



Energy absorption of expansion tubes using a conical–cylindrical die: Experiments and numerical simulation

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ABSTRACT

This paper is concerned with the plastic energy absorption behavior of expansion tubes under axial compression by a conical–cylindrical die. The experiments and numerical simulation using FEM are presented in this paper. Experiments were conducted on circular 5A06 aluminum tubes with an internal radius fixed at 22.5 mm and different thicknesses between 1 and 5 mm; the tubes were pressed axially onto a series of conical–cylindrical dies each with a different semi-angle from 5° to 20°, where the radius of the cylindrical part was 24 mm. A numerical analysis was performed to investigate the tube deformation and the friction between the tube and die. A good fit of the experimental data was obtained by taking the value of the friction coefficient $\mu=0.05$. Based on these experimental and numerical results, characteristics of driving force–stroke curves in different deformation modes are discussed in detail. Effects of tube dimensions and semi-angle of the die on steady-state force and energy absorption efficiency are also presented. Based on these experimental studies, a theoretical analysis to explain the deformation mechanisms of the tube expanded by a die is carried out and will be given in a subsequent paper [1].

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1. Introduction

Energy absorbing devices are employed in vehicles to lessen the potential danger of impact accidents. Lu and Yu [2] published a monograph which introduces fundamental topics pertaining to energy absorbers. It was outlined that energy absorbing devices usually include the following features: (1) controlled and constant reactive force, (2) long stroke, (3) stable and repeatable deformation mode, (4) light weight and high specific energy-absorption capacity, and (5) low cost and easy to install.

Circular tubes, which may be loaded laterally or axially, have drawn much attention due to their good energy absorption characteristics [3,4]. For the lateral compression of a single tube a simple analysis was given by DeRuntz and Hodge [5]. Reid and Reddy [6,7] presented a series of papers on the lateral compression of tubes. The axial collapse of tubes in an axisymmetric or a non-axisymmetric collapse mode is a very efficient energy absorption arrangement. Alexander [8] was the first researcher to analyse the axisymmetric collapse mode, while Guillow et al. [9] provided a detailed experimental analysis into the axial compression of thin-walled circular tubes. An inversion collapse mode has been observed for a given condition, when a tube was

compressed against a shaped die or a plate, and this mode has been studied [10–13]. Another collapse mode is splitting and curling of tubes; Stronge et al. [14], Reddy and Reid [15], Huang et al. [16] investigated this collapse mode experimentally and theoretically.

In addition to the three collapse modes mentioned above, expansion of tubes with a conical die can also be used to dissipate kinetic energy by means of plastic stretching, plastic bending and friction. Eddins [17] first proposed a spacecraft soft landing system with rigid spherical dies placed in the metallic tubes. Fig. 1 shows an energy absorbing device based on the expansion of tubes, which may be applied to spacecraft or aircraft soft landing. When an impact load is transmitted to the device, the conical die is pressed into the expandable tubes. Thus the impact energy will be dissipated by the tubes' plastic expansion and friction between the tube wall and die surface; thus the human body and equipment inside will suffer less severe impact.

To understand the performance of this type of energy absorbers, it is essential to study the deformation mechanisms and the energy absorption characteristics of the tube when it is expanded by a die. Nevertheless, the analysis of expansion tubes has, so far, received very little attention and only a few papers have taken into consideration the tube end flaring or instability. Lu [18] presented theoretical expressions for the flaring ratio, tube end downward depth ratio, and tube end strain rate in terms of the tool stroke and velocity in the tube flaring process. Daxner

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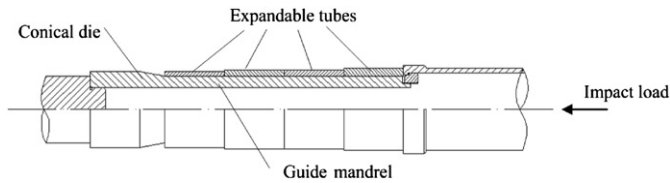


Fig. 1. Sketch of an energy absorber based on tube expansion.

et al. [19] described two instability phenomena which affect the degree of deformation achievable in the tube flaring process: (a) loss of global stability due to ‘concertina’ buckling of the straight part of the tube and (b) diffuse necking caused by the local loss of material stability in the conical part of the tube. Analytical expressions were derived by Fischer et al. [20] for the stress and strain fields as well as the force required for driving the expansion; a rigid-perfectly plastic material model was proposed where the wall thickness within the deformed region of the shell was approximated using a linear function. By means of a comprehensive numerical and experimental investigation, Almeida et al. [21] studied influence of the interfacial friction on material flow and the effect of material damage and strain path on the occurrence of fracture, wrinkling and local buckling. Alves et al. [22] investigated the end forming of thin-walled tubes. They concluded that the expansion and reduction of thin-walled tubes using a die is only achievable within a compact range of process parameters. The final radius, wall thickness, shape and length of the conical section of the tubes as well as the lubrication regime must be properly chosen to avoid ductile fracture, local buckling, and wrinkling. Alves and Martins [23] studied the influence of material flow and damage on the occurrence of successful and unsuccessful modes of deformation with the objective of establishing the formability limits of the free expansion and reduction of thin-walled PVC tubes using a die.

In this paper, the tube and die are considered as a system for impact energy absorption, i.e. a tube and a die energy absorber, and researches have been carried out to obtain a sound understanding of energy absorption characteristics and provide basic guidelines in the application of energy absorbers. For these purposes, we use a series of conical dies to investigate the expansion behavior of circular tubes with different thicknesses experimentally. Next, details of the deformation processes are examined using the non-linear finite-element code MSC.Marc. From the experimental and numerical load–deflection curves, the energy absorption characteristics are then presented. The role of friction and the stress/strain fields are obtained from the finite element analysis for the corresponding experiments. Subsequently, the effect of several parameters is studied; they include the tube thickness, semi-cone angle of the die and the tube length.

From these works it can be found that the energy absorption system with tube expansion has the following advantages: (a) Compared with the tubes axially compressed or in splitting collapse mode, the force–deflection response of expansion tubes is smooth without an initial peak load followed by the fluctuations, which may be insensitive to the impact velocity and thus beneficial for the design of energy absorber. (b) Due to the axial support of the conical dies and the guide mandrels, it is possible to use the expansion tube system as an energy absorber successfully when the angle of load application is no more than 15° off the longitudinal axis of the tube itself, where normally axially compressed systems fail in an Euler-type global buckling mode [6]. (c) Inversion of tubes is only possible when the material is ductile without significant strain hardening, and the overall dimensions of the die radius must be within a compatible range with suitable material properties, in order to achieve the desirable

energy absorbing behavior [3]. When expansion tube is used as an energy absorber less restrictive requirements are needed, which facilitates our design. (d) In addition, expansion tube structures enable thicker tubes to be used to absorb more energy. Thus tubes with a range of thicknesses can be employed in order to obtain a nearly rectangular shaped force–deflection curve, which is ideal in the design of energy absorbers.

2. Experiments

2.1. Experimental setup

The experimental setup is sketched in Fig. 2. Tubular specimens with a fixed inner radius $R_0=22.5$ mm and thicknesses ranging from 1 to 5 mm were placed on the bed of the test machine. All the circular tubes were commercially available and 70 mm long. The rigid die had two parts: the front was cone-shaped with four different semi-angles (γ), 5°, 10°, 15°, 20° and the rest was cylindrical with a radius $R_D=24$ mm. There was a portion in the cone-shaped die where radius is less than the tube’s, in order to guide the die pressing. Its height was fixed, i.e. $S=10$ mm, see Fig. 2. Detailed dimensions of all the specimens and the test results are listed in Table 1.

Tests were carried out on a WAW-100A testing machine under quasi-static conditions. Before the test, the tube was adjusted to ensure that the axes of the die, tube, and testing machine were aligned. Lithium-based grease containing MoS_2 solid lubricant was used to reduce the friction between the tube and the die surface. A preload of 50 N was applied to ensure that the tube was flared symmetrically. The cross-head of the testing machine then pressed the die into the tube at a constant speed of 5 mm/min. The process was stopped when the displacement reached 50 mm.

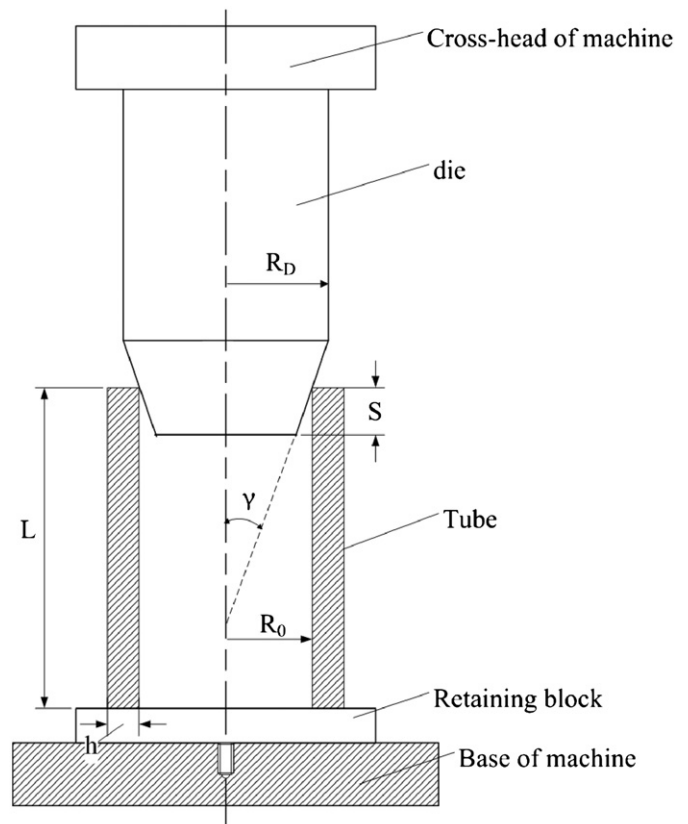


Fig. 2. Sketch of the experimental setup.

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