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## Investigation of External and Internal Inversion for Aluminum Tube with Various Die Parameters Effect

**Abstract-** Finite element modeling has been conducted to investigate the effect of die radius fillet, tube wall thickness, and friction coefficient on both external and internal inversion for the aluminum tube. A 3D model was used to build the contact pair for the aluminum tube and the steel die. Due to the axial symmetry, a  $45^\circ$  sector for the contact pair has been chosen. It has been found that there is an important role for those parameters to govern the inversion process and the mode of deformation beside the value of the applied force. No local buckling was seen in the external inversion in contrast with internal inversion. A good correlation for current results with experimental one that has been got by others.

**Keywords-** Inversion, finite element, aluminum tube

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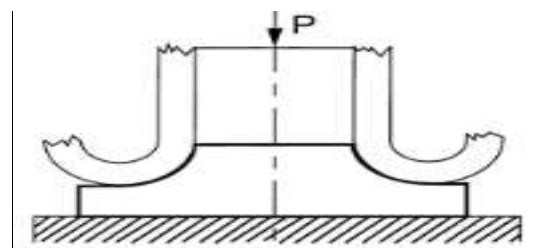
### 1. Introduction

Impact absorbers are used in dynamics parts like lifts, aircraft, vehicles, railway wagons, and machines. These mechanisms are used to reduce accidents to restrict property damage and minimize injuries in people [1]. Aluminum tubes used as efficient shock absorption devices and considerably used to impact absorbers [2]. One of the simplest impact absorbers is tube inversion that can take in energy both in tension or compression forms. Such a process could be shortened by letting aluminum tube (or metal tube) to be turned outside-in as an internal inversion or turned outside-in as an external inversion [3]. A thin wall metal tube pushed inside a hard die with convenient fillet radius, then allows the tube to move in inverse directions (see Figure 1). The big plastic deformation implicated in tube inversion event to ductile materials, like steels or aluminum alloys. The notion of inversion of the tube can be expanded if properties, deformation, and mechanical behavior are completely understood and to many engineering applications can be used depends on this notion especially in safety mechanisms [4]. Common shapes of energy absorbers with different deformation modes have been reviewed in this paper. Different shapes such as circular tubes, frusta, struts, honeycombs, and square tubes. Different modes of formation of circular tubes such as axial crushing, lateral flattening, lateral indentation, splitting, and inversion. Non-collapsible systems like tube expansions or lead extrusions are considered to be beyond the scope of this review [5]. Nowadays, various

applications on tube inversion idea have been done such as cushioning airdrop cargo, helicopter seats, force actuating collapsible steering wheels, and smooth spacecraft landing. An approximate technique of the deformation of cylindrical shells subjected to axial loading has been done by Alexander (Figure 1) [6].

A study was performed by Andrews [7] to investigate the shock absorption rate of metal tube subjected to quasi-static loading. Finite element modeling has been used to study the effect of conical die angle, tube diameter and material behavior both external and internal inversion for the aluminum tube. It has been found that there is a significant role for conical die angle to govern the inversion process and the mode of deformation beside the value of the applied force. A local buckling takes place in the internal inversion for all half die angles [8].

The aim of this investigation is to study the influence of die fillet radius, the wall of the tube, thickness and friction coefficient on the load force in both internal and external inversion of aluminum alloy (Al6061).



**Figure 1: Axial mode of deformation for tube inversion [9]**

**2. Mathematical Model**

Many researchers have analyzed external and internal inversion [10,11] of metal tubes. A steady-state inversion force can be achieved by implementing the theory of virtual work assuming a deformation domain (Figure 2), so that the tube wall suffers axial bending at A, the contact area with the die, circumferential extension in the toroidal region and unbending at B.

$$p = 2\pi\sigma_o t \left[ \ln\left(\frac{a_o}{R}\right) + \frac{t}{4b} + \mu b \int_0^{\phi_o} \frac{\cos\phi}{a} d\phi \right] \quad (1)$$

for  $0 < \phi < \pi/2$ . For  $\pi/2 < \phi < \pi$ , the upper limit of the integral is set at  $\pi/2$ . For  $\phi > \pi$ , the tube has passed hinge B, and equation 1 is replaced by the steady-state equation:

$$p = 2\pi R \sigma_o t \left[ \ln\left(1 + \frac{2b}{R}\right) + \frac{t}{4b} + \frac{\mu b}{b} \right] \quad (2)$$

As shown in Figure 2, these equations provide a reasonable representation for the transient and steady-state load with  $\mu = 0.2$ . Also included in Fig. 2 is the initial elastic response derived using the classical ring-edge load solution for a circular cylinder [13].

**3. Simulation work**

External and internal inversion processes were performed for Al -6061 tube with 70 mm long, walls 1.5, 2, and 3 mm thick, the tube internal radius was 20mm (the same radius of the die was used R).

The investigation was conducted to verify operation feasibility as a function of:

- 1) Die fillet, three radii have been chosen, 3, 5, and 7 mm were examined, so the ratios  $r/R$  between the fillet radius of the die and the internal radius of the tube were 0.15, 0.25, and 0.35.
- 2) Tube wall thickness, where three thicknesses (t) have been tested (1.5, 2, and 3 mm, thus the ratios  $t/R$  between tube thickness and die radius were 0.075, 0.1, and 0.15.
- 3) Friction coefficient, where three coefficients have been chosen 0.02, 0.05, and 0.1 for external inversion and 0.02 for internal inversion for comparison purpose.

The finite element module has been built by using a 45° sector due to the axial symmetry (Figure 3). The simulation has been done by

ANSYS Software release 15. 850-870 solid element (Brick 185) and contact technique with TARGET 170 and CONTACT 175 element have been used. Nonlinear solution and multilinear isotropic material have been chosen to represent the material behavior during the inversion process. Symmetrical boundary condition was used to simulate other sectors. The predicted load multiplied by 8 to get the total value.

The mechanical properties of Al -6061 that have been used were: E (modulus of elasticity) =70GPa,  $\nu$  (poison's Ratio) = 0.3 and yield stress =290 MPa [14]. Displacement has been used in the top area of the tube in order to get the required load that needs to make inversion.

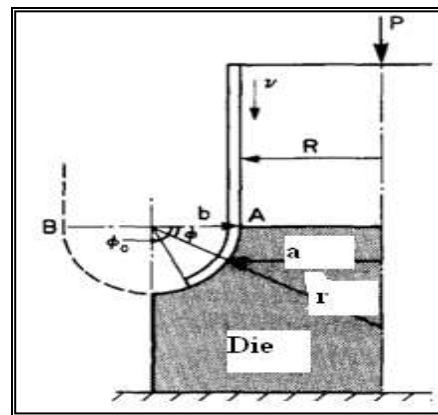


Figure 2: Schematic for inversion parameters [13]

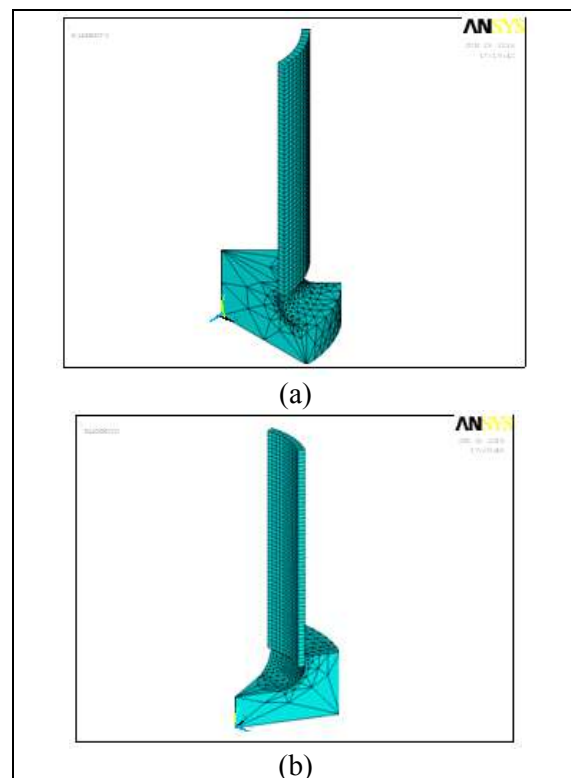
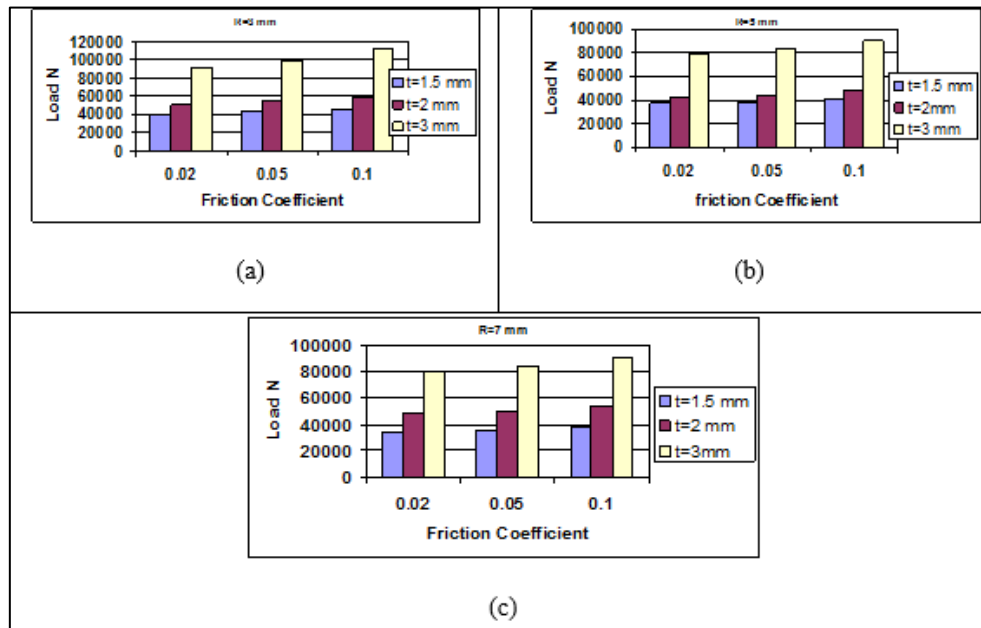


Figure 3: Finite element model for, a) external inversion, b) internal inversion

**Table 1: External inversion results**

	Friction coefficient =0.1			Friction coefficient =0.05			Friction coefficient =0.02		
t/R	0.075	0.1	0.15	0.075	0.1	0.15	0.075	0.1	0.15
r/R	Applied Force N			Applied Force N			Applied Force N		
0.15	91689	98509	110829	43220	53385	59273	39324	50150	91689
	79603	83291	90324	37867	43788	47320	36963	41785	79603
0.35	79411	83800	90729	35844	50454	54190	34174	48093	79411



**Figure 4: Fig.4 Applied load vs friction coefficient (external inversion), a) fillet die = 3 mm, b) fillet die=5 mm, and c) fillet die=7 mm**

**4. Results**

*I. External Inversion*

The deformation process in external inversion is happening by three modes; instability inversion and fracture. The applied force inversely proportional with increasing r/R ratio and proportional with increasing t/R ratio, thus, the die fillet and the tube wall thickness play a common and significant role in the applied force value, the biggest die fillet radius the lowest bending stress, eventually leads to the smallest applied force. The increases in tube wall thickness lead to an increase in applied force due to the increasing radial stress through the wall tube thickness during the inversion process (Table 1). The friction coefficient in the contact area between the tube wall and the die plays a significant role where decreasing this coefficient leads to decreasing the applied force, so controlling the friction coefficient will control the inversion process. Table 1 shows applied force

for several of r/R and t/R with three different values of friction coefficients.

Figure 4 summarizes the results for the applied force versus the coefficient of friction with the die fillet and tube thickness.

No local buckling has been seen and this is because in external inversion the tube undergoes circumference tension in the inversion area, such phenomenon (local buckling) might be seen in very small die fillet or with high friction coefficient.

*II. Internal Inversion*

Two types of deformation have been seen here; inversion and instability but no fracture. In this study, an internal inversion with all parameters in external inversion have been chosen but with friction coefficient 0.02 only. Figure 5 shows the results for the applied load versus tube thickness for internal and external inversion. At thickness 2 and 3mm, the value of force does not include in the figure due to the local buckling.

The results are included in Table 2. Obviously, local buckling occurs in this type of inversion because the circumference stress is compressive.

Generally, the applied force is more than to the corresponding ones in the external inversion.

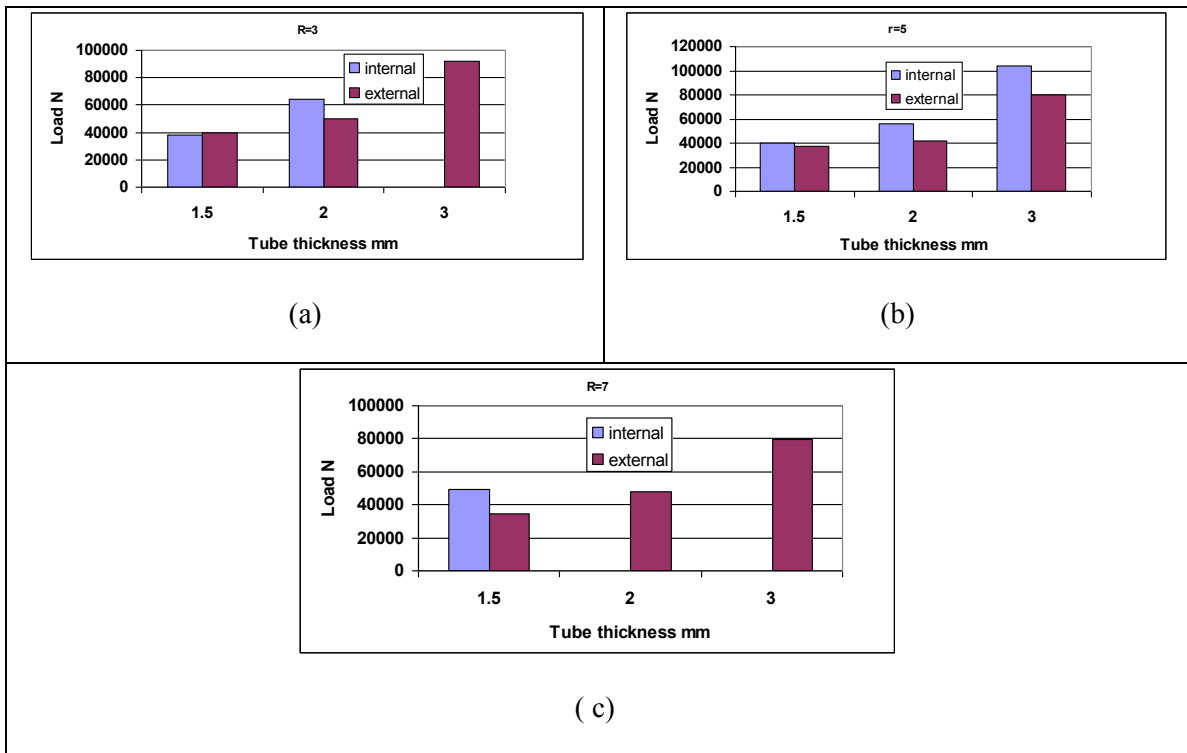


Figure 5: Applied load vs tube thickness for internal and external inversion, a) fillet die = 3 mm, b) fillet die=mm5, and c) fillet die=7 mm

Table 2: Internal inversion results

Friction coefficient =0.02			
t/R	0.075	0.25	0.35
r/R	Applied Force N		
0.15	38304	64354	Buckling
0.25	39819	56181	103654
0.35	49630	Buckling	Buckling

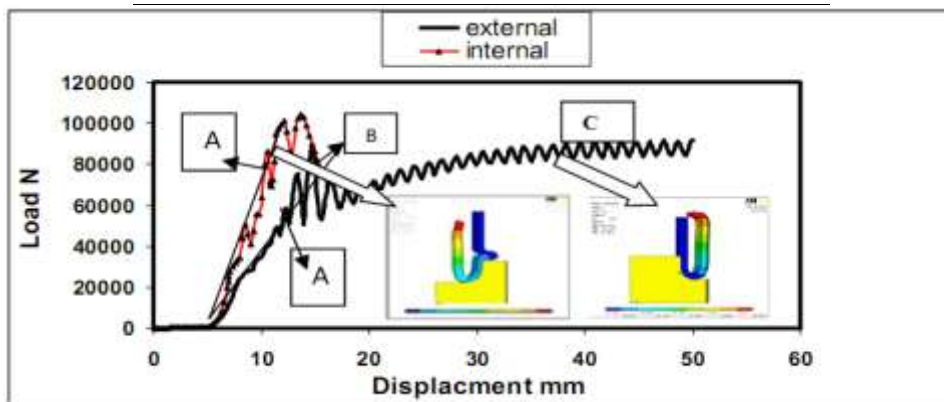


Figure 6: Load-displacement curve for external and internal inversion comparison

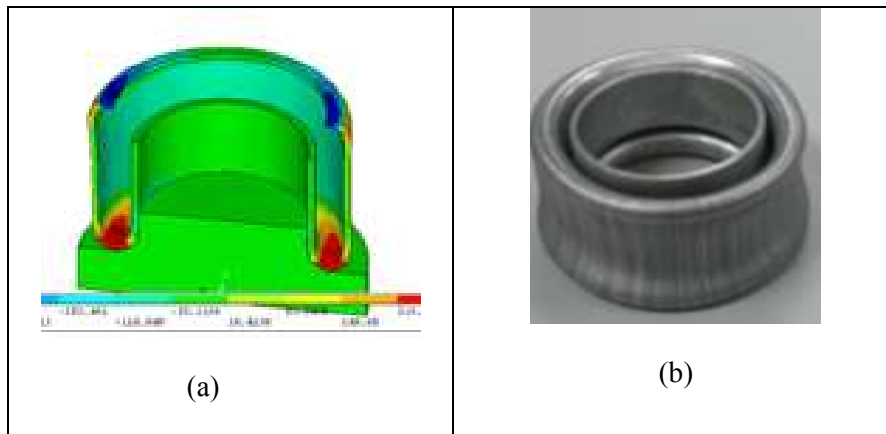


Figure 7: Inversion deformation, a) finite element model, b) experimental inversion [15]

### III. Load-Displacement Curve

Figure 6 shows a load-displacement curve for the simulation of external and internal inversion. Generally, the inversion process consists of three stages:

- 1) From point zero to A: approximately linear relationship between load and displacement.
- 2) From A to B: an inconsistency curve was caused by slipping between the tube wall and die radius.
- 3) From B to C: steady-state tube inversion occurs for external inversion only.

With the same parameters  $r/R$  and  $t/R$  with 0.02 friction coefficients, local buckling has been observed in the internal inversion process.

### IV. Validation of FE Simulation

To validate the results of this study, a comparison with experimental tests has been done. Fig.7 shows the inversion mode performed by finite element simulation and experimental one both for aluminum alloy (Al6061).

## 5. Conclusion

This work shows that the inversion load and the deformation mode govern by different parameters represented by tube thickness, die radius fillet and the coefficient of friction between the tube walls and die surface. So we can conclude the following:

### I. External Inversion

- 1) The ratio  $r/R$  is the most important role parameter that governs this process, where the increase in this ratio the load decrease and vice versa.
- 2) The ratio  $t/R$  has a significant effect in inversion deformation mode and the applied load, where the load proportional with this ratio.
- 3) Friction coefficient has a big influence in specifying the value of the applied load, where increasing friction leads to increasing the load.

- 4) Local buckling occurs with very small fillet radius otherwise no local buckling.

### II. Internal Inversion

The ratios  $r/R$ ,  $t/R$ , and friction coefficient have the same effect in the external inversion process, but local buckling occurs obviously when decreasing die fillet and increasing wall thickness.

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