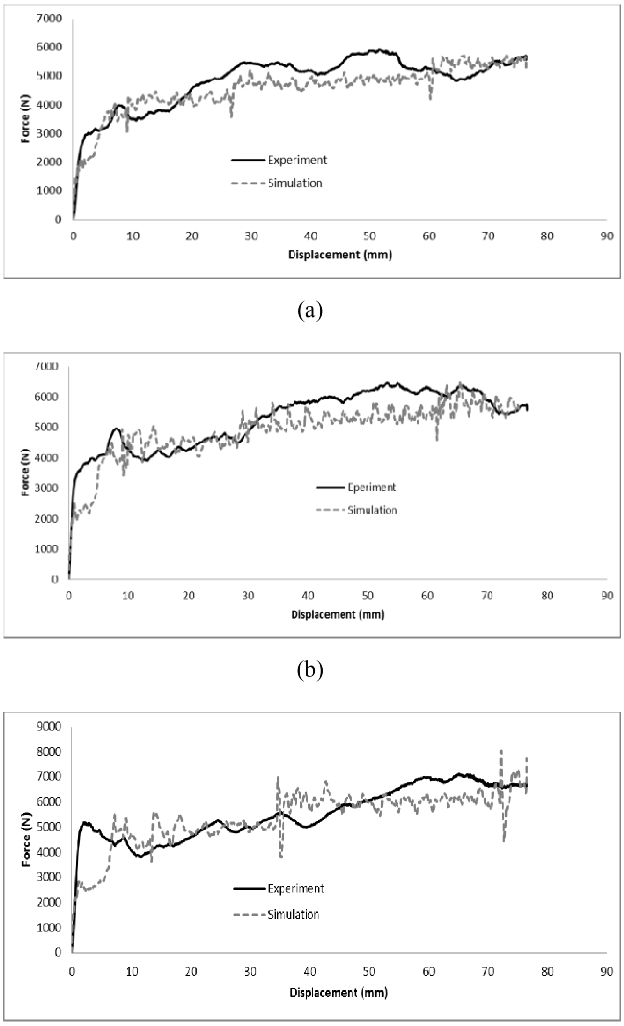


Fig. 5 Comparison experimental and numerical of force-displacement curves of a tube on 15° angled die (μ is constant=0.25)



(a)

(b)

(c)

Fig. 6 Comparison experimental and numerical of force-displacement curves of a tube on (μ varies) (a) 15° die (b) 20° die (c) 25° die

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TABLE III
CHANGE OF FRICTION COEFFICIENTS WITH CHANGE IN TIME

Time (s)	Friction coefficient (μ)
0 – 0.2	0.25
0.2 – 0.4	0.3
0.4 – 0.8	0.35
0.8 – 1	0.4

D. Comparison of Energy Absorption

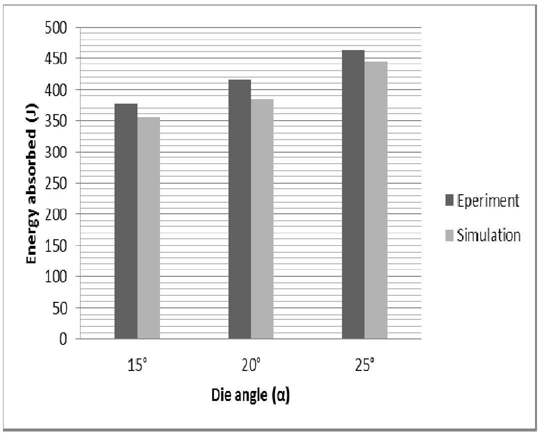

Fig. 7 Experimental-numerical comparison of energy absorption

For comparing the energy absorption of the tubes, the force-displacement graphs shown in Fig. 6 are considered. Fig. 7 shows the comparison of experimental numerical comparison of energy absorption with respect to change in die angles. Both experiments and simulations showed that the energy absorption increases with an increase in die angle.

V. CONCLUSION

The experimental and numerical simulations are carried out for investigating the energy absorption capability of axial tearing aluminium metallic tubes using angled dies. The numerical simulations are carried out with ANSYS/LS-DYNA for investigating the effect of friction between the tube and the die. Both the results showed that the energy absorption increases with an increase in die angle. The deformation modes and force-displacement graphs from experiments and simulations are also well compared and explained. The comparisons showed reasonably good in agreement each other. In the simulations, it was observed the coefficient of friction between the tube and the die keeps on increasing from 0.25 to 0.4 with respect to the crushing displacement. The reason behind the increment of friction with in the system during experiments is unknown. So there is a need to do some experiments which can measure the friction force between the tube and the die during the crushing process is considered as future prospects in accordance with the present analysis.

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